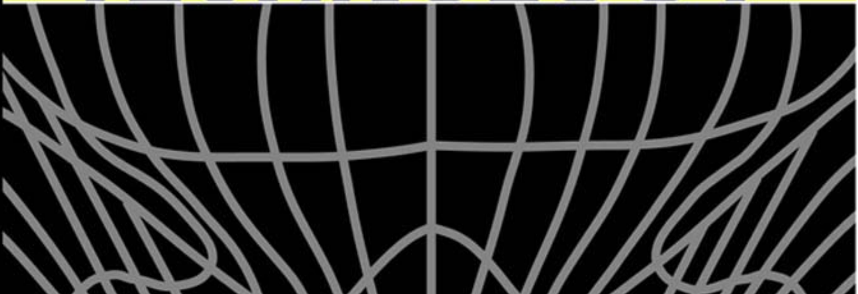
ALUMINUM EXTRUSION TECHNOLOGY



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Aluminum Extrusion Technology

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ASM International®
Materials Park, Ohio 44073-0002

First printing, March 2000

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

ASM International staff who worked on this project included Veronica Flint, Manager of Book Acquisitions, Bonnie Sanders, Manager of Production, Carol Terman, Copy Editor, Kathleen Dragolich, Production Supervisor, and Alexandru Popaz-Pauna, Production Coordinator.

Library of Congress Cataloging-in-Publication Data

Saha, P. (Pradip)
Aluminum extrusion technology / Pradip K. Saha.
p. cm.
Includes bibliographical references and index.
1. Aluminum—Extrusion. I. Title.
TS255.S24 2000 673′.72234—dc21 99-045790

ISBN: 0-87170-644-X
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
http://www.asm-intl.org

Printed in the United States of America

This book is dedicated to the memory of my parents, Sushil K. Saha and Debrani Saha, and my mother-in-law, Hemnalini Saha.

ASM International Technical Books Committee (1999-2000)

Contents

Preface

Aluminum extrusion technology in modern industries, both in the United States and elsewhere, continues to be a subject of discussion and evaluation concerning its application to the working environment. The demand for and application of aluminum extrusion in architecture and in the manufacture of automobiles, small machine components, structural components and especially aircraft, have increased tremendously, and competition in this industry is intense. The extrusion industry is now more than 100 years old. Continuing education is needed to upgrade knowledge about aluminum extrusion technology, both in the academic and industrial communities. Therefore, this book was written to provide many developed ideas, more practical and useful theoretical concepts based on knowledge acquired from research and academic work, industrial working experience, and the review of research and technical papers related to aluminum extrusion technology.

This book provides a comprehensive introduction to the explosion of information that has become available in the field of aluminum extrusion technology during the last fifteen or twenty years. The topics are designed in such a way that this book provides adequate information for the newcomer without boring the expert. Topics are presented with a balanced coverage of the relevant fundamentals and real-world practices so that the relevant person in the aluminum extrusion industry develops a good understanding of the important interrelationships among the many technical and physical factors involved and how engineering science impacts on practical considerations. The ten chapters cover almost all the branches of aluminum extrusion technology:

1. Fundamentals of Extrusion
2. Thermodynamics in Extrusion
3. Extrusion Presses and Auxiliary Equipment
4. Extrusion Die and Tooling
5. Billet Casting Principles and Practice
6. Extrusion of Soft- and Medium-Grade Alloys
7. Extrusion of Hard Alloys
8. Process Control in the Aluminum Extrusion Plant
9. Statistical Process and Quality Control
10. Research and Development

The book *Extrusion,* by Laue and Stenger in German, was revised and translated to English by Castle and Lang and published by ASM International in 1981. In this book, the authors concentrated on process, machinery, and tooling, based on general extrusion technology. *Extrusion* provides a comprehensive and detailed survey of extrusion data, including general principles, extrusion processes, special technology for extruding various materials, design and construction of extrusion presses, extrusion tooling, economics of extrusion, and future developments. In general, there has been no updated information published since 1981.

In the past 18 years, a tremendous amount of technological advancement in aluminum extrusion technology has taken place worldwide, and this information is included in this book, *Aluminum Extrusion Technology*. Furthermore, certain new topics with updated information have been added and described in some detail. This book also provides the key to further information and emphasizes important research and technical papers that are worthy of further study.

Aluminum Extrusion Technology is primarily designed to be used by technical and engineering personnel such as plant managers, process and quality control managers, corporate managers, cast house managers, die shop managers, and research and development managers. The text was written for research students in manufacturing who are working on extrusion technology. It is hoped that by studying this book, the engineering personnel in the aluminum extrusion industry and research students in extrusion will appreciate the current and more detailed information and references.

I would like to express thanks to my wife for her assistance with computer work and to my two lovely daughters for their constant encouragement to accomplish this big effort. I would also like to thank friends and family, especially my father-in-law, Dr. Durgadas Saha.

I am greatly thankful to Dr. Steven R. Schmid (University of Notre Dame), Bill Dixon (QED Extrusion Developments Inc.), Paul Robbins (Castool Precision Tooling), Richard E. Hughes (Physical Metallurgy Consultation and former research scientist of Reynolds Metal Company), and Jeffery D. Morgan (Boeing) for their careful review of the manuscript and valuable suggestions. Special thanks are also due to J.A. Kurtak (SMS, Sutton Division) and Bill Barron, Sr. (Williamson) for providing technical information and photographs. In particular, thanks are due to Tapash Das for his valuable input and suggestions in completing Chapters 8 and 9. I wish to thank Joel Lehman (Florida Extruders International, Inc.) for the opportunity to conduct many experiments and take photographs of many extrusion dies during my stay in this company.

P.K. Saha
Seattle, Washington

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CHAPTER 1

Fundamentals of Extrusion

The first chapter of this book discusses the fundamentals of extrusion technology, including extrusion principles, processes, mechanics, and variables and their effects on extrusion. The extrusion industry is now over 100 years old. A concern within the industry is the continuing education necessary to upgrade knowledge about aluminum extrusion technology, both in the academic and industrial communities.

In a typical university manufacturing engineering and technology course, textbooks, such as Ref 1, normally used in engineering schools across the world cover the principles and very fundamental aspects of manufacturing processes, including metal cutting, rolling, forging, drawing, and extrusion. Engineers and product designers are not specifically taught about the extrusion process in detail in either their university or job training. Surely, proper education is essential for success in the field of aluminum extrusion technology. It is necessary for technical and engineering personnel to be familiar with the fundamental concepts. Once the basics are understood, additional levels of sophistication can be gradually added.

Definition of Extrusion

Extrusion is a plastic deformation process in which a block of metal (billet) is forced to flow by compression through the die opening of a smaller cross-sectional area than that of the original billet as shown in Fig. 1. Extrusion is an indirect-compression process. Indirect-compressive

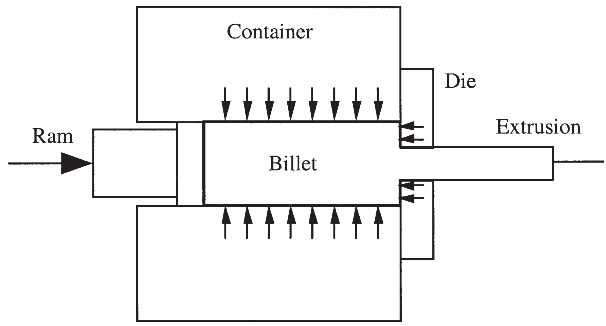

Fig. 1 Definition and principle of extrusion

forces are developed by the reaction of the workpiece (billet) with the container and die; these forces reach high values. The reaction of the billet with the container and die results in high compressive stresses that are effective in reducing the cracking of the billet material during primary breakdown from the billet (Ref 2). Extrusion is the best method for breaking down the cast structure of the billet because the billet is subjected to compressive forces only.

Extrusion can be cold or hot, depending on the alloy and the method used. In hot extrusion, the billet is preheated to facilitate plastic deformation.

Classification of Extrusion Processes

The two basic types of extrusion are direct and indirect, which are commonly used in aluminum industries as shown in Fig. 1 and 6. Solid and hollow shapes are designed and extruded for a wide range of programs:

- Solid sections, bars, and rods extruded from solid billets by direct extrusion (discussed in Chapter 3)
- Tubes and hollow sections extruded from solid billets through porthole or bridge-type dies (for certain alloys) by direct extrusion (discussed in Chapter 6)
- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in the press via floating mandrel) by direct extrusion (discussed in Chapter 3)
- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in the press via stationary mandrel) by direct extrusion
- Critical solid sections, bars, and rods extruded from solid billets with sealed container through the die mounted on the stem by indirect extrusion (discussed in Chapter 3)

- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in press) via stationary mandrel through the die mounted on the stem by the indirect extrusion process

Conventional Direct Extrusion

The most important and common method used in aluminum extrusion is the direct process. Figure 1 shows the principle of direct extrusion where the billet is placed in the container and pushed through the die by the ram pressure. Direct extrusion finds application in the manufacture of solid rods, bars, hollow tubes, and hollow and solid sections according to the design and shape of the die. In direct extrusion, the direction of metal flow will be in the same direction as ram travel. During this process, the billet slides relative to the walls of the container. The resulting frictional force increases the ram pressure considerably. During direct extrusion, the load or pressure-displacement curve most commonly has the form shown in Fig. 2. Traditionally, the process has been described as having three distinct regions:

1. The billet is upset, and pressure rises rapidly to its peak value.
2. The pressure decreases, and what is termed "steady state" extrusion proceeds.
3. The pressure reaches its minimum value followed by a sharp rise as the "discard" is compacted.

Billet-on-Billet Extrusion

Billet-on-billet extrusion is a special method for aluminum alloys that are easily welded together at the extrusion temperature and pressure. Using this process, continuous lengths of a given geometry (shape) can be produced by different methods. Billet-on-billet extrusion is also a viable process in the production of coiled semifinished products for further

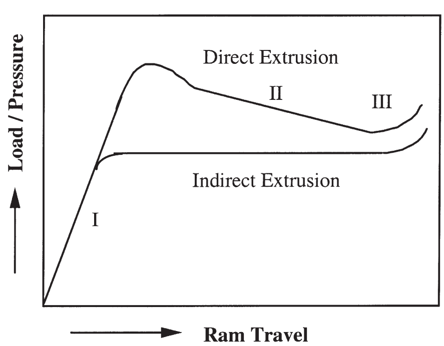

Fig. 2 Variation of load or pressure with ram travel for both direct and indirect extrusion process

processing, such as rod and tube drawing production. Perfect welding of the billet in the container with the following billet must take place as the joint passes through the deformation zone. The following requirements have to be fulfilled (Ref 3):

- Good weldability at the temperature of deformation
- Accurate temperature control
- Cleaned billet surface
- Sawn, clean billet ends free from grease
- Bleeding of air from the container at the start of the extrusion using taper-heated billet as shown in Fig. 3 to avoid blisters and other defects

Two methods of billet-on-billet extrusion have been developed. In the first method, the discard is removed, and the following billet is welded to the one remaining in the welding or feeder plate (Fig. 4).

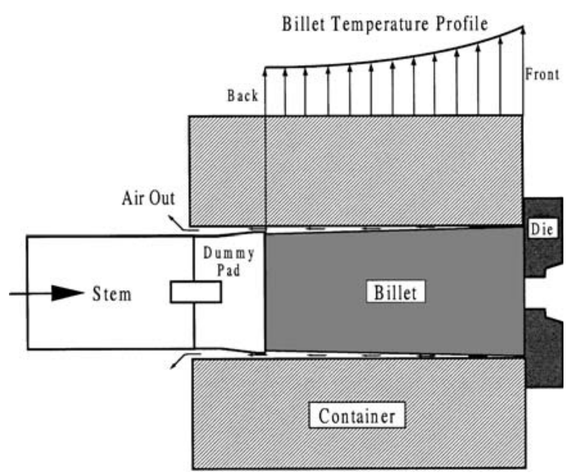

Fig. 3 Bleeding out air during upsetting

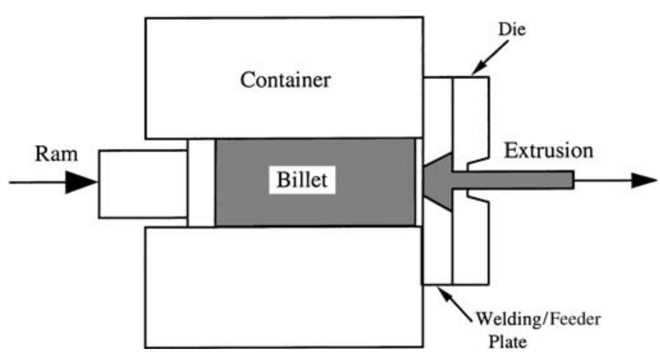

Fig. 4 Continuous-type extrusion using welding plate in front of the die (method 1)

The second method does not need a discard; the subsequent billet is pressed directly onto the billet still in the container as shown in Fig. 5. The dummy block attached with the stem shears an aluminum ring from the container during each return stroke, and this has to be removed from the stem (Ref 3).

Indirect Extrusion

In indirect extrusion, the die at the front end of the hollow stem moves relative to the container, but there is no relative displacement between the billet and the container as shown in Fig. 6. Therefore, this process is characterized by the absence of friction between the billet surface and the container, and there is no displacement of the billet center relative to the peripheral regions. The variation of load or pressure with the ram travel during both direct and indirect extrusion processes is shown in Fig. 2.

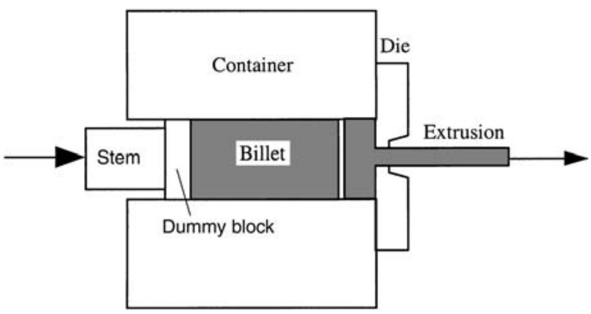

Fig. 5 Billet-on-billet extrusion (method 2)

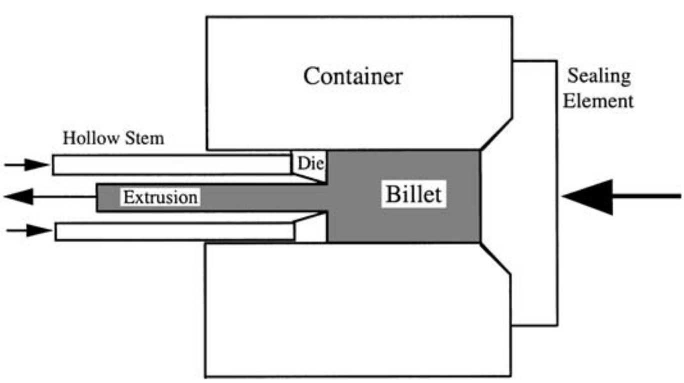

Fig. 6 Indirect extrusion process

Mechanics of Extrusion

Plastic Deformation and Metal Flow

In metal forming, plasticity theory is applied to investigate the mechanics of plastic deformation. The investigation allows the analysis and prediction of the following:

- Metal flow, including velocities, strain rates, and strain
- Temperature and heat transfer
- Variation of local material strength or flow stress of material
- Stresses, forming load, pressure, and energy

The mechanics of plastic deformation provide the means for determining how the metal flows in different forming operations, the means of obtaining desired geometry through plastic deformation, and the means for determining the expected mechanical and physical properties of the metal produced. Different mathematical equations can be obtained through a different approach (Ref 4 to 7) for different forming operations, including extrusion.

In simple homogeneous (uniaxial) compression or in tension, the metal flows plastically when the stress, σ, reaches the value of flow stress, $\overline{\sigma}$. The flow of aluminum during extrusion is intermetallic shear flow. The significant difference in the shear flow of aluminum compared with other metals being extruded is that the center of the aluminum billet is extruded first, and the peripheral part of the billet flows later, causing more severe shear deformation. As soon as the force required to push the billet into the container surface exceeds that of the shear strength of the billet material, sticking friction predominates, and deformation proceeds by shear in the bulk of the billet. Metal flow during extrusion depends on many factors, such as the following:

- Billet material property at billet temperature
- Billet-container interface and metal-die interface friction
- Extrusion ratio

A fairly large number of investigations of the flow characteristics of metal, such as lead, tin, and aluminum, have been made by using a split-billet technique (Ref 3 and 7 to 9). Typical flow patterns observed in extrusion are shown in Fig. 7 (Ref 3).

In extrusion of homogeneous materials, flow pattern S is found in the absence of friction at the container and die interfaces. The extrusion properties should be uniform in both longitudinal and transverse directions, respectively. This flow pattern is usually obtained in fully lubricated conditions in both container and dies.

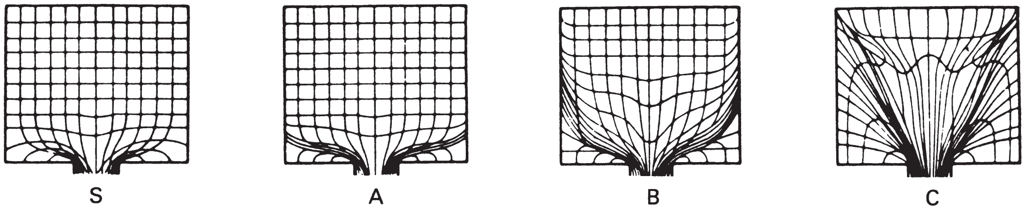

Fig. 7 Schematic of the four different types of flow in extrusion. Source: Ref 3

Flow pattern A is obtained in extrusion of homogeneous materials in the presence of friction at the die interface, not at the container-billet interface. This flow pattern is good for indirect extrusion. The metal at the center of the billet moves faster than the metal at the periphery. In the corner of the leading end of the billet, a separate metal zone is formed between the die face and the container wall, known as a dead-metal zone. The material near the surface undergoes shear deformation compared with the pure deformation at the center, and it flows diagonally into the die opening to form the outer shell of extrusion.

Flow pattern B is obtained in homogeneous materials when there is friction in both container and die interfaces. This flow pattern is good for direct extrusion processes. An extended dead-metal zone is formed. In this case, there is more shear deformation compared with that in flow pattern A. The extrusion has nonuniform properties compared with that in flow pattern A.

Flow pattern C is obtained with billets having inhomogeneous material properties or with a nonuniform temperature distribution in the billet. Materials undergo more severe shear deformation at the container wall and also form a more extended dead-metal zone.

The properties of the extruded aluminum shapes are affected greatly by the way in which the metal flows during extrusion. The metal flow is influenced by many factors:

- Type of extrusion, direct or indirect
- Press capacity and size and shape of container
- Frictional effects at the die or both container and die
- Type, layout, and design of die
- The length of billet and type of alloy
- The temperature of the billet and container
- The extrusion ratio
- Die and tooling temperature
- Speed of extrusion

Type, layout, and design of the die might change the mechanical working of the billet material during extrusion. Hollow dies perform much more mechanical work on the material than simple-shape solid dies do.

A dead-metal zone builds up in the corners of the die, and the material shears along this face. The material may continue to extrude over this generated zone, which acts like a conical die surface. The surface and subsurface defects are likely to occur on the extruded product if the sufficient amount of butt is not kept. Typical etched cross section of a 7075 alloy butt remaining after extrusion is shown in Fig. 8(a). Figure 8(b) shows schematically two clear zones. Zone 1 shows the flowing metal through the rigid conical zone 2, which is defined to be a dead-metal zone. The darker patches carry oxides and other inclusions into the extruded section, leading to extrusion defects.

The dead-metal zone semiangle may be represented in the functional form:

$$\alpha = f(\mathrm{ER}, \bar{\sigma}, m, m') \qquad \text{(Eq 1)}$$

where ER is the extrusion ratio, which is defined by the ratio of container bore area and the total cross-sectional area of extrusion, $\bar{\sigma}$ is the flow stress, m is the friction factor between billet and container interface, and m' is the friction factor between flowing metal and die-bearing interface.

Under the same friction condition at the billet-container interface for the same alloy billet, the dead-metal zone semiangle (α) varies with the extrusion ratio, ER, as shown in Fig. 9. As the extrusion ratio increases, α increases, and as α increases, the length of shear line decreases. In Fig. 9, ER_1 is the extrusion ratio for the bigger opening die, whereas ER_2 is the extrusion ratio of the smaller opening die, and α_2 is the semidead-metal zone angle corresponding to ER_2.

Butt Thickness. According to industry practice, standard butt thickness for direct extrusion is kept to 10 to 15% of the billet length. Butt thickness may be a function of the dead-metal zone, which is also a function of the extrusion ratio, type of die, billet temperature, billet-container friction condition, and flow stress of the billet material. Figure 10 shows the relationship between butt thickness and the dead-metal zone conical surface. Stopping extrusion at the safe margin zone prevents oxide and other metallic or nonmetallic inclusions from flowing into the extrusion. It is always recommended to continue research on macroetching of the longitudinal section of the butt to gain a better understanding of the following aspects:

- Change of the dead-metal zone conical angle with the change of extrusion variables
- Change of the dead-metal zone with the change of die opening (number of holes) and types of dies (solid and hollow)

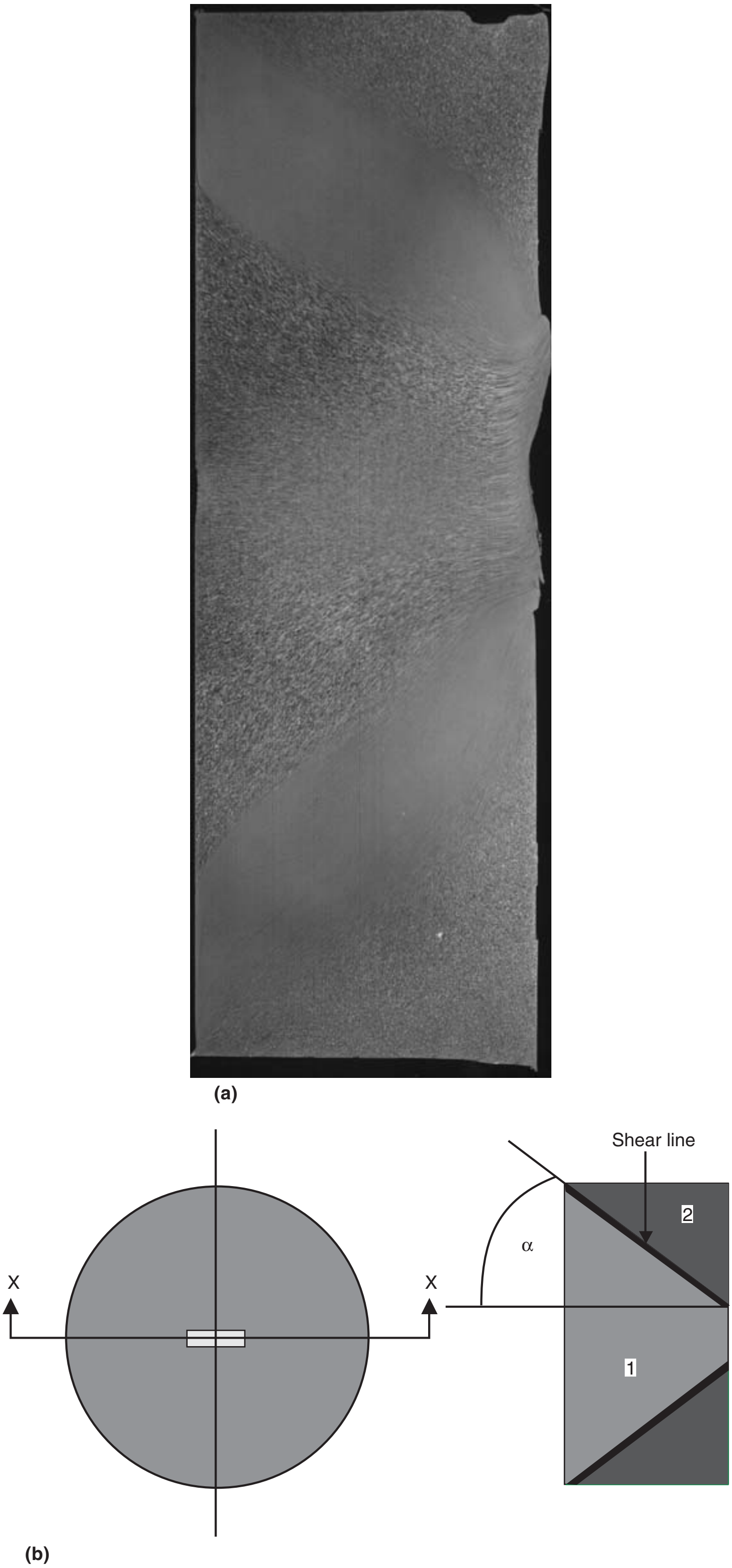

Fig. 8 Longitudinal cross section of butt after extrusion. (a) Typical etched cross section of a 7075 butt. (b) Schematic diagram of butt cross section showing dead zone

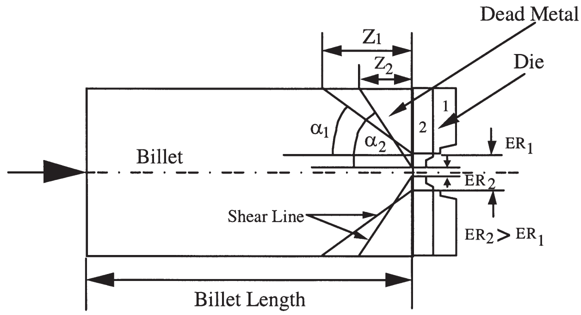

Fig. 9 Relationship between extrusion ratio and semidead-metal zone angle

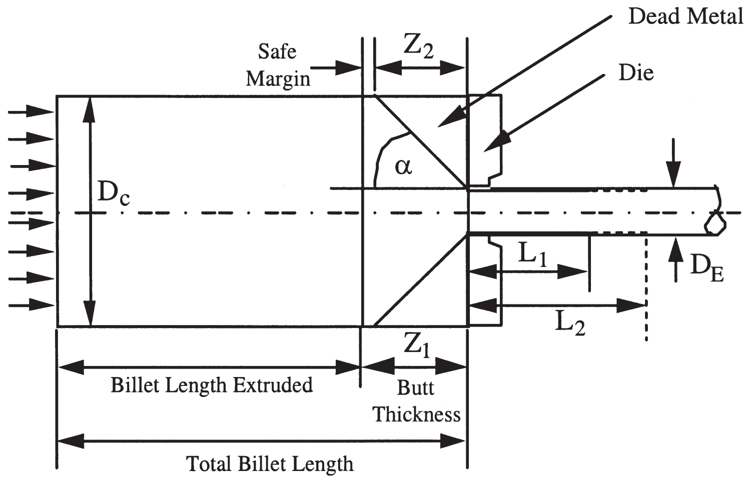

Fig. 10 Relationship between dead zone and butt thickness

- Determination of the optimum butt thickness for a set of extrusion and die variables
- Metal flow and formation of the dead-metal zone in case of indirect extrusion

This is more important for harder alloy extrusion, especially in the aircraft industry. The press should be stopped within the safe margin zone as shown in Fig. 10.

Plastic Strain and Strain Rate

In order to investigate metal flow quantitatively, it is necessary to define the strain (deformation) and strain rate (deformation rate). In the theory of metal forming plasticity, the initial condition cannot be used as a frame of reference; therefore, the change in length must be related to instantaneous length. The natural or effective strain is defined by:

$$d\bar{\varepsilon} = \frac{dl}{l} \qquad \bar{\varepsilon} = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} \qquad \text{(Eq 2)}$$

where, l_0 is the initial length, and l is the final length.

The natural strain, $\bar{\varepsilon}$, obtained by integration is thus a logarithmic function and is often referred to as the logarithmic strain. The strain in metal working is given as the fractional cross-sectional area. The volume constancy relation is given by:

$$Al = A_0 l_0 \qquad \text{(Eq 3)}$$

Now, the natural strain is given by:

$$\bar{\varepsilon} = \ln \frac{l}{l_0} = \ln \frac{A_0}{A} \qquad \text{(Eq 4)}$$

where A_0 is the original area, and A is the final area.

Therefore, the effective strain is defined in the case of extrusion as:

$$\bar{\varepsilon} = 2 \ln \frac{D_C}{D_E} = 2 \ln \sqrt{ER} \qquad \text{(Eq 5)}$$

where D_C is the inside diameter of the container and D_E is the equivalent diameter of the extruded rod, and ER is the extrusion ratio.

In determining the strain rate, the complex flow pattern in the deformation zone creates a problem. The material undergoes a rapid acceleration as its passes through the deformation zone, and therefore, a mean strain rate has to be estimated for determining the flow stress. The deformation zone is assumed to be conical for simplicity as shown in Fig. 11.

From the geometry, the length of deformation zone is given by:

$$L = \frac{(D_C - D_E)}{2 \tan \alpha} \qquad \text{(Eq 6)}$$

where D_C is the bore of the container, D_E is the diameter of the extruded rod, and α is the dead-metal zone semiangle.

Equivalent rod diameter for the same extrusion ratio can also be determined. The extrusion ratio of a single-hole die is defined by:

$$ER = \frac{A_C}{A_E} \qquad \text{(Eq 7)}$$

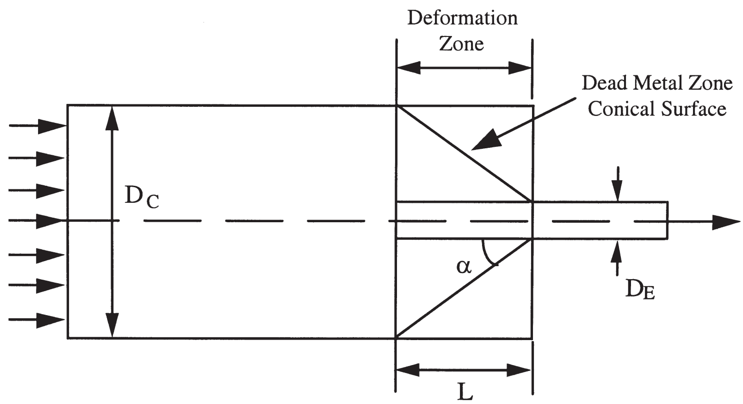

Fig. 11 Billet geometry inside the container

where A_C is the area of the container bore, and A_E is the final area of the extruded rod. Therefore, the equivalent diameter of the extruded rod is given by:

$$D_E = \frac{D_C}{\sqrt{ER}} \quad \text{(Eq 8)}$$

The mean effective strain rate is given by (Ref 10 and 11):

$$\dot{\varepsilon} = \frac{6VD_C^2 \tan\alpha}{(D_C^3 - D_E^3)} 2 \ln \frac{D_C}{D_E} \quad \text{(Eq 9)}$$

where V is the average ram speed, D_C is the container bore, D_E is the diameter of the extruded rod, and α is the dead-metal zone semiangle.

Friction Models

Fundamentals of tribology (friction, lubrication, and wear) are essential in dealing with the field of metal-working processes. During the extrusion of aluminum, the tribology of the die/material interface has a considerable influence on the accuracy of the shape and surface quality of the extrusion. In this section, friction modeling of the extrusion process is discussed.

Friction components are totally dependent on the type of extrusions used, such as direct or indirect. Figure 12 shows the friction-force components in direct extrusion, and similarly, Fig. 13 shows the friction components in the indirect process using the most common flat-face dies.

From the flow pattern in indirect extrusion using a flat-face die, it is revealed that a dead-metal zone exists with a much higher angle compared with that in direct extrusion. For the same size extrusion, $\alpha_i > \alpha_d$. Thin butt may be allowed in indirect process. The metal flow in the indirect process using a flat-face die may be very similar to the flow with lubricated direct extrusion process.

Friction is the resistance to relative motion that is experienced whenever two solids are in contact with each other. The force necessary to overcome the resistance, which is directed in the direction opposite to the relative motion, is the friction force. The Amontons-Coulomb model (Ref 12) gives the friction force as:

$$F_f = \mu N \quad \text{(Eq 10)}$$

where μ is the coefficient of friction, N is the normal force, and F_f is the friction force. The model holds fairly well where contacts are relatively lightly loaded, and the surfaces contact only at occasional asperity peaks. This model is of questionable value in bulk deformation processes, such as extrusion, where the contact is more intimate and the pressures are significantly higher.

Billet-Container Interface. The real area of contact increases with contact pressure as shown in Fig. 14. According to Bowden and Tabor

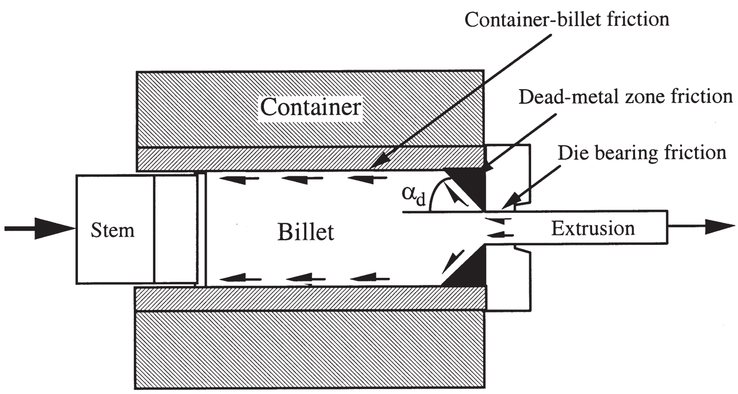

Fig. 12 Friction components in direct extrusion

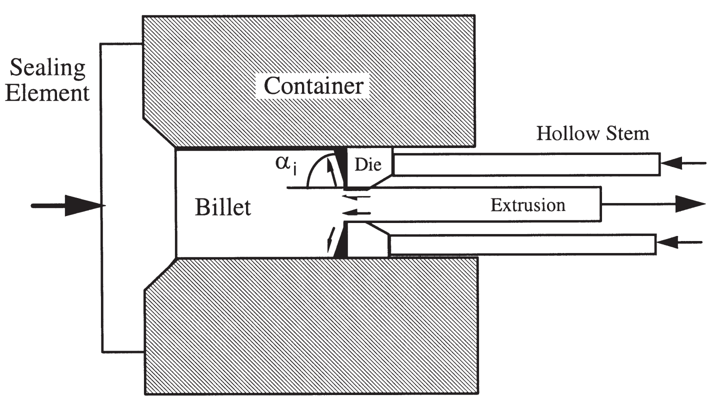

Fig. 13 Friction components in indirect extrusion

(Ref 13), the friction force using adhesion theory is directly proportional to the real area of contact. In the case of direct extrusion (where contact pressures are very high), the real area of contact, A_R, gradually becomes equal to the apparent area of contact, A_A, as the billet upsets in the container.

Important considerations in the direct extrusion process are the friction forces developed between the billet and the container and interface friction between the flowing metal and the dead-metal zone conical interface. In the direct extrusion process, the large pressure developed demands that the billet be supported by the container wall. From a practical point of view, there are two types of friction conditions:

- Billet-container friction is arrested (sticking friction)
- Lubricated interface flow is ensured (sliding friction)

In aluminum extrusion, the friction condition at the billet-container interface is considered to be sticking friction as the skin of the billet is being separated in the container wall. Schey (Ref 14) provides a useful review of using the friction factor, m, in metal-forming operations where the contact pressure is very high. The friction factor model, sometimes referred to as a stiction model, is:

$$F_f = mkA_R \qquad \text{(Eq 11)}$$

where m is the friction factor, k is the material shear strength, A_R is the real area of contact (which, for this model, equals the total area of contact), and F_f is the friction force. In the case of sticking friction, $m = 1$, while for thick film lubrication conditions, m approaches zero. Therefore, the frictional stress, τ_f, is given by:

$$\tau_f = k = \frac{\bar{\sigma}}{\sqrt{3}} \qquad \text{(Eq 12)}$$

where k is equal to $\bar{\sigma}/\sqrt{3}$ according to Von Mises yield criteria, and $\bar{\sigma}$ is the flow stress of the material.

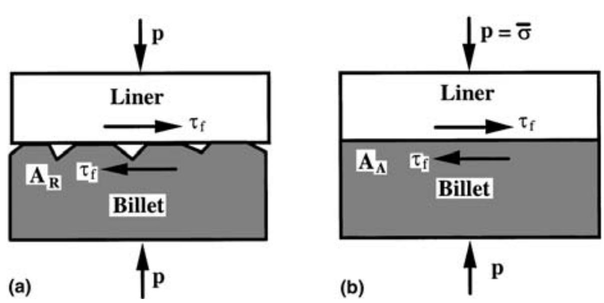

Fig. 14 Friction model in direct extrusion process. (a) $A_R < A_A$. (b) $A_R = A_A$, $p = \bar{\sigma}$

Dead-Metal Zone-Flowing Metal Interface. The dead-metal zone shown in Fig. 12 occurs when a material is extruded through square dies (i.e., the bearing surface is perpendicular to the face of the die). In such geometry, the material in the corners no longer takes part in the flow but adheres to the die face, forming a conical die-like channel through which the billet passes in a still-converging kind of flow. Friction between the dead-metal zone and the flowing material is no more than the shear stress of the material. The friction stress is also given by Eq 12 with friction factor equal to unity.

Die-Material Interface. Based on the observation of the die surface after several extrusion cycles, it is understood that friction in the die can vary in a complicated way when metal is flowing through the die opening. It has been observed that an adhesive layer on the die develops due to the strong adhesion of materials such as aluminum with the dies, typically constructed from tool steels. It is also understood that surface treatments (such as nitriding or thin hard coatings) that result in harder die bearing can reduce the amount of adhered aluminum on the die bearing. Research is continuing on die bearing treatments for wear resistance.

A friction model developed by Abtahi (Ref 15) is based on measured slipping and sticking lengths using a split die. This model shows almost constant friction in the sticking region, whereas in the slipping region, friction is changing with the die angle.

Proposed Model. In a recent study, Saha (Ref 16) suggested a friction model at the die-material interface. Figure 15 is a schematic of the bearing surface based on the morphology of aluminum buildup on the die bearing, which is normal to the extrusion direction. Figure 15 also shows the sticking and slipping zones of the die that are used to develop a friction model at the die-material interface. Figure 15(a) shows partial sticking and slipping zones, and Fig. 15(b) shows a completely adhered surface. After several press cycles, a completely adhered surface is developed on the die face.

During extrusion, the normal pressure on the bearing surface of the die is very high. This pressure is assumed to be equal to the extrusion pressure, which is equal to or higher than the flow stress of the material. Based on the definition of the friction factor, the friction force F_f on the die is given by:

$$F_f = m_1 k A_{R_1} + m_2 k A_{R_2} \quad \text{(Eq 13)}$$

where a 1 subscript denotes a sticking zone, a 2 subscript denotes a sliding zone, m is the friction factor, A_R is the real area of contact, and k is the material shear strength. The friction stress is given by:

$$\tau_f = k \frac{A_{R_1}}{A_A} + m_2 k \frac{A_{R_2}}{A_A} \quad \text{(Eq 14)}$$

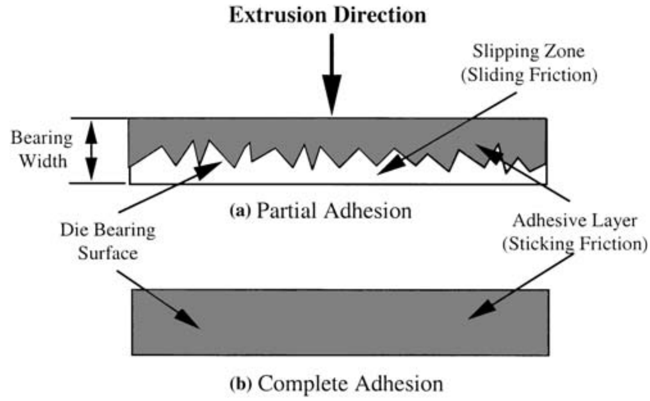

Fig. 15 Schematic of the morphology of the die bearing surface

where A_A is the apparent area of contact for the entire bearing surface, and m_1 has been set equal to unity to reflect sticking friction.

In the case of complete adhesion (sticking friction) on the die bearing, $m_2 = 1$; accordingly, the frictional stress will be changed to:

$$\tau_f = k\frac{A_{R_1} + A_{R_2}}{A_A} = k = \frac{\bar{\sigma}}{\sqrt{3}} \qquad \text{(Eq 15)}$$

Extrusion Pressure

The parameter that determines whether extrusion will proceed or whether a sticker will result is the magnitude of the maximum pressure that must be within the extrusion press capacity. The factors that influence successful extrusion are as follows:

- Extrusion temperature
- Temperature of container, die, and associated tooling
- Extrusion pressure
- Extrusion ratio
- Extrusion speed
- Billet length
- Chemistry of the alloy

In the direct extrusion process, pressure reaches a maximum at the point of breakout at the die. A typical pressure curve is shown in Fig. 2. The difference between the maximum and minimum pressures can be attributed to the force required in moving the billet through the container against the frictional force. The actual pressure exerted on the ram is the total pressure. The total extrusion pressure required for a particular extrusion ratio is given by:

$$P_T = P_D + P_F + P_R \qquad \text{(Eq 16)}$$

where P_D is the pressure required for the plastic deformation of the material, which is given in the functional form as:

$$P_D = f(\bar{\sigma}, \bar{\varepsilon}) \qquad \text{(Eq 17)}$$

where the flow stress, $\bar{\sigma}$, is defined by:

$$\bar{\sigma} = f(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \qquad \text{(Eq 18)}$$

strain and strain rate are defined by:

$$\bar{\varepsilon} = \ln \frac{A_C}{A_E} \qquad \text{(Eq 19)}$$

$$\dot{\bar{\varepsilon}} = \frac{d\bar{\varepsilon}}{dt} \qquad \text{(Eq 20)}$$

and T is the temperature of the material.

P_F is the pressure required to overcome the surface friction at the container wall friction, dead-metal zone friction, and die bearing friction, which is given in the functional form

$$P_F = f(p_r, m, m', m'', D, L, L') \qquad \text{(Eq 21)}$$

where p_r is the radial pressure, m is the friction factor between the billet and container wall, m' is the friction factor at the dead-metal zone/flowing metal interface, m'' is the friction factor between extruded material and die bearing, D is the billet diameter, L is the length of the billet, and L' is the die bearing length of a solid die.

P_R is the pressure to overcome redundant or internal deformation work, which is given in the functional form

$$P_R = f(\bar{\sigma}, \alpha) \qquad \text{(Eq 22)}$$

where α is the semidead-metal zone angle as a function of the extrusion ratio.

Dieter (Ref 2) has given a nice explanation of the redundant work. Elements at the center of the billet undergo essentially pure elongation in the extruded rod, which corresponds to the change in cross section from billet to extrusion. The elements shown in Fig. 16, near the container wall, undergo extensive shear deformation due to billet-container interface friction. The elements at the dead-metal zone interface also undergo extensive shear deformation. The shear deformation, which occurs over much of the cross section of the extruded rod, requires an expenditure of energy. This energy expenditure, which is not related to the change in dimensions from the billet to the extrusion, is called redundant work, as shown in Fig. 16. The redundant work is mainly responsible for the large difference between the actual extrusion pressure and the calculated pressure on the basis of uniform plastic deformation.

For a given size of billet extruded under a particular set of conditions, there will be an upper limit to the extrusion ratio that can be obtained with a press of a given capacity. The temperature of extrusion plays the most important role in getting a properly extruded product, and extrusion speed are also important factors. An increase in the length of the billet, however, results in raising the pressure required for extrusion. This increase in pressure is due to the frictional resistance between the billet and the container wall, which is greater for the longer billet. Normally, the maximum length of the billet is four times its diameter.

In extrusion of metals, there are certain interrelations between extrusion pressures, extrusion temperatures, extrusion ratios, and extrusion speeds:

- Increase in the temperature of the billet reduces the pressure required for extrusion.
- The higher the extrusion ratio, the higher the extrusion pressure.
- The greater the billet length, the higher the extrusion pressure.

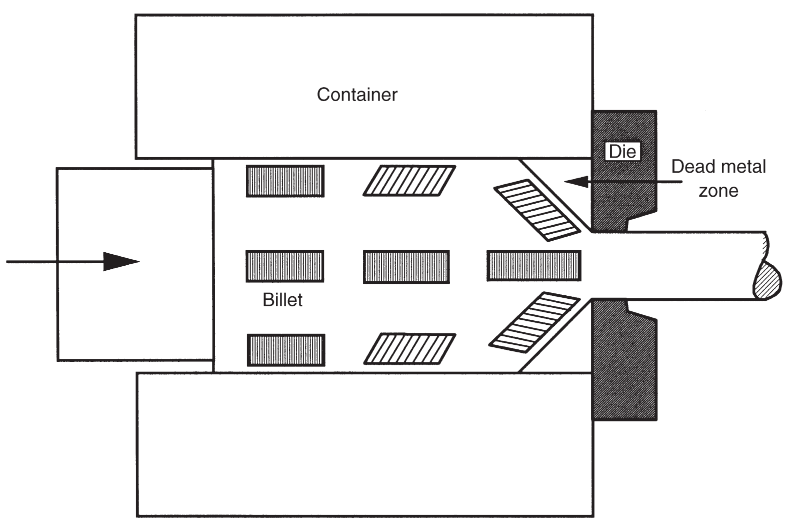

Fig. 16 Redundant work

- Billet temperature remains within extrusion range; extrusion pressure remains fairly unaffected when extrusion speed is increased within normal limits.

Analysis of Extrusion Pressure

Slab Method. In this section, the average extrusion pressure during direct extrusion of aluminum is calculated by using the slab method. Thomsen et al. (Ref 7) have shown an analysis by using a uniform energy method, slab analysis, and slip-line field theory. Altan et al. (Ref 17) have performed a slab method analysis to determine the extrusion pressure. The following considerations were used in making the analysis:

- Extrusion using a cylindrical billet through a flat die
- Extrusion shape equivalent to a rod of diameter D_E
- Frictional shear stress at the dead-metal/flowing metal interface
- Frictional shear stress at the billet-container interface

Consider the static equilibrium of the forces acting on the shaded element within the dead-metal zone area as shown in Fig. 17. The stresses acting on this slab are shown in Fig. 18(b). The equilibrium equation is given by:

$$-(p_z + dp_z)\frac{\pi(D+dD)^2}{4} + p_z\frac{\pi D^2}{4} + p_r \pi D\, ds \sin\alpha + \tau_f \pi D\, ds \cos\alpha = 0 \quad \text{(Eq 23)}$$

where τ_f is the frictional stress at the dead-metal zone/flowing material interface, p_r is the radial pressure and α is the semidead-metal zone angle.

This equation can be simplified by using the following geometric relationship among *dz, dD,* and *ds*:

$$ds \sin\alpha = dz \tan\alpha = \frac{dD}{2} \quad \text{(Eq 24)}$$

$$ds \cos\alpha = dz = \frac{dD}{2\tan\alpha} \quad \text{(Eq 25)}$$

From the yield criterion,

$$p_r = p_z + \bar{\sigma} \quad \text{(Eq 26)}$$

where p_r is the radial pressure, p_z is the pressure in the *Z* direction and $\bar{\sigma}$ is the flow stress of the material.

Combining Eq 23, 24, 25, and 26, substituting τ_f from Eq 12, and neglecting the higher order differentials, the equilibrium equation is obtained in the integral form:

$$\frac{dp_z}{\bar{\sigma}\left(1+\frac{\cot\alpha}{\sqrt{3}}\right)} = \frac{2dD}{D} \qquad \text{(Eq 27)}$$

Assuming the flow stress remains constant, the integration of the equation yields:

$$\frac{p_z}{\bar{\sigma}\left(1+\frac{\cot\alpha}{\sqrt{3}}\right)} = \ln D^2 C \qquad \text{(Eq 28)}$$

where C is the integration constant.

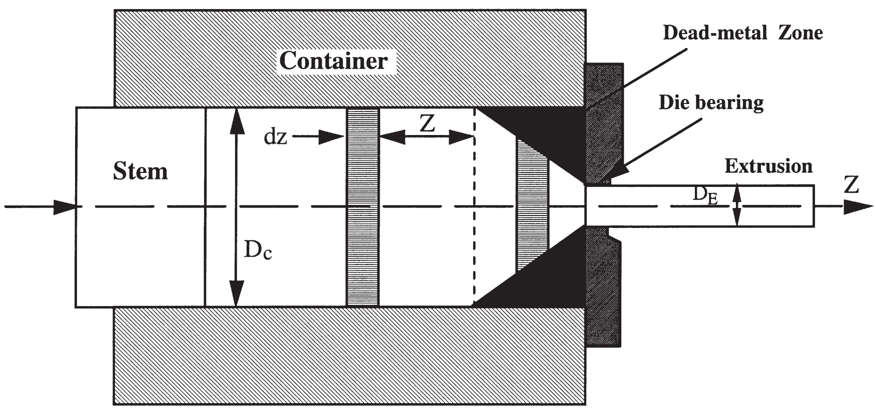

Fig. 17 Extrusion through a square die with dead-metal zone and equivalent rod diameter

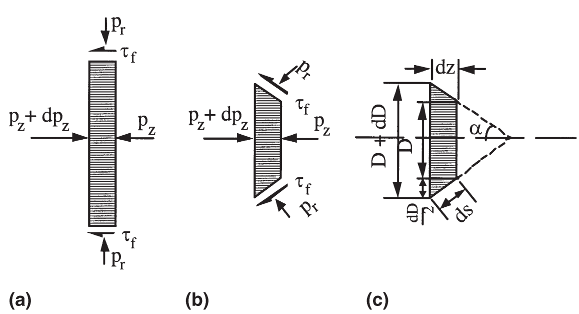

Fig. 18 State of stress for the extrusion shown in Fig. 17. (a) Freebody diagram of element inside the container wall. (b) Freebody diagram of element under the dead-metal zone. (c) Geometric relationship among *dz, dD,* and *ds*

Substituting the boundary conditions at $D = D_E$, $p_z = 0$, C will be determined by:

$$C = \frac{1}{D_E^2} \quad \text{(Eq 29)}$$

where D_E, the equivalent diameter of extruded rod, could be calculated by using Eq 8.

Substituting the value of constant, C, in Eq 28 and simplifying, the average extrusion pressure is given by:

$$p_{ave, z=0} = 2\bar{\sigma}\,(1 + \frac{\cot\alpha}{\sqrt{3}}) \ln \frac{D_C}{D_E} \quad \text{(Eq 30)}$$

where D_C is the equivalent diameter of the billet (container bore diameter) filled in the container after upsetting.

Billet-Container Interface Friction. Billet-container interface friction must be included to determine the total pressure required for extrusion from a round-shaped billet to an equivalent rod. Considering the shaded element in the cylindrical portion (Fig. 17), the equation expressing static equilibrium in the Z direction is given by:

$$[(p_z + dp_z) - p_z]\frac{\pi D_C^2}{4} = \pi\, D_C \tau_f\, dz \quad \text{(Eq 31)}$$

where, τ_f is the friction force at the billet-container interface, D_C is the diameter of the container bore. Equation 31 may be written in the integral form:

$$\frac{dp_z}{\tau_f} = \frac{4}{D_C}\, dz \quad \text{(Eq 32)}$$

Integrating Eq 32 and putting the boundary condition: at $Z = 0$, $p_z = p_{ave,\, z=0}$, the average extrusion pressure may be written as:

$$p_z = \frac{4\tau_f\, Z}{D_C} + p_{ave, z=0} \quad \text{(Eq 33)}$$

Now substituting $p_{ave,\, z=0}$ from Eq 30 and τ_f from Eq 12, the average extrusion pressure may be written as:

$$p_{ave} = 2\bar{\sigma}\,(1 + \frac{\cot\alpha}{\sqrt{3}}) \ln \frac{D_C}{D_E} + \frac{4\bar{\sigma} Z}{\sqrt{3}\, D_C} \quad \text{(Eq 34)}$$

Avitzur (Ref 18) used an upper-bound method to derive an equation to predict extrusion load.

Extrusion Force

The force required for extrusion depends on the flow stress of the billet material, the extrusion ratio, the friction condition at the billet container interface, the friction condition at the die material interface, and the other process variables, such as initial billet temperature and the speed of extrusion. The required extrusion force, F_r, is given by:

$$F_r = P_T A_C \quad \text{(Eq 35)}$$

where P_T is the extrusion pressure, and A_C is the area of the container bore.

The force term is essential in determining the capacity of the extrusion press. The external force given by the extrusion press will determine the press capacity. For successful extrusion, the force balance has to be satisfied as follows:

$$F_p > F_r$$

where F_p is the force applied by the press, and F_r is the force required for extrusion. Force (compression power) applied by the press is given by:

$$F_p = pA_1 + p(2A_2) \quad \text{(Eq 36)}$$

where A_1 is the area of the main cylinder, A_2 is the area of each side cylinder, and p is the applied hydraulic pressure to the cylinders as shown in Fig. 19.

Specific pressure (inner pressure in the container liner) as shown in Fig. 20 is given by:

$$P_s = \frac{F_p}{A_C} \quad \text{(Eq 37)}$$

Effect of Principal Variables on Extrusion

Extrusion can become impossible or can yield an unsatisfactory product when the load required exceeds the capacity of the press available or when the temperature of the extrusion exceeds the solidus temperature of the alloy. Knowledge of the initial billet temperature, the strain-rate, flow stress of the working material, and the extrusion ratio are required if correct and economical use is to be made of expensive extrusion facilities.

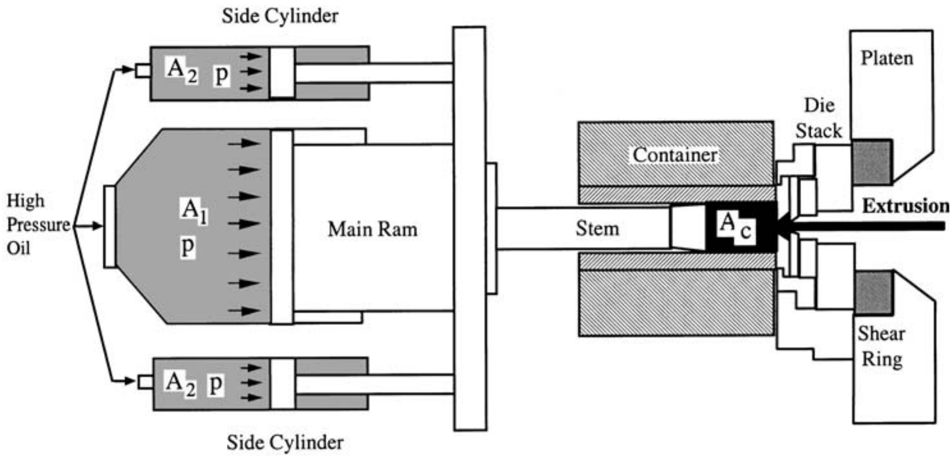

Fig. 19 Schematic of direct extrusion press

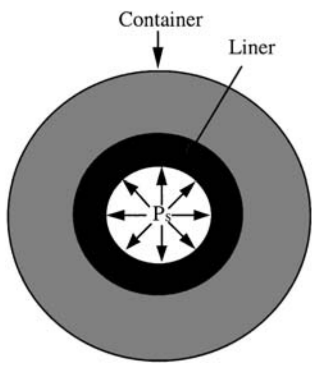

Fig. 20 Specific applied pressure

Principal Variables

The principal variables (Fig. 21) that influence the force required to cause extrusion and the quality of material exiting from the die are as follows:

- Extrusion ratio
- Working temperature
- Speed of deformation
- Alloy flow stress

Extrusion Ratio. The extrusion ratio (ER) of a multihole die is defined by:

$$ER = \frac{A_C}{n(A_E)} \qquad \text{(Eq 38)}$$

where n is the number of symmetrical holes, A_C is the area of container, and A_E is the area of extrusion. The extrusion ratio of a shape is a clear indication of the amount of mechanical working that will occur as the shape is extruded.

The effective strain is a function of the extrusion ratio, and finally, extrusion pressure required to extrude is a function of strain. When the extrusion ratio of a profile is low, the amount of plastic strain is also low. As a result, the amount of work done during extrusion will be less. In aluminum extruded with a low extrusion ratio, the structure will be similar to that of as-cast (coarse grain) aluminum. This structure will be mechanically weak, and as a result, shapes with an extrusion ratio of less than 10 to 1 may not be guaranteed to meet the mechanical and physical properties specifications of the material.

When the extrusion ratio is high, the situation is just the opposite as expected. The extrusion pressure required to push the metal through the die will be higher due to a higher amount of plastic strain. The normal extrusion ratio range in industry practice for hard alloys is from 10 to 1 to 35 to 1, and for soft alloys, 10 to 1 to 100 to 1. However, these normal limits should not be considered absolute because the actual shape of the extrusion affects the results.

Extrusion Temperature. Extrusion is commonly classified as a hot-working process. Hot working is defined as deformation under conditions of temperature and strain-rate such that recovery processes take place simultaneously with deformation. Extrusion is carried out at elevated temperatures for metals and alloys that do not have sufficient plasticity range at room temperature and also to reduce the forces required for extrusion.

Temperature is one of the most important parameters in extrusion. The flow stress is reduced if the temperature is increased and deformation is, therefore, easier, but at the same time, the maximum extrusion speed is reduced because localized temperature can lead to the incipient melting temperature. The changes during extrusion depend on the billet

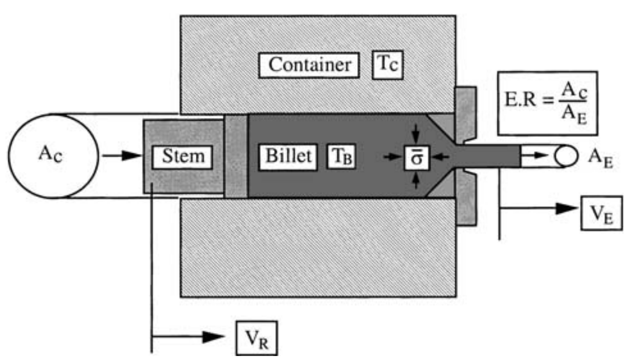

Fig. 21 Principal extrusion variables

temperature, the heat transfer from the billet to the container, and the heat developed by deformation and friction. In actual aluminum extrusion practice, very complex thermal changes commence as soon as the hot billet is loaded into the usually preheated container, and extrusion is started.

Temperature rise and temperature distribution during extrusion have been investigated by many researchers (Ref 10, 11, 16, and 19–23). In the next chapter, thermal considerations in aluminum extrusion, including isothermal extrusion, will be discussed in more detail.

Extrusion Speed. The response of a metal to extrusion processes can be influenced by the speed of deformation. Increasing the ram speed produces an increase in the extrusion pressure. The temperature developed in extrusion increases with increasing ram speed. This increase is due to the fact that the strain rate is directly proportional to the ram speed, and the magnitude of the generated heat is proportional to the strain rate. The slower the ram speed is, the more time will be available for the generated heat to flow. The heat conduction is more pronounced with aluminum because of its higher conductivity.

Relationship Between Ram Speed and Extrusion Speed (Ref 24). This section explains how to calculate the extrusion speed in terms of ram speed by using simple mathematical relations. The extrusion speed could be calculated for any extrusion die by using volume constancy relation, which means that the volume metal in the container becomes equal to the volume of extrusion coming out of the die because there is no loss of metal during extrusion.

From volume constancy as shown in Fig. 21, it is given by:

$$V_R A_C = V_E A_E \qquad \text{(Eq 39)}$$

where V_R is the ram speed, A_C is the area of the container bore, V_E is the extrusion speed, and A_E is the area of the extruded shape.

If it is a multi-hole die, the relationship will be changed according to the number of holes in the die, which is given by:

$$V_R A_C = V_E(n A_E) \qquad \text{(Eq 40)}$$

where n is the number of symmetrical holes.

The extrusion speed is given by:

$$V_E = V_R \frac{A_C}{n(A_E)} \qquad \text{(Eq 41)}$$

The extrusion speed could also be written as:

$$V_E = V_R \, \text{ER} \qquad \text{(Eq 42)}$$

where ER is defined by:

$$\frac{A_C}{n(A_E)}$$

Material Flow Stress. A true stress-strain curve is frequently called a flow curve because it gives the stress required to cause the metal to flow plastically to any given strain. The flow stress, $\bar{\sigma}$, is important because in plastic deformation process, the forming load or stress is a function of part geometry, friction, and the flow stress of the deforming material. The flow stress of the material is influenced by the following factors:

- Chemistry and the metallurgical structure of the material
- Temperature of deformation, the amount of deformation or strain, $\bar{\varepsilon}$, and the rate of deformation or strain-rate, $\dot{\bar{\varepsilon}}$

Therefore, the flow stress can be written in a functional form:

$$\bar{\sigma} = f(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \qquad \text{(Eq 43)}$$

Because the flow stress for hot-working metal is quite markedly affected by the speed of deformation, there are no specific methods for measuring the flow stress during the hot-working process. The flow stress of the billet material depends on both strain rate and temperature. The decrease in flow stress with increasing temperature and the increase at higher strain rate have been measured in several studies. The flow stress of metal for the actual working conditions is determined experimentally. The methods most commonly used for obtaining flow stress are tensile, uniform compression, and torsion tests.

The effect of temperature measured in the experiments to determine the flow stress can be directly applied to extrusion. Laue and Stenger (Ref 3) have given a complete review of experimental values of flow stress by many authors. The relationship between flow stress and strain rate has been used in numerical analysis to determine the influence of plastic strain and strain rate on temperature in aluminum 6063 extrusion (Ref 21). Because the accuracy of this type of analysis is very much dependent on the flow stress of material, this relationship fits very well for determining the flow stress of different aluminum alloys for the most common working temperature.

The relationship is given by (Ref 3):

$$\bar{\sigma} = \bar{\sigma}_0 \left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0} \right)^{m^*} \qquad \text{(Eq 44)}$$

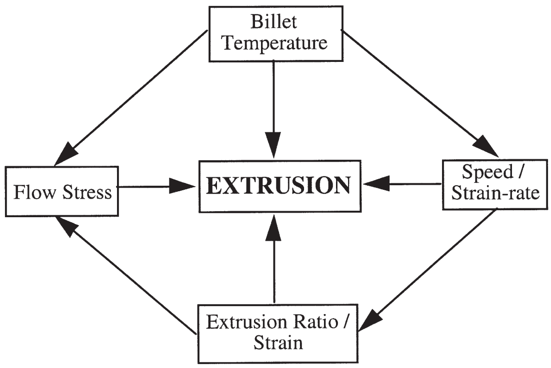

Fig. 22 Effect of principal variables on extrusion

where, $\bar{\sigma}_0$ is the known flow stress at a known strain-rate $\dot{\bar{\varepsilon}}_0$, and similarly, $\bar{\sigma}$ is the flow stress at the strain rate $\dot{\bar{\varepsilon}}$. For example, a typical value of the exponent, m*, at 932 °F (500 °C) for AlMgSi1 alloy is 0.125.

As a rule, for the flow stress of the alloy being extruded, the lower the extruded rate, the greater the friction between the billet and the container wall because of higher critical shear stress, and the longer the time required to overcome friction and start the extrusion. Primarily, this is the result of the increased flow stress of the material, and the hard alloy requires maximum pressure for extrusion. The extrusion of hard alloy is even more difficult because of poor surface characteristics, which demand the lowest possible billet temperatures.

A summary of the effects of different factors on extrusion and their interrelationship are shown in Fig. 22 as a closed-loop chain.

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CHAPTER 2

Thermodynamics in Extrusion

The term *thermodynamics* refers to the study of heat related to matter in motion. All thermodynamics systems require some energy source and transfer media to carry the heat to raise the temperature in the system. In extrusion, heat is generated by both the frictional work and the work of deformation. Heat generation and transfer take place simultaneously right from the start of extrusion. Some of the generated heat remains in the extruded metal, some is transmitted to the container and die, and some even increases the temperature of the part of the billet that is not yet extruded. The process of heat conduction through the billet during extrusion is a complex one, and it becomes difficult, if not impossible, to get a complete analytical solution of the differential equation of heat transfer. The temperature increase and temperature distribution during extrusion have been investigated by many researchers (Ref 1–5) since 1960. Approximate but useful information regarding the temperature distribution in the billet can be obtained if the differential equation can be written in the finite difference form, and the temperature at any point of the billet is solved numerically with suitable boundary conditions.

Altan and Kobayashi (Ref 6) performed an excellent study using numerical methods to calculate the nonsteady-state temperature distribution in extrusion through conical dies. They included the temperature dependencies of the flow stress and of the thermal constants of the billet and the tool materials into the analysis. The researchers considered both cooling of the billet in air and heat conduction between the billet and the container before extrusion started. They studied the effects of several factors, such as materials properties, friction conditions, ram velocity, extrusion ratio, and die geometry. Castle and Sheppard (Ref 7) developed an equation that predicts temperature rise as a function of several variables, one of which is ram speed. Laue and Stenger (Ref 8) presented a useful review, including Akeret's method and Lange's analytical method, to determine the temperature distribution during extrusion. Macey and Salim (Ref 9) developed a two-dimensional computer model for the hot extrusion of aluminum based on a commercially available finite difference code (NOVA 20). They used the model to predict how the effects of extrusion speed, initial billet temperature, and static yield stress would affect the peak temperature and ram load generated in the extrusion. They also presented an example to demonstrate how the model can be used in the alternative plane-strain model to give an indication of behavior during extrusion under nonaxisymmetric conditions.

Castle (Ref 10) discussed the factors that control the exit temperature, which is important in the optimization of the extrusion speed during the extrusion cycle to compensate the temperature rise in extrusion. Tashiro et al. (Ref 11) performed an experimental study on the verification of the interactive effects of billet temperature and die temperature, which influenced distortion and variation in the shape of the extruded product's cross section in the hot extrusion process. The temperature distribution in extrusion billets is a critical process variable affecting pressure, speed, surface finish, and mechanical properties. Johannes and Jowett (Ref 12) discussed the influence of temperature on these factors and analyzed the thermal behavior of aluminum billets from preheat to the start of extrusion. They presented analytical solutions to a number of classical heat transfer problems in cylinders and rods along with some finite element analyses. The results are given in practical numerical form.

Heat transfer mechanisms of extruded sections as they come out of the extrusion press were examined and a model was developed by Pham (Ref 13) to simulate the temperature profile of the extruded sections on the run-out table. The model is based on the assumption of uniform temperature across the section and negligible heat loss from the section to the contact surfaces of the run-out table. The results are very much dependent on the extrusion speed and the extrusion ratio. The model is effective in predicting the metal temperature when the extrusion is undergoing spray quenching by water. This chapter will discuss the thermodynamics in extrusion, including a simplified mathematical model, influence of extrusion variables on temperature rise, temperature measurements, and isothermal extrusion.

Extrusion Thermodynamics

Heat Balance in Direct Extrusion. The sources of heat energy to the direct extrusion process are shown in Fig. 1. Most of the work of deformation is transformed into heat. This temperature rise due to plastic deformation can be several hundred degrees. Friction forces acting in three different locations affect the overall temperature change in the billet as well as in the extruded product leaving the die.

Temperature is one of the most important parameters in extrusion. The flow stress is reduced if the temperature is increased, and deformation is, therefore, easier. At the same time, however, the maximum extrusion speed is reduced because localized temperature can lead to incipient melting of the specific alloy. The temperature changes during extrusion depend on many factors, such as the following:

- Initial billet temperature
- Flow stress of alloy at given temperature, strain and strain rate
- Plastic deformation (homogeneous and redundant work)
- Friction at billet container, dead-metal flowing material, die-bearing flowing material interfaces
- Heat transfer (both conduction and convection)

In industry practice, a very complex thermal change commences as soon as the hot billet is ejected from the billet heater before entering the preheated container and after the actual extrusion is started. The heat balance model is shown in Fig. 2.

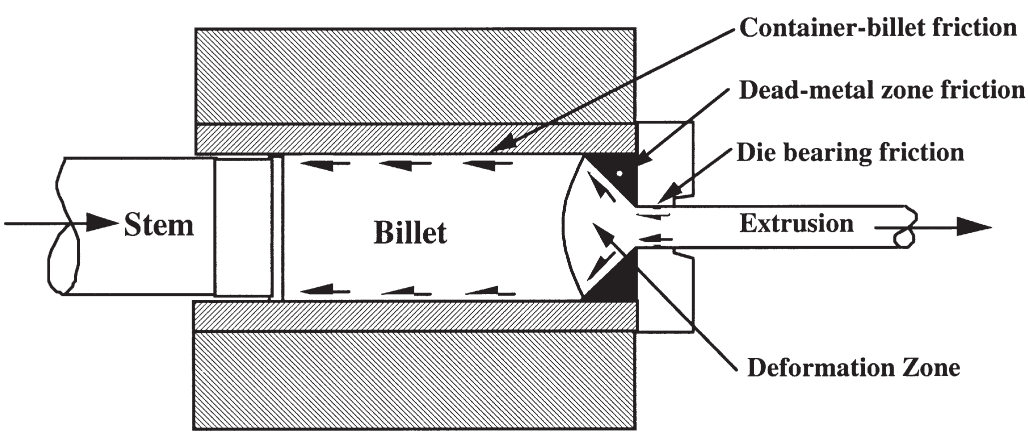

Fig. 1 Friction-assisted direct extrusion mechanism

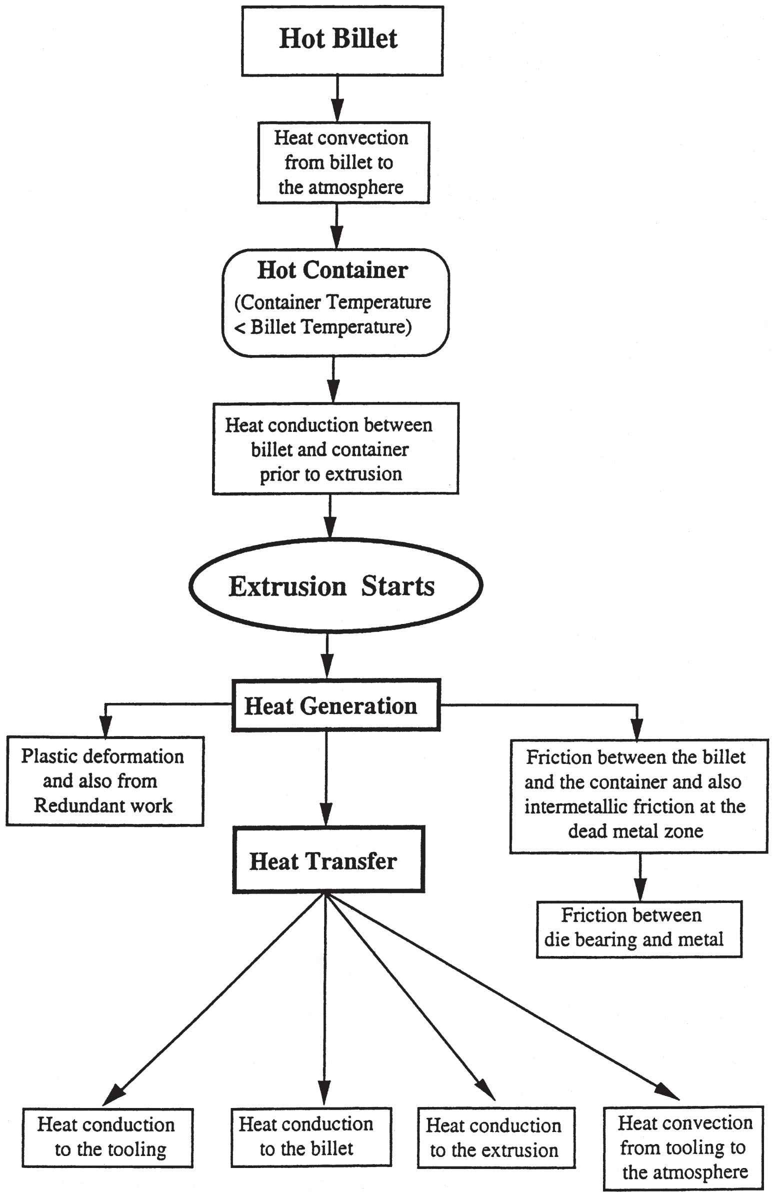

Fig. 2 Flow chart of heat balance in direct extrusion

Thermodynamics Model

Significant research has been done on temperature model and temperature distribution during extrusion. One of the current and simple finite difference models is discussed in this section. A modified model for the temperature rise in an aluminum billet during extrusion with friction is presented by Saha (Ref 14). The model uses realistic input parameters

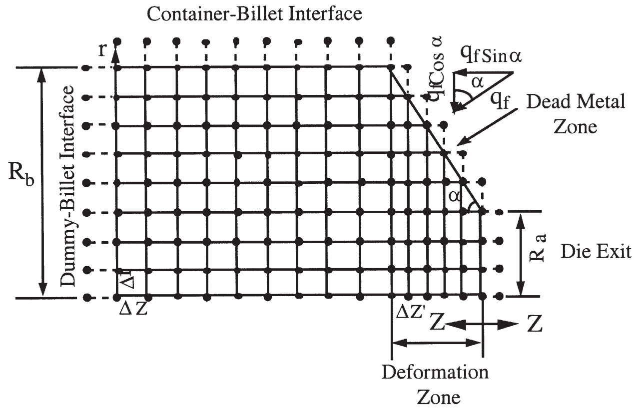

Fig. 3 Gridded meridian plane of the billet (all extended dotted points are fictitious points)

typical of industry practice in the extrusion of 6063 aluminum alloy. Temperature and strain-rate sensitivity have been incorporated into the flow stress. The thermodynamics model predicts the influence of plastic strain and strain rate on temperature rise in extrusion. In this section, the thermodynamic model is discussed briefly.

The differential equation of unsteady heat conduction developed by Carslaw and Jaeger (Ref 15) for an axis-symmetric case was used by Saha (Ref 16) and Saha and Ghosh (Ref 17) to determine the temperature distribution in the billet during extrusion and is given by:

$$a\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{R_m}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{U'''}{\rho c}=\frac{\partial T}{\partial t}+U_z\frac{\partial T}{\partial Z} \quad \text{(Eq 1)}$$

where a is the thermal diffusivity, T is the temperature of the billet material, r is the radial direction, R_m is the radius of the billet at any nodal point (m, j), $U'''=\bar{\sigma}\dot{\varepsilon}/J$ is the deformation energy/unit volume/unit time, $\bar{\sigma}$ is the average flow stress, $\dot{\varepsilon}$ is the strain rate, J is the mechanical equivalent of heat, ρ is the specific weight, c is the specific heat, and U_Z is the speed of material along the Z-axis with respect to stationary coordinates. The average values of the flow stress and thermal properties are assumed. The expressions to calculate strain, strain rate, and the flow stress of the billet material were shown by Saha (Ref 14).

Figure 3 shows the gridded meridian plane of the billet for numerical computation of the temperature distribution during extrusion.

Finite Difference Approximation. The expressions can be written in the finite difference form as per the scheme shown in Fig. 4(a) and (b) for equal and unequal spacing as:

$$\frac{\partial^2 T}{\partial r^2}=\frac{T_{m,j+1}+T_{m,j-1}-2T_{m,j}}{(\Delta r)^2} \quad \text{(Eq 2)}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T_{m+1,j} + T_{m-1,j} - 2T_{m,j}}{(\Delta Z)^2} \tag{Eq 3}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{2T_{m+1,j} + 2\phi T_{m-1,j} - 2(1+\phi)T_{m,j}}{(\Delta Z)^2(\phi+\phi^2)} \tag{Eq 4}$$

$$\frac{\partial T}{\partial r} = \frac{T_{m,j+1} - T_{m,j-1}}{2\Delta r} \tag{Eq 5}$$

$$\frac{\partial T}{\partial Z} = \frac{T_{m+1,j} - T_{m-1,j}}{2\Delta Z} \tag{Eq 6}$$

$$\frac{\partial T}{\partial Z} = \frac{T_{m+1,j} - \phi^2 T_{m-1,j} - (1-\phi^2)T_{m,j}}{\Delta Z(\phi + \phi^2)} \tag{Eq 7}$$

where $\phi = \Delta Z'/\Delta Z$. When $\Delta Z = \Delta Z'$, $\phi = 1$. The semidead-metal zone angle, α, is assumed to be 45°, or $\phi = 1$ in the analysis.

Substituting these finite difference approximations in the differential Eq 1 of heat conduction, the temperature at any nodal point (m,j) after time increment Δt can be calculated. Similarly, the temperature rise at the nodal points on the billet container interface and the dead-metal zone conical surface would be calculated by using the frictional heat flux equations and other boundary conditions. Separate boundary conditions are also assumed in the billet dummy interface, die exit nodal points, and nodal points on the centerline of the billet as discussed by Saha (Ref 16) and Saha and Ghosh (Ref 17).

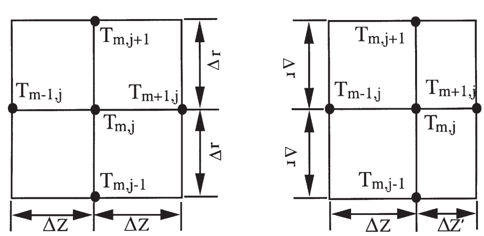

Fig. 4 Two different configurations of five adjacent points used in numerical calculation

Heat Generation Due to Billet-Container Interface Friction. It is assumed that shearing will occur along the entire boundary of the billet. In actual practice, during upsetting, the entire billet comes in full contact with the container bore under high pressure before actual extrusion starts. Frictional heat flux per unit area per unit time is given by:

$$q_f = \frac{\bar{\sigma} V}{\sqrt{3} J} \quad \text{(Eq 8)}$$

where V is the speed of the material at the billet-container interface, which is assumed to be the ram speed, V_R, and J is the mechanical equivalent of heat.

Heat Generation Due to Dead-Metal Zone-Flowing Metal Interface Friction. The frictional heat flux per unit area per unit time is given by:

$$q_f = \frac{\bar{\sigma}(V_{m,j})}{\sqrt{3} J} \quad \text{(Eq 9)}$$

where $V_{m,j}$ is the speed of the following material at the interface nodal points. $V_{m,j}$ is approximately calculated from the relationship:

$$V_{m,j} = \frac{V_R}{\cos \alpha} \quad \text{(Eq 10)}$$

where V_R is the ram speed. In actual hot extrusion practice, it is very difficult to obtain the velocity field inside the billet grid meridian plane. Saha (Ref 14) assumed steady-state ram speed as the material speed of the billet at each grid point. The longitudinal grid method is normally used to study the velocity field at each nodal point by generating square grids on a split billet face and analyzing the grids after a given amount of deformation. Thomsen et al. (Ref 18) have discussed a visio-plasticity experimental technique to obtain a steady-state velocity field using 4.3 in. (109 mm) diameter commercially pure lead billet at room temperature.

It is assumed that the dead-metal zone surface is straight conical. q_f has one component, $q_f \cos \alpha$, acting in the radial direction, and another component, $q_f \sin \alpha$, acting in the axial direction, where α is the semidead-metal zone angle.

Heat Generation Due to Die Bearing-Material Interface Friction. In the case of sliding friction, the frictional heat flux per unit area per unit time is given by:

$$q_f = \frac{\tau_f V_E}{J} \quad \text{(Eq 11)}$$

where friction stress, τ_f, will be calculated by using Eq 14 in Chapter 1. The friction factor, m_2, in Eq 14 (Chapter 1) may vary according to the surface condition of the die bearing. V_E is the material speed leaving the die and can be calculated by using the relationship:

$$V_E = V_R \cdot \text{ER} \qquad \text{(Eq 12)}$$

where V_R is the ram speed and ER is the extrusion ratio.

Influence of Principal Variables on Temperature Rise

Influence of Temperature in Extrusion. The critical temperature in extrusion is the exit temperature of the metal leaving the die, as discussed previously. It increases if the heat produced by deformation and friction exceeds the heat losses and decreases if the reverse is true. Heat conduction requires a definite time, and, therefore, depending on the alloy and the extrusion conditions, heat production dominates above a certain ram speed. This explains the ram speed dependence of the temperature profile along the length of the extrusion.

The exit temperature of aluminum just leaving the die is important for many reasons. Extrusion temperature has two distinct effects on product quality and die life as shown in Fig. 5. Regarding product quality, exit temperature affects heat treatment processes and dimensional stability and also causes extrusion defects. Exit temperature is a critical issue to the die life. Die wear and its performance may depend on exit temperature, which, in turn, causes temperature rise to the die bearing.

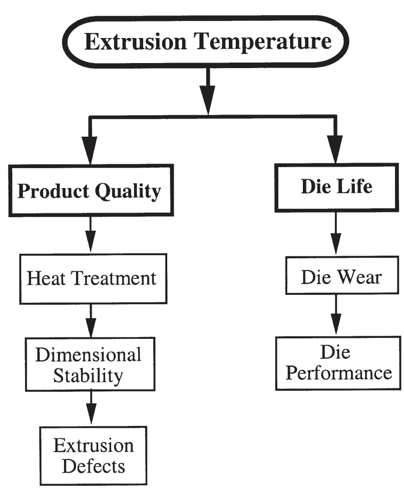

Fig. 5 Effect of exit temperature

Principal Variables and Their Effects. The temperature distribution in the billet during extrusion depends on several factors, such as billet material properties, friction conditions at billet container interface and die material interface, ram speed, extrusion ratio, outside perimeter, and die design parameters (type of die). The effects are summarized as follows:

- *Materials properties:* The mechanical properties of the billet material considerably affect the magnitude of the heat generated due to deformation and boundary friction. In the case of deformation, the dissipated heat is proportional to the flow stress of the material at a given temperature, strain rate, and strain. In the case of friction, the temperature increase is proportional to the friction shear stress. Thermal properties influence the temperature increase as well as heat conduction.
- *Friction:* The temperature distribution depends heavily on the friction factor at the billet and container interface, as well as at material and die interface, assuming other variables are kept constant. Temperature increases also occur due to higher friction shear stress at the dead metal zone interface.
- *Ram speed:* The temperatures developed in extrusion increase with increasing ram speed. This increase is due to the fact that the strain rate is directly proportional to the ram speed, and the magnitude of the generated heat is proportional to the strain rate. The lower the ram speed, the more time available for the generated heat to flow, and heat conduction is also more pronounced with aluminum because of its higher conductivity.
- *Extrusion ratios:* In the case of larger extrusion ratios, the exit temperature becomes higher due to severe plastic deformation at higher strain.
- *Outside perimeter:* The exit temperature developed in extrusion increases with increasing outside perimeter of the die geometry. This increase occurs because the die bearing frictional area increases with the increase of outside perimeter for the same bearing length.

Temperature Measurements

Existing Measurement Systems. Temperature measurements of the extrusion leaving the die can be done in several ways, as described by Castle (Ref19):

- Inserting a thermocouple into the die
- Measuring outside the die with a contact-type thermocouple
- Using an optical pyrometer

All of these methods have both merits and drawbacks. Historically, there has been no practical method of accurately measuring and controlling the aluminum extrusion surface temperature as it leaves the die at a certain speed.

The technique of inserting thermocouples into the die has been used in laboratories as well as in industry for many years. However, the response time might be too slow to detect rapid changes in the temperature if the measurement point is located some distance below the die bearing. If the thermocouple is inserted into the die bearing, thus scraping the profile, the correct surface temperature of the profile is measured. This method could yield the best performance, but its complexity precludes its use as an industrial routine; such a system would be practical only in laboratory experiments. Lefstad (Ref 20) investigated the exit temperature profile by inserting thermocouples into the die both in laboratory and industrial environments. The results showed great differences between the die temperature and the temperature of the extrusion on the run-out table. Measurements made at different positions in a variety of profiles showed higher temperatures in the central part of the profiles than at the edges or in the corners.

Many extrusion companies are still using higher resolution digital thermometers to detect the exit temperature of extrusion. The application of this system is a manual operation, and the accuracy of the measurement is dependent on the following:

- The position of the two-point, spring-type thermocouples (probe) with the extrusion surface
- Probe condition (oxidation and wear)
- Holding time
- Proper thermocouple material to measure aluminum temperature

With the thermocouple measurement system, the thermocouple position has to be perpendicular to the surface of the extrusion. The proper position will provide the full contact of the thermocouple with the extruded surface. The system does require certain holding time to reach the thermocouple to read the steady-state temperature. A low holding time means a higher resolution of the system. It should also be made certain that the proper probe material is being used to measure the aluminum surface temperature. Another limitation of this type of thermometer is that the system can read properly only when the extrusion is stopped, or the extrusion is moving with a very slow speed. Besides the operational limitations, the system is a discontinuous type that is not appropriate to record the temperature profile of the extrusion from the start to the end of extrusion.

In the extrusion industry, a continuous and automatic temperature control system is very important, and necessary, to maintain higher dimensional accuracy, uniform mechanical properties, and optimization of extrusion speed with exit temperature to increase the productivity. Barron (Ref 21) represented the use of multiwavelength infrared thermometry for noncontact temperature measurement of aluminum extrusion. Glasman et al. (Ref 22) also introduced a new optical pyrometer for measuring the temperature of aluminum alloys. They found the temperature measurement error under conditions of changing emissivity lies less than 1%. Both systems are widely and successfully used in the extrusion industry to measure billet temperature, press-exit temperature monitoring and control, and especially for isothermal extrusion.

A typical noncontact temperature sensor is shown in Fig. 6. The noncontact temperature measurements are made within seconds after the extrusion leaves the die and the sensor continuously monitors the temperature from the start to the end of extrusion. The continuous monitoring of extrusion temperature enables the process to be operated as much as possible at a constant temperature (isothermal extrusion) by controlling the ram speed, thereby optimizing productivity.

The system could be utilized to control and monitor both billet and extrusion temperature more accurately to maintain consistent extrusion quality. The schematic of the system for aluminum extrusion application is shown in Fig. 7.

Two-point temperature probes are normally used in both gas-fired and induction-type billet heaters used to preheat the aluminum billet

Fig. 6 Typical noncontact temperature measurement unit. Courtesy of Williamson Corp.

prior to extrusion. This type of probe requires constant maintenance to provide accurate temperature measurements. These probes are subjected to high temperatures, constant oxidation, and subsequent tip wear. Other issues affecting the accuracy of the probe-type thermocouples surface when the probe is not properly seated on the billet surface (both induction- and gas-fired types) or when the probe points span across two adjacent billets (gas-fired type). An additional concern are the intermittent temperature readings for control, which occur when there is no billet in the zone or the probe is retracted (gas-fired type). Compared to the probe-type temperature control system in the billet heater, noncontact temperature sensors have added advantages, such as continuous and consistent control of measurement for temperature verification at the exit of the furnace prior to push the billet into the container.

Dail et al. (Ref 23) examined the emissivity features of the linear spectral ratio (LSR) method and evaluated other forms of dual wavelength emissivity compensation. This method was applied on three different alloys, 1100, 5052, and 7075, under different surface conditions.

Mester et al. (Ref 24) developed a noncontact eddy-current system to measure both temperature and the cross-sectional area of aluminum extrusion exiting the die. Temperatures near 1000 °F (538 °C) were measured within ±10 °F (±5 °C). The system could measure average internal temperatures of the solid round, solid square, and hollow square cross sections. This system could operate on eddy-current principles rather than infrared radiation as the more common optical pyrometers do. Since the eddy currents were generated in the product and made to penetrate below the surfaces, the temperature measured by the system was the average of the radial temperature profile from the surface to the depth of penetration.

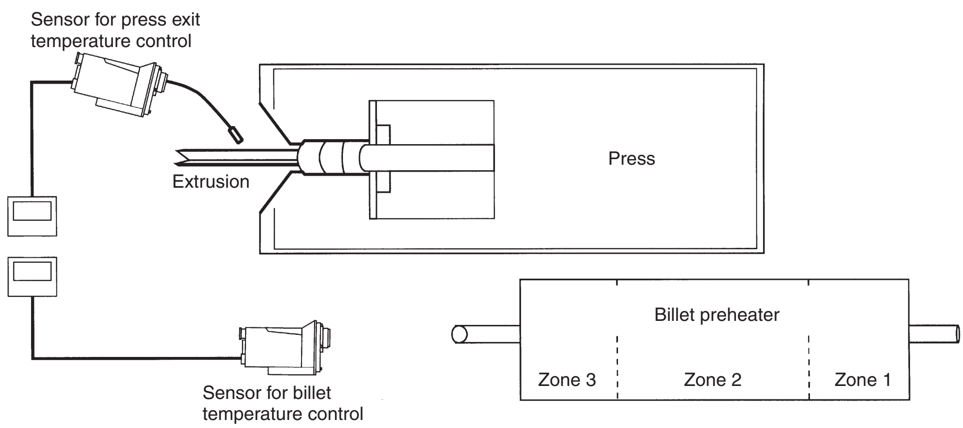

Fig. 7 Typical billet and extrusion temperature measurement system. Courtesy of Williamson Corp.

Research on Temperature Measurements. Temperature measurements are very important in understanding the relationship between exit temperature and the process parameters such as extrusion ratio, initial billet temperature, extrusion speed, and die bearing surface condition. Results of a fundamental research have been discussed in this section, especially for beginners in the extrusion technology.

Temperature measurements on the exit-surface of an extruded square tube, just after extrusion, were conducted by Saha (Ref 25) in an industrial environment using a high-resolution digital contact thermometer. The basic purpose of this experiment was to measure the exit temperature of a thin-gage 6063 extrusion just leaving the die under different conditions to gain a better understanding of the range of temperature developed during extrusion and to compare the experimental results with the computer simulation. The variables used in the test included the following:

- Billet length (for fixed billet temperature and ram speed)
- Ram speed (for fixed billet length and billet temperature)
- Outside perimeters (for fixed billet length, billet temperature, and ram speed)

The extrusion parameters, the alloy composition of the billet material, and the composition of the die steel are shown in Tables 1 to 3. The die used in the test is shown in Fig. 24 in Chapter 4.

Temperature measurements were taken using the direct-contact higher resolution digital thermometer on the extruded surface. Each point on the plots is the average value of five measurements. The measurements were easily reproduced. Because it becomes difficult to measure the surface temperature accurately on the moving extruded material, it was decided to measure the temperature at the end of the stroke where the temperature was found to have a maximum value. The thermometer needed 3 to 4 s to reach the steady values.

Table 1 Extrusion parameters

Parameter	Value
Billet	
Diameter, in. (mm)	6 (152)
Length, in. (mm)	19–21 (482–533)
Temperature (steady), °F (°C)	
Front	860 (460)
Middle	801 (427)
Back	759 (404)
Container	
Bore, in. (mm)	6.38 (162)
Temperature, °F (°C)	806 (430)
Die	
Shape	Hollow square, 2 in.^{2} (50.8 mm^2)
Bearing length, in. (mm)	0.08–0.14 (2.0–3.5) (blended)
Temperature (start), °F (°C)	824 (440)
Extrusion ratio	90

Because the die temperature is among the major factors of die wear, it is important to measure the die bearing temperature and the exit temperature of the extruded aluminum. In the past, there were several techniques used to measure the die temperature very close to the die bearing and the extrusion exit temperature. Ward et al. (Ref 26) conducted computer-assisted extrusion and die bearing temperature measurements in their study on the effects of nitrogen (liquid and gaseous) on aluminum extrusion productivity.

A series of temperature measurements were conducted by Saha (Ref 25) to study the exit temperature of 6063 alloy thin tube of cross-sectional area 0.355 in.^{2} (229 mm^2) with a wall thickness of 0.03 in. (0.762 mm). The three different variables studied were billet length, surface condition of the die bearing, and outside perimeter of the die or extrusion profile. Thus, three series of temperature measurements were conducted, in which each of these quantities was varied, in turn, while the other two were kept constant. The resulting measured average exit temperatures are shown in Fig. 8 to 10 as a function of ram speed.

Figure 8 indicates that the exit temperature of 6063 square tube increases with ram speed, keeping other variables constant. The results are shown with the two different billet lengths. However, the most pronounced effect is the increase in exit temperature with increasing billet length because the extrusion cycle time becomes longer in the case of longer billet length. For larger billet lengths, more friction must be overcome resulting in more heat generation due to friction between billet-container interface.

Figure 9 shows the variation of exit temperature with ram speed for two different surface conditions of the die bearing. A new nitrided (hard) die bearing surface normally sticks less to the aluminum than an old (soft) die surface. Based on the nature of the aluminum buildup on

Table 2 Chemical composition of billet (6063 alloy)

Element	Composition, %
Si	0.35
Fe	0.17
Cu	0.01
Mn	0.01
Mg	0.50
Cr	0.01
Ni	0.01
Ti	0.01
V	0.01
Al	rem

Table 3 Composition of H13 hot die steel

Element	Composition,%
C	0.37
Cr	5.02
Mn	0.36
Mo	1.25
Si	0.98
V	0.85
Fe	rem

the die bearing, an old die surface provides more sticking friction, whereas a new die surface provides more sliding friction. As expected, temperature rise in a new die surface is found to be lower compared with that of an old die surface because the heat generation due to friction stress in the new die bearing surface becomes less.

Figure 10 shows the variation in exit temperature with ram speed for two different outside perimeters of the die geometry. Because the frictional area is larger in the case of a larger perimeter, the temperature rise becomes slightly larger in the case of a larger perimeter compared with

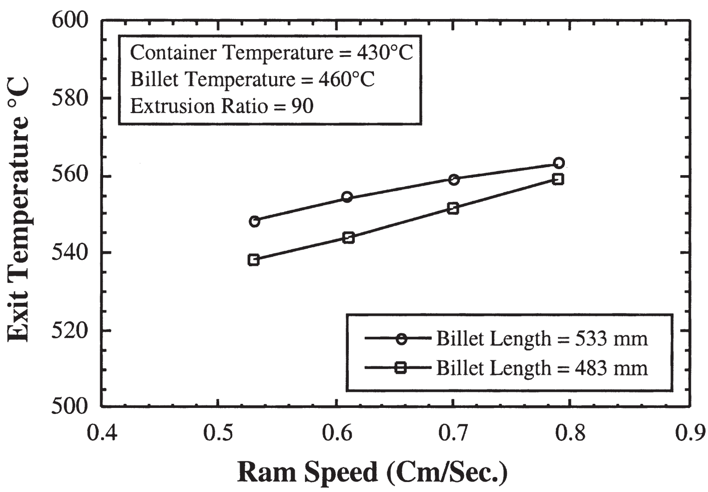

Fig. 8 Variation of exit temperature with ram speed for two different billet lengths on 6063 aluminum alloy

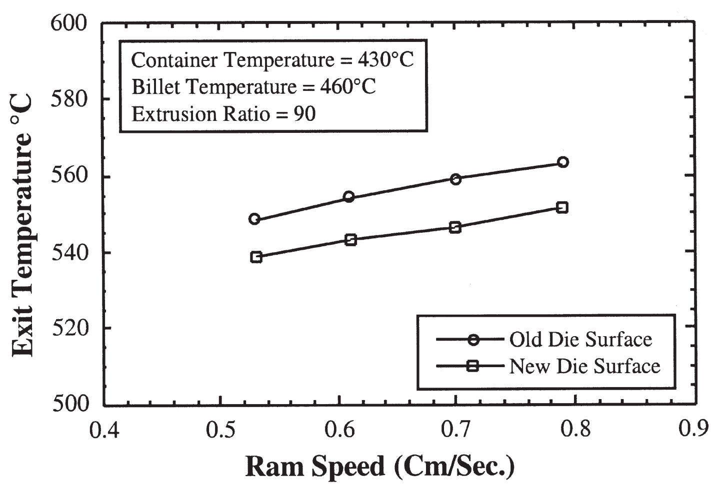

Fig. 9 Variation of exit temperature with ram speed for two different surface conditions of the die bearing on 6063 aluminum alloy

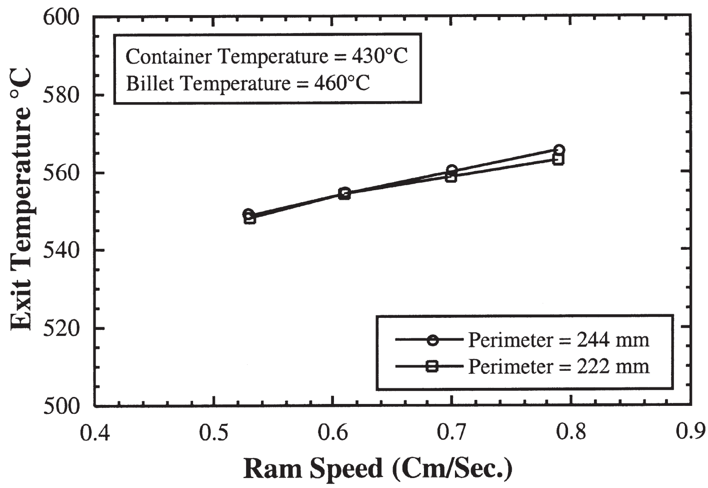

Fig. 10 Variation of exit temperature with ram speed for two different outside perimeters of the die geometry on 6063 aluminum alloy

that of a smaller perimeter. Variation could be higher if the difference between the perimeters becomes larger.

Figures 8 to 10 also show that exit temperature increases apparently linearly with respect to an increase in ram speed. Ward et al. also found a linear relationship between temperature and extrusion velocity, both with and without nitrogen cooling die systems.

Temperature measurements in this research were conducted without a nitrogen die cooling system. The temperature rise on the extruded aluminum, as well as on the die bearing, becomes much higher compared with the rise measured with a nitrogen cooling system. Because the temperature on the die bearing increases gradually with the increase of press cycle, it will influence the adhesive layer development on the die bearing. The wear mechanism and the change of flow of aluminum through the die bearing due to die wear are explained in the next section.

Figure 11 compares the temperature rise (for a fixed extrusion ratio) for two extrusions. One is a simulated billet where the extrusion speed was predicted by the modified model (Ref 14); the other is an actual billet where the temperature was measured by a digital contact thermometer on the exit surface of the extrusion as soon as it left the die bearing. Results show that the temperatures predicted by the model are very close to the measured value. The variation lies between 2 and 4%. This variation could be minimized by using a more sophisticated online temperature measurement system. To measure the exit temperature using the contact thermometer, the press has to stop after the same time interval used for computer simulation.

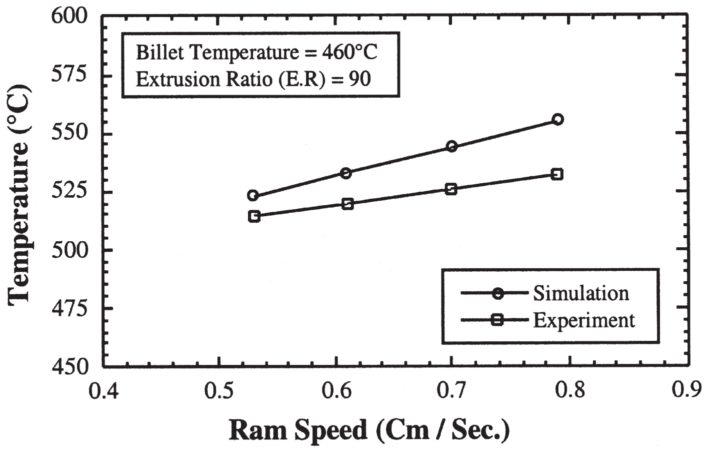

Fig. 11 Comparison of maximum temperature rise in the billet obtained from simulation and experiment in the billet with extrusion speed for fixed extrusion ratio on 6063 aluminum alloy

Isothermal Extrusion

As discussed in the previous sections, the exit temperature can vary during extrusion with a constant ram speed due to mechanics and thermodynamics of deformation processes. A temperature increase toward the beginning and the end of extrusion is observed for a given billet and container under different extrusion conditions, such as ram speed, die parameters, and alloy characteristics. This change of temperature during extrusion is in full agreement with many theoretical calculations. Extrusion with a constant exit temperature is referred to as *isothermal extrusion* and has practical interests for achieving a uniform product quality and higher productivity. The basic idea of so-called isothermal extrusion developed from the knowledge of the relationship between the exit temperature and the ram speed. The exit speed is varied via the press control system to provide a constant exit temperature.

Laue and Stenger provided an overview of isothermal extrusion. The practical and economical value of isothermal extrusion is that, except at the very beginning, it allows the use of the optimum extrusion speed over the complete extrusion cycle. On the other hand, if the exit temperature varies during extrusion by an unknown amount, the press speed is usually adjusted in accordance with the maximum prevailing temperature. This adjustment sets the speed for the whole cycle, and there is a wasted surplus speed capacity in the region of low-exit temperature. The temperature profile at a constant speed must first be determined measuring each case in order to decide whether isothermal extrusion is feasible and how the press control system should be modified. In the case of a continually increasing exit temperature of aluminum alloy extrusion, isothermal extrusion can be carried out in the following ways:

- Reducing the exit speed during the extrusion according to the measured exit temperature. This requires continuous temperature measurement.
- Reducing the extrusion speed according to a preselected speed program. On a modern press, the ram displacement can be divided into steps of varying lengths, each with a programmed speed.
- Nonuniform heating of the billet to give a lower temperature at the back of the billet. This is known as "taper heating" and can be achieved by induction heating with suitable coil connections or by using additional burners, which transfer more heat to the front of the billet than to the rear, in gas furnaces. Another method is to heat the billet uniformly, and then quench the back end with a water spray as the billet is transferred from the furnace to the container.

The most common industrial methods of isothermal extrusion of aluminum alloys are the following:

- Taper heating or taper quenching billet prior to feeding into the container
- Direct measurement of the extrusion temperature using noncontact system and a feedback between measured temperature and the extrusion ram speed

A system for isothermal extrusion was developed in which the variation in ram speed necessary for maintaining the product temperature within the required limits than was initially programmed by Laue (Ref 27). In presses designed to operate on this principle, the working stroke is divided into zones, each having a preset speed. In a press used for the extrusion of high-strength alloys, a time savings of 60% was claimed. Savings would be lower for more easily extrudable alloys. Chadwick (Ref 28) suggested that the temperature variations in the emerging extrusion be reduced by imposing a temperature gradient in the billet. The billet is inserted into the container such that the hot end is extruded first while the temperature of the cooler end increases during extrusion. This practice is not entirely satisfactory because of the relatively high thermal conductivity of aluminum alloys; therefore, if any delays occur in the extrusion sequence, the temperatures in the billet tend to become uniform throughout the billet length. A better method consists of water quenching the feed table to the container. Another approach for increasing extrusion speed is to cool the die with water or nitrogen.

Kelly and Kelly (Ref 29) described a simulated isothermal extrusion system. The system is designed to operate with or without taper heating of the billet. By use of a modern programmable logic controller (PLC) system with a ram displacement transducer, it is possible to store in the PLC a number of extrusion speed curves that automatically control the speed of extrusion so as to achieve constant exit temperature. Their research showed that these isothermal speed curves not only produce constant exit temperature but result in reduced extrusion time and, therefore, improved productivity.

Kialka (Ref 30) developed a method of isothermal extrusion employing a force-speed feedback system to control the extrusion process. The method is characterized by a variable with programmable extrusion speed and real-time process adaptable to the variable conditions of the heat transfer providing the required exit temperature. This method could be useful in the design and manufacture of control systems for extrusion presses. The extrusion method and control systems designed were prepared for industrial application at all presses driven by hydraulic pumps of a variable delivery.

A control and signal processing system was developed by Pandit et al. (Ref 31) for isothermal extrusion. The pyrometer, as well as control and signal processing algorithms, have been implemented and installed in an industrial extruder. Simulations and experiments show that satisfactory isothermal operation of an extruder was obtained. Productivity increased up to 23% and enhanced the product quality. The control of exit temperature offered a basis for total automation of an extruder in which the exit temperature and the extruder velocity were controlled at their constant optimal values. However, these powerful measures can be introduced effectively only if the plant operates efficiently, and the operating team pays keen attention to the success of the measures.

Jenista (Ref 32) discussed a fully developed taper quench unit that could provide the required range of precise temperature profiles. This unit was available for the production extrusion environment and has been supplied in billet diameters from 7 in. (178 mm) to 15 in. (381 mm). The tapered quench provided a cost-effective, efficient, and simple method of realizing the advantages of isothermal extrusion.

Venas et al. (Ref 33) developed a simulation procedure for the extrusion process by means of finite element modeling (FEM). The model includes the container, die, billet, and ram variables. Using this model, the effect of different process conditions has been studied. It was shown that extrusion speed could be significantly increased by isothermal extrusion compared with conventional extrusion with uniform or tapered billet temperature.

Biswas and Repgen (Ref 34) developed computer aided direct extrusion (CADEX) pc-based software for calculation of extrusion parameters, such as speed and billet temperature, to optimize the quality and productivity of extrusion. The extrusion quality is influenced by extrusion temperature, load on the die, and speed. These process variables are considered in the optimization procedure and in this way enable isothermal and isopressure extrusion. By direct linking of the CADEX pc and the PLC of the press, working with optimized values is ensured at any time. They reported that with CADEX, the extrusion time can be reduced by an average of 10%, which gives an investment payback in less than one year.

OPTALEX (Alu-Mac A/S, Alleroed, Denmark) (Ref 35) is an advanced isothermal extrusion control system developed for the production of aluminum profiles. The system measures profile exit temperature and uses a closed-loop control algorithm to enable a press to be run at a near constant profile exit temperature by controlling the press speed/pressure. Press efficiency is significantly improved, and the pressing time per billet is reduced, resulting in higher productivity. All the optimized production and process data are stored, and each time the same die is run, the press operator can use the optimized parameters in the new production. OPTALEX can easily be connected to a network, and the data can be used to produce statistics, management reports, QA documentation, administration, planning, and so on. OPTALEX is easy to install and to connect to the press PLC, and all component parts of the system are designed for use in an extrusion plant environment. OPTALEX can be installed on presses with both gas billet heaters and taper-heating induction billet heater.

Bryant et al. (Ref 36) reviewed and gave an overview of isothermal extrusion, including the development and the key pieces of process equipment and control software.

Principle and Benefits of Isothermal Extrusion. The principle of isothermal extrusion as shown in Fig. 12 is to get constant extrusion temperature for a set of input variables, including billet length, initial billet temperature, extrusion ratio, and ram speed. The benefits of isothermal process in direct extrusion are quite significant:

- Improved dimensional stability
- Uniform surface quality
- Improved or consistent mechanical properties with uniform microstructure
- Faster extrusion speed to increase productivity
- Better air venting through the container, reduced breakthrough pressure, and so on

Several methods of isothermal extrusion have been mentioned according to the published research in the previous section. The most practical method in the production environment seems to make use of a preheated billet that has been determined to have an optimal temperature gradient between the front and the back of the billet before it is fed into the container with variable ram speed. The temperature gradient required by the billet to perform isothermal extrusion depend on the factors, including billet length, die geometry and design, and alloy and its working temperature range.

Methods to Yield Consistent Mechanical Properties. One of the important benefits of isothermal extrusion is that it makes it possible to obtain consistent mechanical properties, a critical consideration, especially for structural and aerospace applications. The deformation process within the container in direct extrusion is normally inhomogeneous, causing some variation of structure along the length and cross section of the extrusion. Mechanical properties of extrusions are initially dependent on the deformation of grain structure from billet (coarse) to extrusion (fine) and followed by subsequent heat treatment processes. The finer the grain structure, the higher the strength (tensile properties). Mechanical properties of extrusions could also be related to tribology and thermodynamics of extrusion.

It is important to have an understanding of the mechanics and thermodynamics of extrusion to obtain uniform temperature distribution throughout the cross section of the extrusion profile as shown in Fig. 13(a). In direct extrusion, the temperature profile could be either of the distributions shown in Fig. 13(b) and (c), depending on tribological aspect (die-bearing friction), mechanics (speed), and thermodynamics (heat transfer) of extrusion.

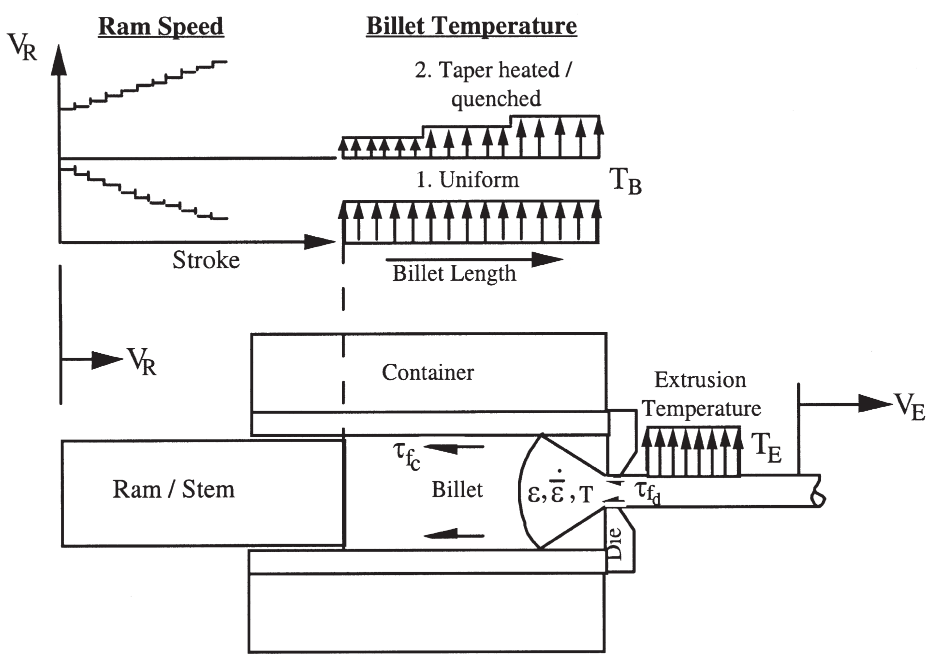

Fig. 12 Principle of isothermal extrusion. τ_{f_c}, friction stress at the billet-container interface; τ_{f_d}, friction stress at the die bearing-flowing material interface

The higher the bearing length, the greater the effect of frictional heat generation due to the increase in frictional surface area. There will be a greater chance for localized temperature to rise on the surface to a certain depth within the cross section of extrusion. Temperature gradient is also a function of cross-sectional size and circumscribed circle diameter (CCD) of the extrusion.

With the increase of extrusion speed, the localized frictional heat generation at the die-bearing interface also increases, causing a momentary increase in surface temperature of extrusion because there is less time to transfer heat from the outer surface to the center of extrusion. The slower the speed of extrusion, the greater the time to allow heat conduction from surface to the center of the extrusion, provided the surface temperature or the temperature of the extrusion at the die corner before leaving the die is higher than that at the center of the extrusion.

The variation in deformation and temperature in the extrusion cross section from the surface to the center could cause the variation of grain sizes shown in Fig. 14 along the cross section and the length of extrusion. This is a very common problem, especially in harder alloy extrusion. This is an undesirable grain structure. In many cases, the undesirable area is machined off and discarded, depending on the application.

The variation of temperature in the extrusion is one of the major factors for recrystallization in the outer band of the extrusion, as shown in

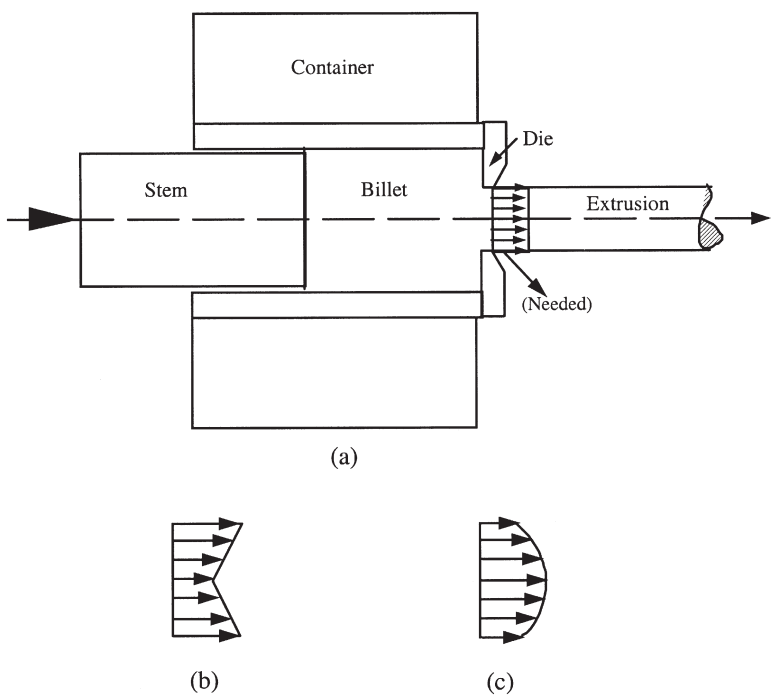

Fig. 13 Temperature distribution of extrusion

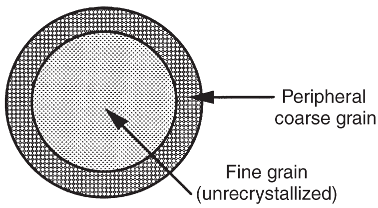

Fig. 14 Schematic of recrystallized peripheral grain growth

Fig. 14. The other factors include extrusion ratio (strain), strain-rate, alloy structure, flow stress, and recrystallization temperature of the alloy to be extruded. Recrystallization temperature is not a fixed value; it depends on billet composition, metallurgy, extrusion conditions, rate of heating, and time at temperature. The usual structural changes first happen during subsequent solution heat treatment. Figure 14 shows a coarse-grain recrystallized outer band with fine unrecrystallized structure at the core. The localized recrystallization around the periphery of the extrusion is known as peripheral coarse grain. The recrystallized outer band may cause a variation in mechanical properties, namely, a lower tensile stress than the unrecrystallized core.

The coarse grain formation in aluminum alloy extrusion could be avoided in several ways:

- Controlling the exit temperature during extrusion
- Increasing the recrystallized temperature by adding some recrystallization-inhibiting elements, such as manganese, chromium, and zirconium
- Reducing the recrystallization temperature by avoiding these elements, which are not required in the alloy
- Casting sound billet with effective homogenization
- Maximizing the possible extrusion ratio of the shape to get the critical strain value

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CHAPTER **3**

Extrusion Press and Auxiliary Equipment

The development of extrusion presses from the first simple lead press to the modern automatic extrusion plant represents an interesting chapter in the history of extrusion technology. Recently, to meet the requirements of larger-sized, thinner-walled extrusion shapes with improved dimensional accuracy, prestressed frame structure presses have been adopted. Press rigidity and alignment are much improved compared with conventional presses. Most modern presses have a relative position indicator to monitor the alignment of the container and the moving crosshead during extrusion. They are also provided with press monitoring equipment to display press operation data on the monitor screen in real time. The programmable controllers are linked to operate the billet heater, extrusion press, puller, cooling table, stretcher, saw table, saw, and so on. Extrusion data are measured and stored using the computer system for each die, and those data are available and effective for designing and modifying dies and selecting optimum extrusion parameters, including billet temperature, container temperature, billet size, ram speed/displacement, and extrusion puller speed.

Fielding (Ref 1) gave a complete overview of the developments in extrusion presses with handling systems from 1969 to 1996. Fielding (Ref 2) wrote an excellent paper on the maintenance of extrusion plants including presses, handling systems, and other ancillary equipment.

Laue and Stenger (Ref 3) discussed the fundamentals of design and construction of extrusion presses and other auxiliary systems. There are few manufacturers that can design, manufacture, and supply both extrusion presses and associated handling equipment. Belt conveyor-type

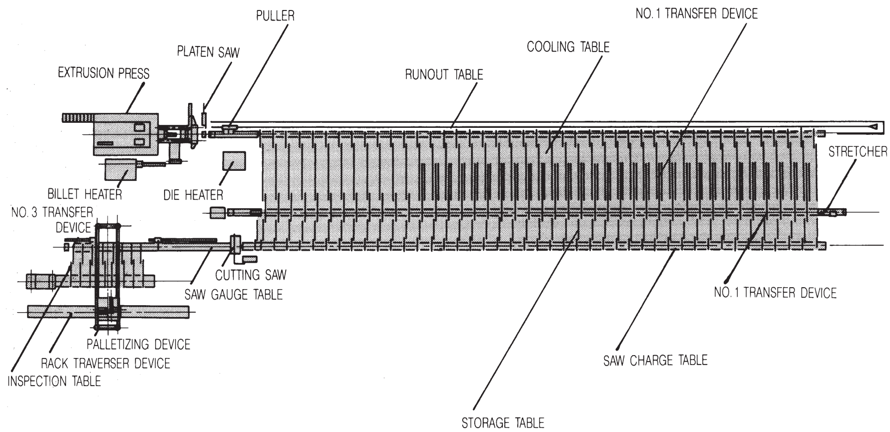


Fig. 1 Layout of an aluminum extrusion installation. Source: UBE Industries, Ltd.

handling equipment was originally developed in Japan to cope with customer needs such as minimization of labor and quality improvement. This is now an industry standard. Figure 1 shows the layout of an aluminum extrusion installation from press to automatic palletizing devices. In this chapter, the fundamental concepts of different types of extrusion presses and major press components are discussed. An outline of the recently integrated system from billet furnace and log shears to age ovens and stacking equipment to control the entire manufacturing process with high productivity is also included in this chapter.

Types of Extrusion Presses

Direct Press. A schematic of a direct extrusion press is shown in Fig. 2. Direct presses are used to make solid bars, rods, strips, and integrated sections. The presses can also be used to extrude tubes and hollow sections from softer grade aluminum using a solid billet through a porthole or bridge dies. A direct extrusion press with laminated tie rods is shown in Fig. 3. This press could also handle both round and rectangular billets separately. The alignment of the laminated tie rods toward the centerline of the press ensures precise control of moving parts and optimum power transmission. A safe and precise guide for the billet container allows the convenient use of a fixed dummy block. The press platen of a modern press is designed in such a way that it can support even extremely large tools to safely and reliably manufacture large and wide sections with minimum tolerances of the extruded product and higher product quality. Modern presses are generally equipped with special

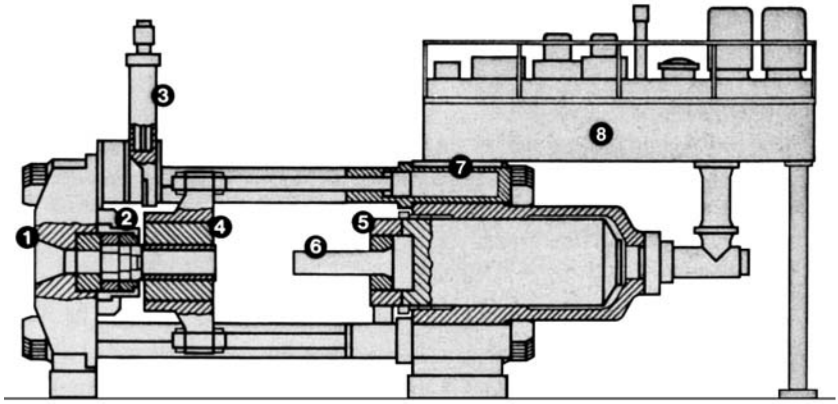


Fig. 2 Schematic of a direct extrusion press. 1, counter platen; 2, die slide or rotary die head; 3, shear; 4, billet container; 5, moving crosshead; 6, stem; 7, cylinder crosshead; and 8, oil tank with drive and controls. Source: Schloemann-Siemag

features, including die clamping, quick-release stems, automatic alignment checking, bolster shearing, telescopic billet loaders, short-stroke design, and computer software for higher production and quality. The hydraulic equipment, including pumps and valves, could be placed on the oil tank of the press or at the floor level or below floor level. It is very easy to access the floor-based system, as shown in Fig. 4.

Figure 5 shows a schematic of a direct extrusion press for seamless hollow and tubes. Tubes from harder aluminum alloys are generally done from hollow short billets with the floating or fixed mandrel on the stem.

Indirect Press. The basic type of press developed for indirect extrusion (Fig. 6) consists of the same elements as the presses used for direct extrusion. Generally, for hard alloy extrusion, especially for use in the aerospace industry, the metal flow properties obtained with indirect extrusion are much more favorable than those obtained with the direct method. With the aid of the flow pattern occurring during direct extrusion, it is possible to decide for which materials and products the indirect extrusion method should be considered. Indirect extrusion is often more economical in the manufacture of rods, bars, sections, and tubes from many aluminum alloys.

The difference between the two extrusion methods is that, in direct extrusion, there is no relative motion between the die and container during extrusion. In the case of indirect extrusion, however, the die fixed on the front end of the hollow stem penetrates into the container. Thus, in comparison with direct extrusion, indirect extrusion has advantages in that the process reduces the extrusion pressure, increases the billet diameter, and starts extrusion with a lower billet temperature for critical shapes.

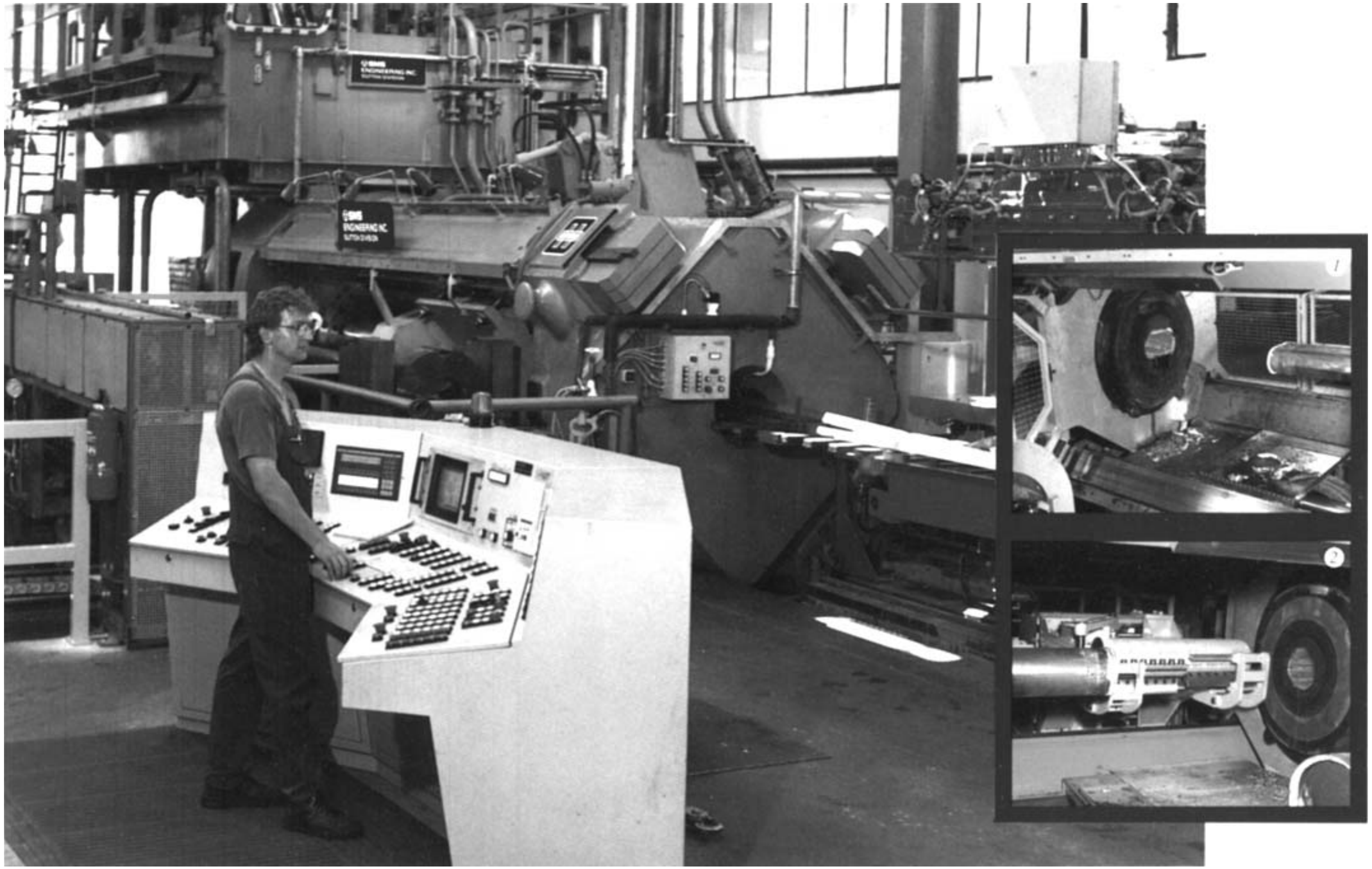


Fig. 3 Modern 3465 ton (31.5 MN) direct extrusion press with laminated tie rods, operated from central control desk. 1, container and extrusion stem for flat billets; 2, two-part linear billet loader. Source: SMS Engineering Inc.

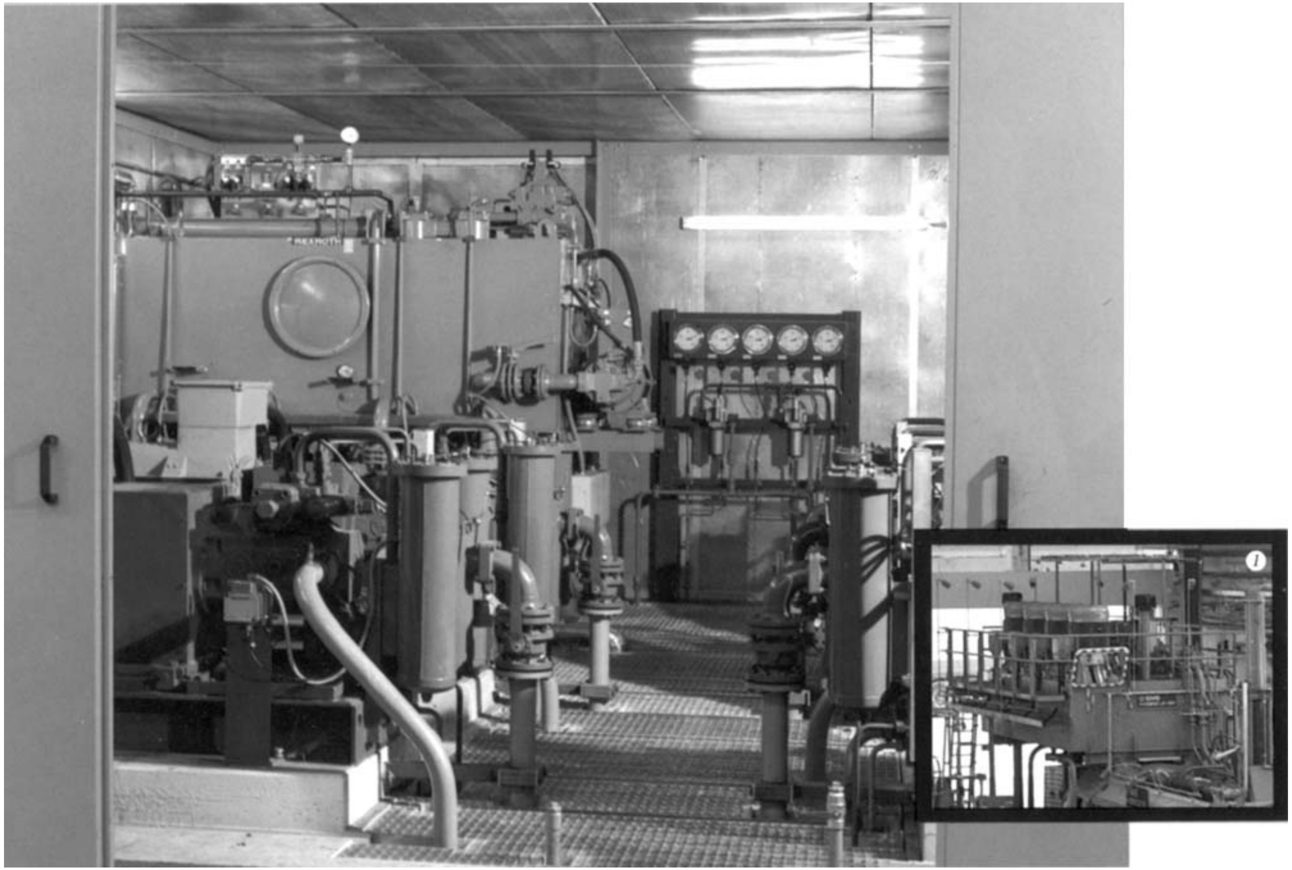


Fig. 4 Floor-based, soundproofed pump system. 1, pumps on the oil tank of the press. Source: SMS Engineering Inc.

With indirect extrusion, the circumscribed circle of section is smaller than with direct extrusion, and the stress on the stem is higher. The indirect method, however, affords the following advantages:

- Longer initial billets
- Higher extrusion speed for many materials
- Thinner butt ends
- More uniform structure over the extruded length
- Thinner sections
- Closer tolerances over the entire length of the product
- More uniform container and billet temperatures during extrusion
- Longer service life of the container and liner

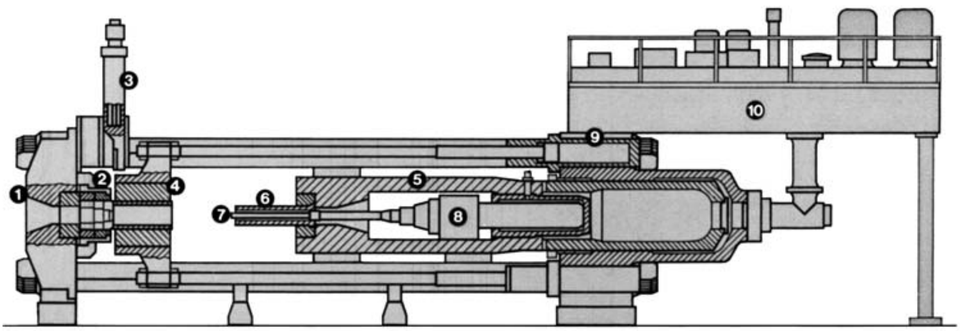


Fig. 5 Schematic of a direct extrusion press for seamless hollow and tube. 1, counter platen; 2, die slide or rotary die head; 3, shear; 4, billet container; 5, moving crosshead; 6, stem; 7, mandrel; 8, piercer; 9, cylinder crosshead; and 10, oil tank with drive and controls. Source: Schloemann-Siemag

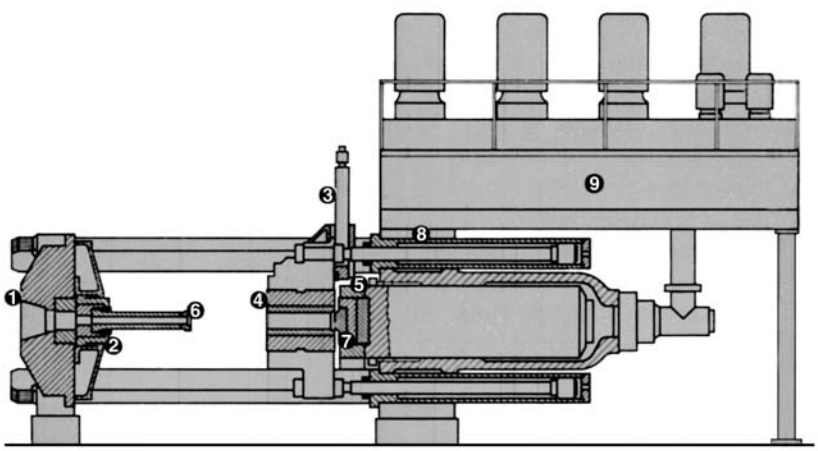


Fig. 6 Schematic of an indirect extrusion press. 1, counter platen; 2, die slide; 3, shear; 4, billet container; 5, moving crosshead; 6, die stem; 7, sealing element; 8, cylinder crosshead; and 9, oil tank with drive and controls. Source: Schloemann-Siemag

Larson and Bland (Ref 4) provided an overview of developments in indirect presses. There are some disadvantages of indirect presses:

- Machining of billet skin is required to prevent surface imperfections.
- Size of extrusion is limited with the bore of hollow stem.
- Die handling is difficult.

Combination Direct/Indirect Press. There are few combinations of direct/indirect presses for aluminum extrusion in operation. Several designs of combination direct/indirect presses are available, each with advantages and disadvantages. Larson and Bland (Ref 4) provided an overview of different designs of indirect and combined direct/indirect presses. The main objective of the combination press is to convert from indirect to direct extrusion. However, there is no compensation for the advantages of indirect extrusion in the combination press. There are three types of combination presses:

- Single stem, direct/indirect rod presses with conventional die slide
- Two stem, (die stem and extrusion stem) direct/indirect rod press with gate lock (Fig. 7)
- Two stem (die stem and extrusion stem) combination direct/indirect press with gate lock die slide arrangement

Extrusion with Active Friction Force (EwAFF). Both direct and indirect extrusion presses are normally used for the extrusion of harder aluminum alloys. Within the limitations of indirect extrusion, the process is perfect for smaller and thin-gage extrusions to achieve better dimensional and more uniform mechanical properties. Very heavy extrusions with higher circumscribed circle diameter (CCD) are normally

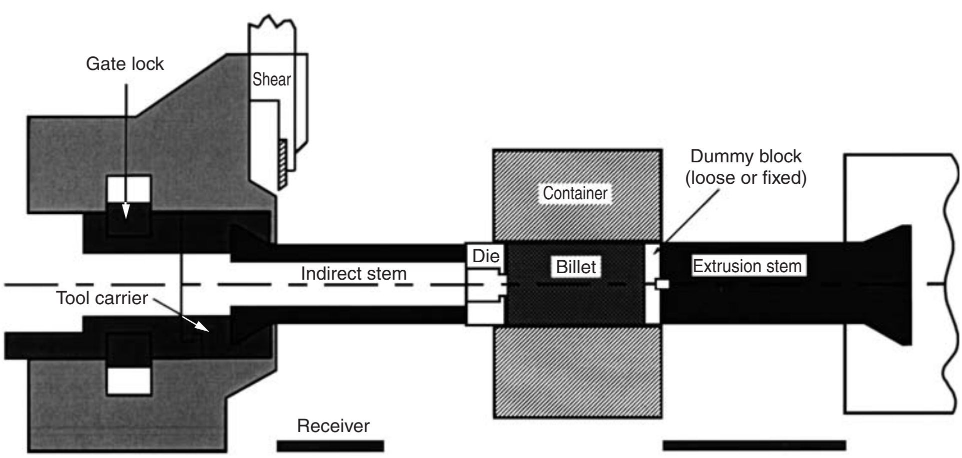


Fig. 7 Schematic of combined direct/indirect press. Source: Ref 4

extruded using a direct press of high capacity. Besides these two processes, a new process, "extrusion with active friction forces or active indirect extrusion," with advantages over the indirect process, was proposed in 1965 by Berezhnoy (Ref 5). The process was developed and found industrial use in Russia in 1988. Later, Shcherba (Ref 6) performed a further study on the feasibility of extrusion with active friction force (EwAFF) process.

A schematic of one of the concepts of the active-indirect extrusion process is shown in Fig. 8(a). A brief explanation about the EwAFF process compared with the existing conventional direct and indirect processes is discussed in this section. Frictional forces at the billet-container interface are in the direction of metal flow, thus allowing acceleration of peripheral flow and deceleration of central flow. This creates uniformity of distribution of the longitudinal speed component in the reduction zone across the billet's section. In other words, EwAFF is a derivative of indirect extrusion with an additional movement of the container or die relative to the motion of the ram. Due to the change of mechanics in this process, EwAFF has advantages compared with direct or indirect processes:

- Produces high quality rods, bars, and shapes of harder and more difficult alloy extrusions with higher uniform mechanical properties
- Reduces the formation of defects, thus reducing the scrap rate
- Extrusion speed increases 3 to 4 times that of the direct process and 2 to 3 that of the indirect process
- Improves surface finish, minimizes coarse-crystalline structure and enhances corrosion resistance

For scientific reasons, the EwAFF process is recommended for applications in the extrusion industry. In Russia, there are two extruders of 1600 and 3500 ton capacity in operation. Research on the process variables is still ongoing.

In the direct extrusion process as shown in Fig. 8(b), there is a relative sliding action between the billet and the container; hence, friction at the billet-container interface restricts the flow of metal compared with the flow at the center of the billet. Direct extrusion of harder alloys, such as 2024 and 7075, has some limitations:

- Limited in billet weight
- Limited extrusion speed
- Lower recovery
- Lower productivity
- Dimensional inaccuracy
- Structural inhomogeneity and nonuniform mechanical properties

In the indirect extrusion process, the die at the front end of the hollow stem moves relative to the container, but there is no relative displacement between the billet and the container as shown in Fig. 8(c). Therefore, this process is characterized by the absence of friction between the billet surface and the container. Compared with direct extrusion, indirect

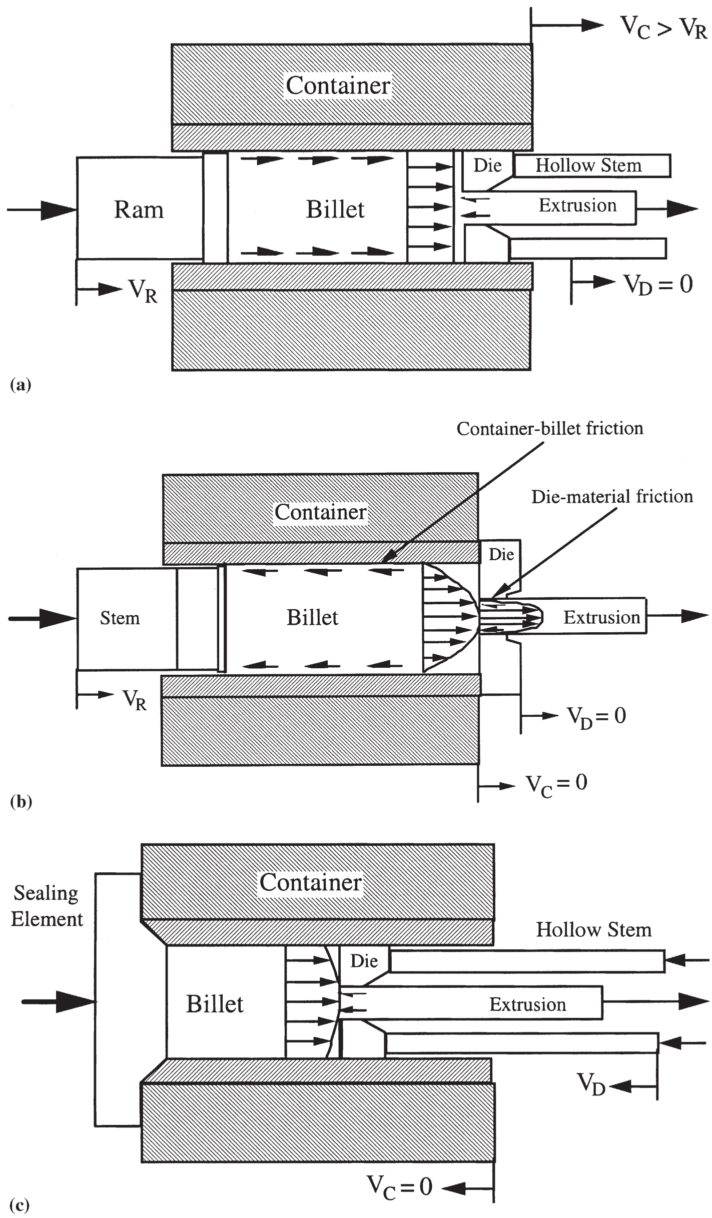


Fig. 8 Variation of friction components and longitudinal speed components of metal flow in the reduction zone across the billet cross section in the case of (a) EwAFF, (b) direct, and (c) indirect extrusion processes. (V_D, V_C, and V_R are speed of die, container, and ram, respectively.)

extrusion allows a twofold increase in billet weight and extrusion speed along with a 30 to 45% decrease in extrusion force, because there is no friction between the billet and container.

For the same die cross section, the longitudinal velocity field as shown in Fig. 8(b) is expected to have a greater distribution than that for the indirect extrusion process due to the influence of container friction.

Press Selection and Specification

The unit pressure required for extrusion is the principal consideration in the selection of an extrusion press. For a press with a given force capacity in tons (MN), a higher unit pressure can be obtained if the container bore is smaller in diameter. As the container bore increases, the specific pressure inside the container decreases, and as a result, extrusion capability decreases. The typical unit pressure, or the specific pressure, is listed in Table 1 for different press capacities and container

Table 1 Standard press capacity and specific pressure chart

Press capacity, tons (MN)	Maximum billet length (average)(a), in. (mm)	Container diameter(b), in. (mm)	Specific pressure, P_c, psi (N/mm^2 or MPa)
500 (5.0)	14 (355.6)	3 (76.2)	140,800 (971)
		4 (101.6)	79,400 (547)
		5 (127.0)	51,000 (352)
750 (7.5)	16 (406.4)	3.5 (88.9)	155,900 (1075)
		4 (101.6)	119,000 (821)
		5 (127.0)	76,500 (527)
1000 (10.0)	20 (508.0)	4 (101.6)	158,000 (1089)
		5 (127.0)	102,000 (703)
		6 (152.4)	70,700 (487)
1250 (12.5)	23 (584.2)	5 (127.0)	127,600 (880)
		6 (152.4)	88,300 (609)
		7 (177.8)	64,900 (447)
1500 (15.0)	24 (609.6)	6 (152.4)	106,000 (731)
		7 (177.8)	77,900 (537)
		8 (203.2)	59,000 (407)
1750 (17.5)	26 (660.4)	6 (152.4)	123,000 (848)
		7 (177.8)	90,900 (627)
		8 (203.2)	69,600 (480)
2000 (20.0)	27 (685.8)	7 (177.8)	103,900 (716)
		8 (203.2)	79,500 (548)
		9 (228.6)	62,900 (434)
2250 (22.5)	28 (711.20)	7 (177.8)	116,900 (806)
		8 (203.2)	89,500 (617)
		9 (228.6)	70,800 (488)
2500 (25.0)	30 (762.0)	8 (203.2)	99,400 (685)
		9 (228.6)	78,600 (542)
		10 (254.0)	63,700 (439)
2750 (27.5)	30 (762.0)	8 (203.2)	109,300 (754)
		9 (228.6)	86,500 (596)
		10 (254.0)	70,100 (483)
3000 (30.0)	32 (812.80)	9 (228.6)	94,300 (650)
		10 (254.0)	76,400 (527)
		11 (279.4)	63,200 (436)
3500 (35.0)	36 (914.40)	9 (228.6)	110,100 (759)
		10 (254.0)	89,200 (615)
		11 (279.4)	73,700 (508)
4000 (40.0)	38 (965.2)	10 (254.0)	101,900 (703)
		11 (279.4)	84,200 (581)
		12 (304.8)	70,700 (487)

(a) Maximum billet length ≅ 4× billet diameter. (b) Container diameter is generally 0.375 in. (9.53 mm) more than the specified.

sizes. The unit or specific pressure of the press has to be greater than the required pressure for a particular extrusion under certain conditions. The required pressure for extrusion could vary with the alloy and its condition, the extrusion ratio, length and billet temperature, extrusion speed, and circumscribed circle diameter.

It is always recommended to use a press of sufficient capacity when using lower billet temperatures and higher speeds to improve physical and mechanical properties of the extrusion. The press requires a rigid structure with a tie rod and platen to withstand the associated stresses. Modern presses use prestressed tie-rod construction with long die stacks to provide minimum deflection to improve the extrusion tolerance. The press should also have accurate and adjustable alignment, which means the stem, container, and die should lie on the same centerline as shown in Fig. 9.

Some of the important variables considered in direct press specifications are shown in Fig. 9. Some typical parameters of the press specifications are also mentioned in Table 2. In Fig. 9, P_m is the maximum pressure applied on the main ram, and P_c is the specific pressure. V_R is the main ram speed in idle operation. In actual extrusion of a particular

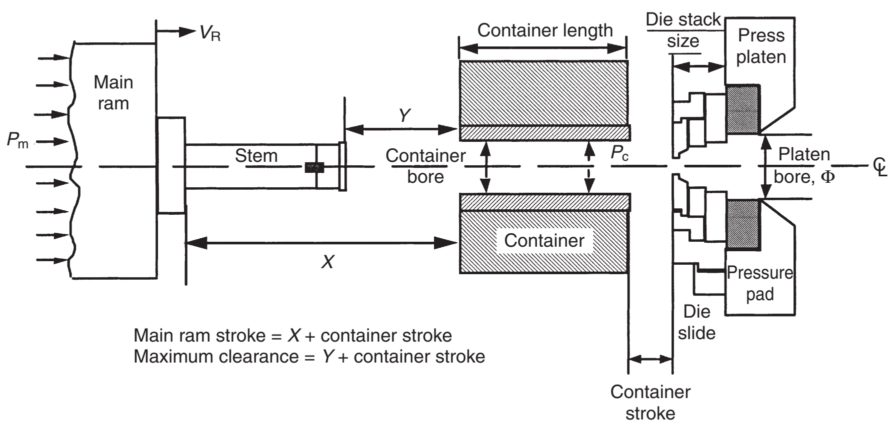


Fig. 9 Specifications of a direct extrusion press

Table 2 Specifications of an extrusion press

Parameter	Unit	Parameter	Unit
Type of press	…	Pull-back capacity	ton (MN)
Make	…	Main ram stroke	in. (mm)
Capacity	ton (MN)	Main ram speed (idle)	ipm (mpm)
Capacity available	ton (MN)	Maximum billet length	in. (mm)
Capacity available at pressure	psi (MPa)	Maximum clearance	in. (mm)
Total ram area	in.^{2} (mm^2)	Container stroke	in. (mm)
Maximum main ram pressure	psi (MPa)	Sealing capacity	ton (MN)
Container size		Sealing pressure	psi (MPa)
Bore	in. (mm)	Shearing capacity	ton (MN)
Length	in. (mm)	Die stack size	
Platen exit bore	in. (mm)	Outside diameter	in. (mm)
Maximum pressure inside the container	psi (MPa)	Width	in. (mm)

shape, the ram speed, V_R, changes with many variables, such as alloy, billet size, billet temperature, extrusion ratio, and type of die.

Extrusion Press Components

The major components of basic types of extrusion presses for making solid sections, bars, strips, rods, tubes, and hollow sections are shown in Fig. 2, 5, and 6. The following three components must be properly aligned, as shown in Fig. 9, to achieve the best performance of the die with respect to metal flow, the life of the die, productivity, and quality of extrusion:

- Container with liner
- Stem with dummy pad
- Die slide with die stack

A sample of a preventive maintenance checklist for these components is shown in Table 3.

Container. The container is an expensive component of the extrusion press. The profitability of the extrusion plant is closely related to the service life of the container and other extrusion tooling. The container needs care to prevent damage due to incorrect handling and premature failure. The container is designed to withstand high stresses at elevated temperatures. However, the container is more highly stressed at the die end where the pressure and temperature are higher and applied over longer times because the billet length decreases as extrusion proceeds. The container is of a two- or three-part design with a shrunk-in liner as

Table 3 Preventive maintenance checklist

Item	Check
Container	Alignment
	Thermocouples and control
	No thermal shocks
	No direct-contact, gas-flame heating
	Hardness
	Position with the holder
Liner	Sealing face
	Hardness
	Cracks
	Not cooling inside the bore
	Cleaning of inside bore with cleaning block
Stem	Alignment with the container
	Stem holder bolts
	Cracks
Dummy pad	Outside diameter compared with the bore diameter of the container liner
	Contact surface areas
	Buildup of excess aluminum
Die slide/die stack	Alignment with the container and stem
	Bolster key slot
	Die clamp
	Aluminum buildup on die face
	Clearance between die face and shear blade

shown in Fig. 10. The complete design of the container and liner was discussed by Laue and Stenger (Ref 3). The decisive criteria for the design of liner-container assemblies are the following:

- The specific pressure (inner pressure in the container liner), P_c is press power in ton/lb (N)/area of liner bore, in.^{2} (mm^2)
- The maximum outside container diameter
- The width to height ratio (rectangular container)

Normally, the round-shaped container liner used for round, solid billets is applied for most of the direct and indirect presses worldwide. Very few presses operate with both round and rectangular containers. Two of the advantages of using a rectangular container (Fig. 11) are to produce wide sections, such as landing mats for aircraft (Fig. 12), and more uniform flow of materials, which subsequently lowers the specific press load.

The container is mounted in such a way that, when subjected to heat, it expands freely on all sides while retaining its position relative to the press centerline. The container can be turned axially to ensure even wear of the liner. The container is locked into the container holder, which can move by hydraulic means along the longitudinal axis of the press. The container is heated to a temperature of about 800 °F (427 °C) by a resistance heating unit installed in the container itself or in its holder. Due to the mass and length of the huge container of large capacity presses, the inside temperature of the liner is difficult to maintain with conventional wraparound container heating elements. For better control of extrusion temperature, especially in aerospace extrusions,

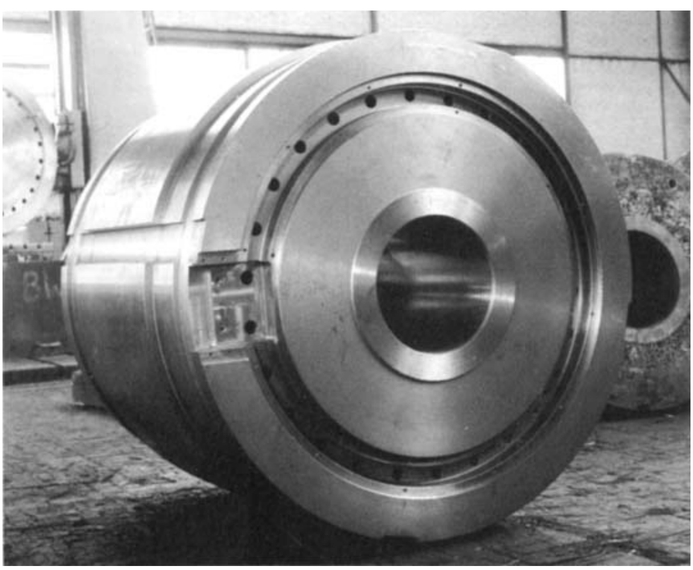


Fig. 10 Round container with liner. Source: Edelstahlwerke Buderus AG

multizone temperature control for proper heating of the container was developed (Ref 7). Heaters are independently controlled in six zones in (Fig. 13). The induction heater, installed in the container, could heat up to about 932 °F (500 °C). If the container liner is made of a suitable

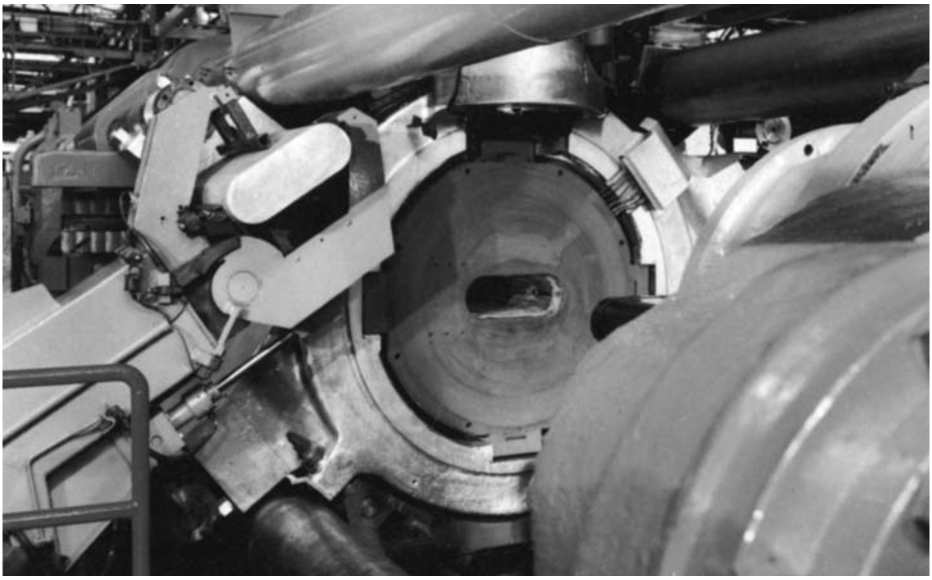


Fig. 11 Rectangular container with stem and billet loader. Source: Edelstahlwerke Buderus AG

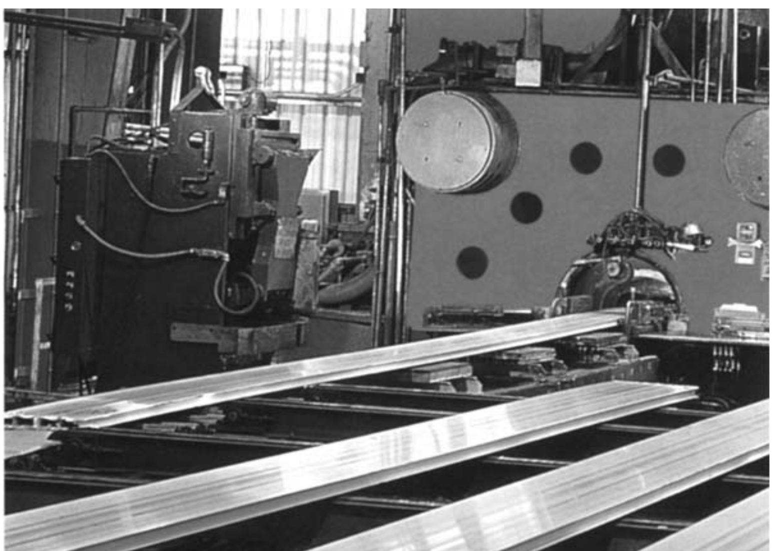


Fig. 12 Direct press extrudes aluminum landing mats for aircraft from rectangular container. Source: Taber Metals L.P.

steel, with associated high resistance to softening, and fitted in a correctly designed container, it can withstand 30,000 to 40,000 cycles.

Stem. A stem with a fixed dummy block has become a standard technique in the extrusion industry, especially with softer alloys such as 6063, using puller systems. Most of the extrusion presses have been converted to fixed dummy blocks, with many factors taken into consideration, including the alignment of the dummy block with the container bore and the design of the dummy block. Castle (Ref 8) gave an overview of using a fixed dummy block. Clecim (Ref 9) presented one design showing two or three parts to achieve complete sealing at all extrusion pressures. He also analyzed design parameters. There are a few designs of the fixed dummy block supplied by specialized manufacturers. One of the typical designs of a dummy block is shown in Fig. 14(a). Figure 14(b) shows the stem with a fixed dummy block. The successful fixed dummy block operation depends as much on working practices as on design. Castle (Ref 10) pointed out that performance depends on many factors. The factors that determine fixed dummy block performance, apart from the design, include the following:

- Lubrication
- Alignment
- Preheating
- Clearance between the dummy block and container

As mentioned before, quick stem release is one of the main features of the modern extrusion press. One design in which the stem is removed

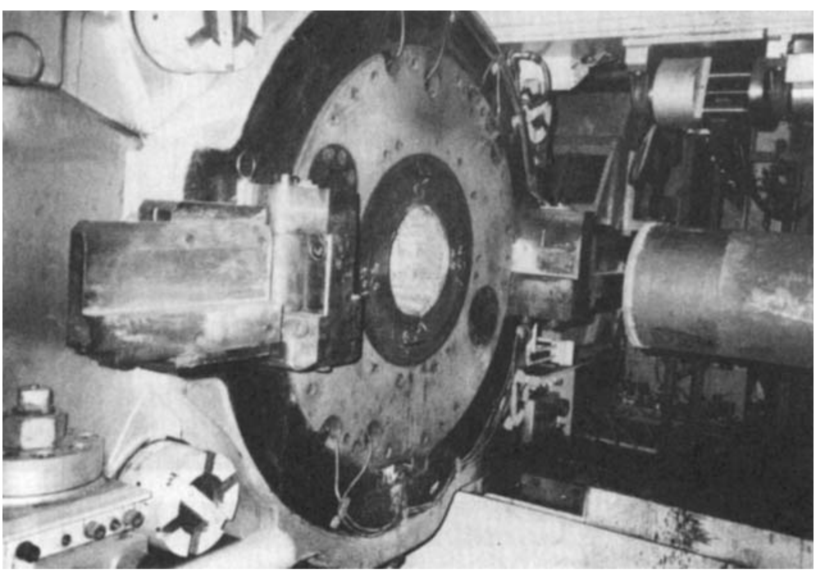


Fig. 13 Multizone control of the container heat. Source: Ref 7

from the stem-holding ring easily and quickly without removing or loosening the fixing bolts is shown in Fig. 15.

Die Slide or Rotary Die Head. A die slide or rotary die head is a major component of presses in which the dies and support tooling are mounted. Die slides move at right angles to the press centerline as shown in Fig. 16(a). Both the die slide and the rotary die head are located on the counter platen of the press. The die slide with additional

(a)

(b)

Fig. 14 Typical design of a dummy block. (a) Dummy block and coupling. (b) Stem with fixed dummy pad. Source: Castool

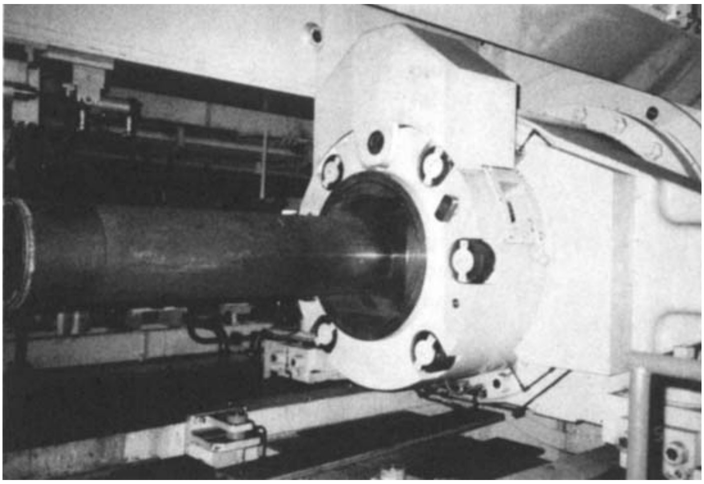
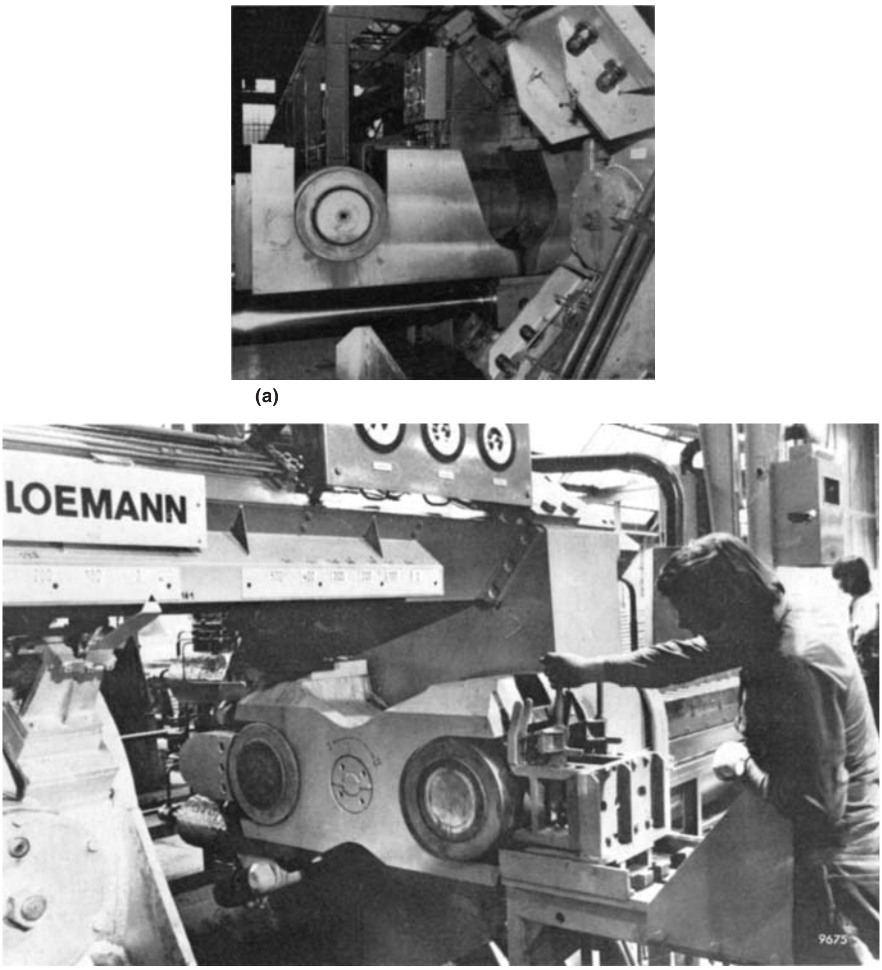


Fig. 15 Stem quick-changing device. Source: Ref 7



(a)

(b)

Fig. 16 Die carrier. (a) Die slide. (b) Rotary die head. Source: Schloemann-Siemag central ejection opening is generally designed to accommodate one or two dies, whereas the rotary die head can handle two dies as shown in Fig. 16(b). In the case of the rotary head, replacement, correction, and cooling of the dies can always be carried out on the same side of the press. Dies and die holders and backups are mounted on the slide or rotary head in U-shaped openings in such a way that they can be changed easily and rapidly.

Recent developments (Ref 7) have occurred in several features of the die carriers of large-capacity extrusion presses, including a die-positioning device (Fig. 17) for accurate shearing and a cassette-type die heater. Because the die stack length is long compared with the

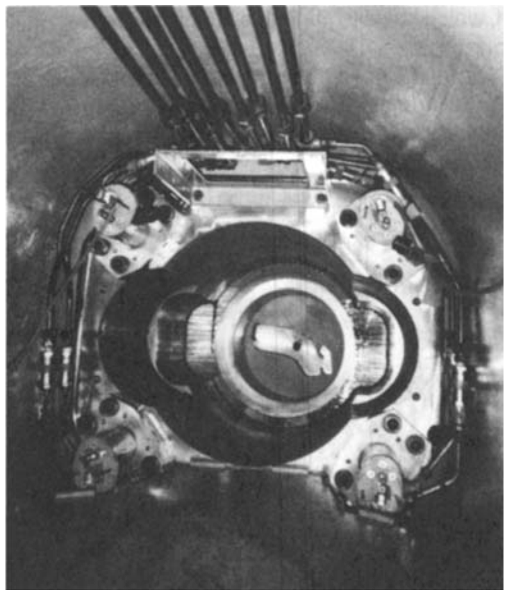


Fig. 17 Die-positioning device for accurate shearing. Source: Ref 7

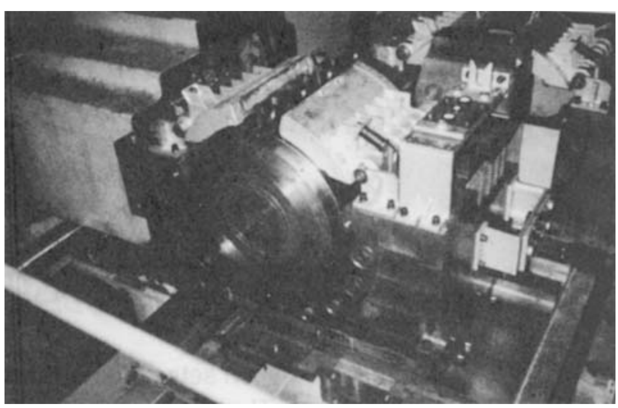


Fig. 18 Die cassette heater. Source: Ref 7

midsized presses, the shearing face of the die varies quite a bit in position due to thermal expansion and contraction. When the shearing face is not positioned properly, smeared aluminum appears on the die face, causing flares and/or blisters in subsequent billets. A cartridge heater is embedded in the die cassette (Fig. 18) to keep the die temperature stable and to detect and monitor die temperature at the die-change position.

Auxiliary Equipment

In addition to the press, aluminum extrusion requires some equipment to be connected to the press line as shown in Fig. 19. For many installations, induction type (Fig. 20) or gas-fired log heaters (Fig. 21) equipped with hot log shears (Fig. 22) have replaced gas-fired and induction billet heaters. Logs are sheared to the optimum billet length for the particular die being used and for the desired extrusion length. Hot log shear is also very useful, especially for hollow extrusions, starting with a small-sized billet to reduce the breakthrough pressure on the initial billet when the die is not properly heat balanced to avoid any undesirable crack that develops in the die bridges. An induction shock heater or a taper water quench (Fig. 23) are also installed after log shear to run isothermal extrusion. A hot-billet scalper (Fig. 24) has also been developed for indirect extrusion of aircraft alloys.

In order to run an extrusion die properly and not to waste valuable press time, a proper die-heating system is essential to the modern extrusion system. Fielding and Macey (Ref 13) reviewed systems for heating extrusion dies. Multichamber die ovens with multiple drawers (Fig. 25)

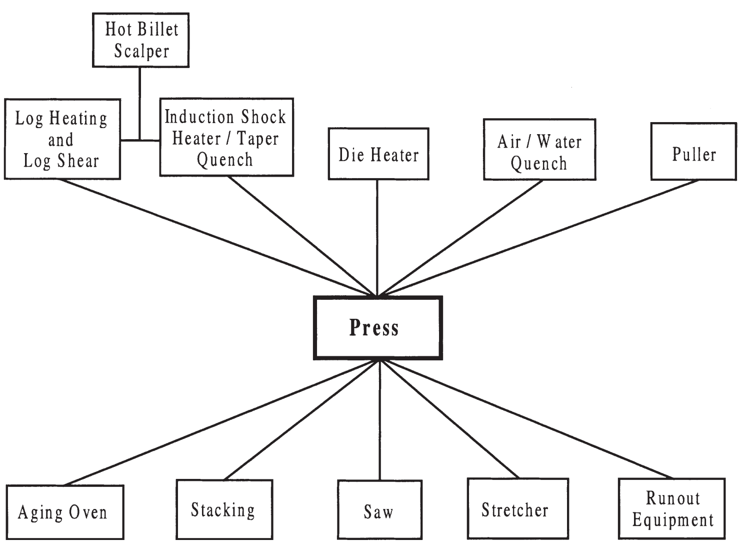


Fig. 19 Auxiliary equipment connected to press

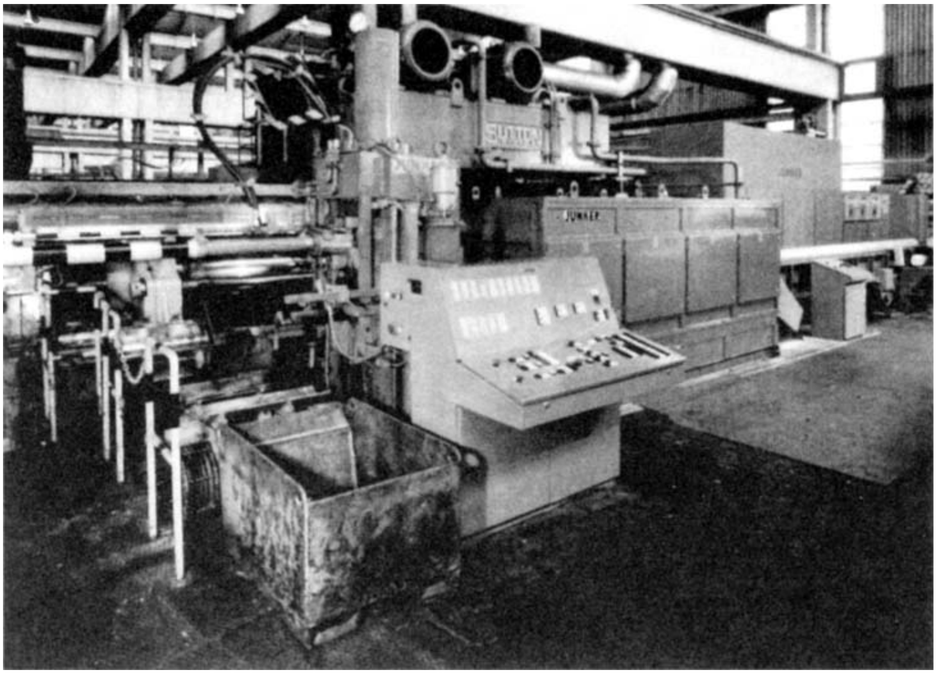


Fig. 20 Induction heater with hot log shear. Source: Ref 11

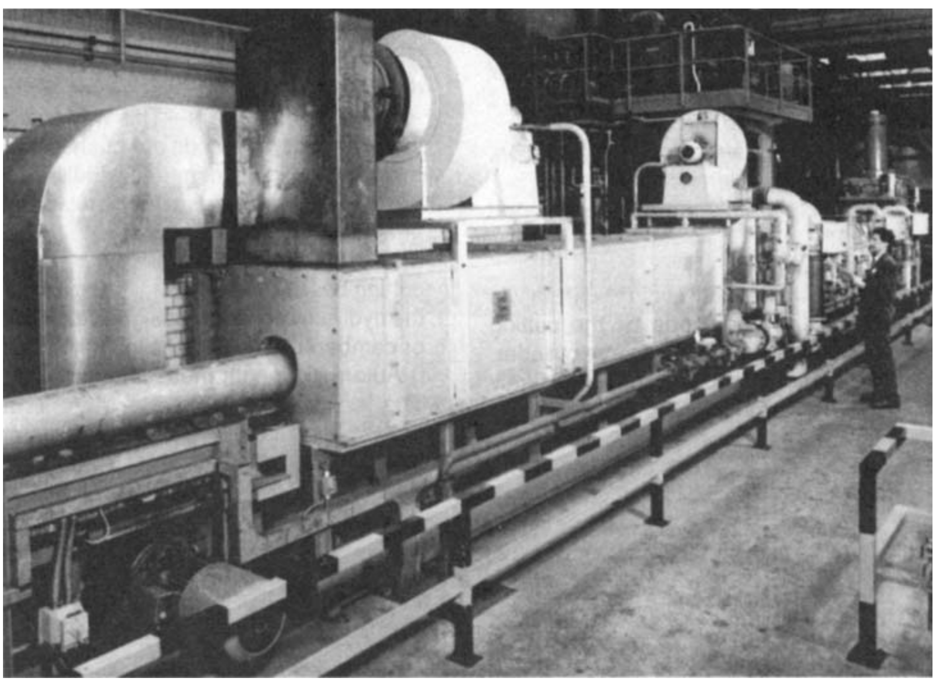


Fig. 21 Log-heating, gas-fired furnace. Source: Ref 11

have replaced traditional top-loading, chest-type die ovens. Each drawer has a separate heating and temperature control system to control specific die or tooling temperatures. Another multichamber die oven

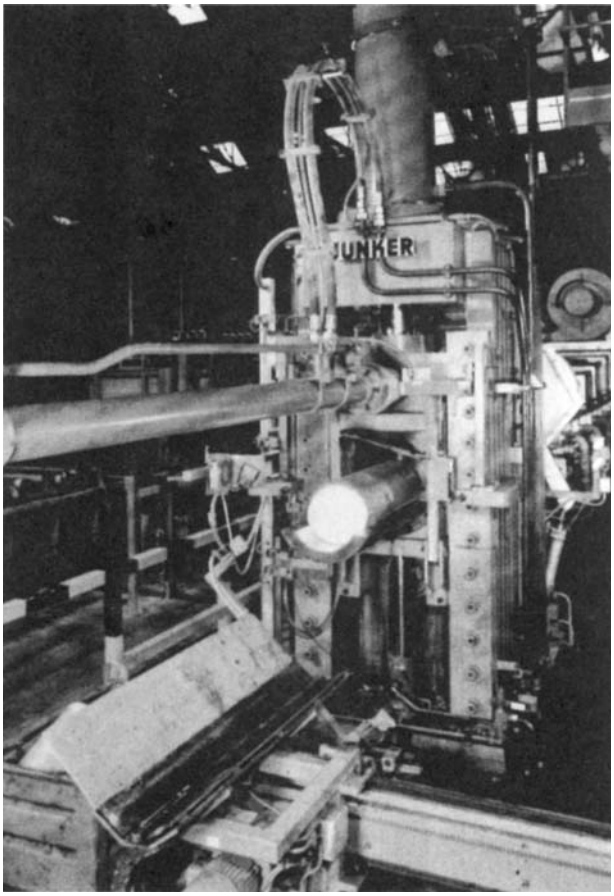


Fig. 22 Hot log shears. Source: Ref 11

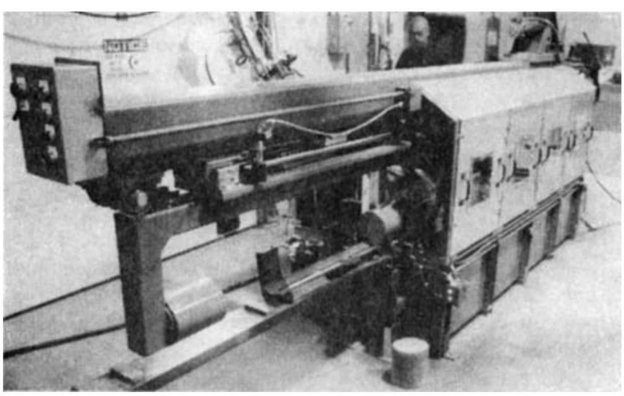


Fig. 23 Taper quench after hot log shear. Source: Ref 12

was developed to maintain each die at a precise temperature in a controlled nitrogen atmosphere as shown in Fig. 26. This design greatly improves die life while providing protection from high-temperature oxidation, resulting in better profile finish quality. Die temperature is precise, unaffected by the thermal shocks that occur in a conventional chest-type oven when other dies are put in or taken out.

Quenching of extrusion on the runout table is an important concern throughout the aluminum extrusion industry. Water-spray systems are gradually replacing tank-type water quench and over-table and under-table cooling fans. High-pressure, high-velocity sprays, with or without air-assisted atomization systems (Fig. 27), have been developed to quickly cool difficult shapes well below critical temperatures to attain higher mechanical properties and desired finish.

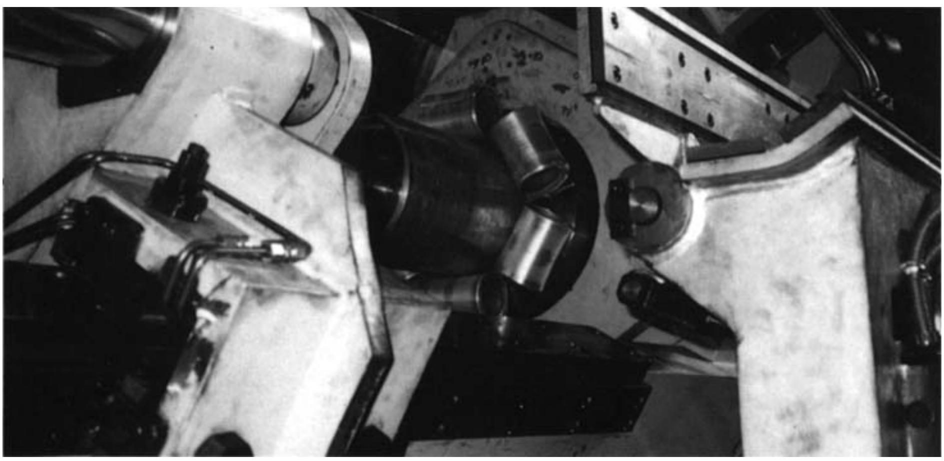


Fig. 24 150 ton hot-billet scalper. Source: UBE Industries, Ltd.

Fig. 25 Multicompartment die oven. Source: Granco Clark

A puller with an adjustable hot saw system as shown in Fig. 28 (inset photos 1 to 3) is normally used to run extrusion using a feeder plate, cavity, and hollow porthole dies. Double-puller systems with more advantages (Ref 15) than conventional single pullers with adjustable hot saw systems have been developed. One of the present systems is shown in Fig. 29.

A runout system of 4400 ton (44 MN) extrusion press line is shown in Fig. 28. It includes rollers that are gentle on sections, minimum use of

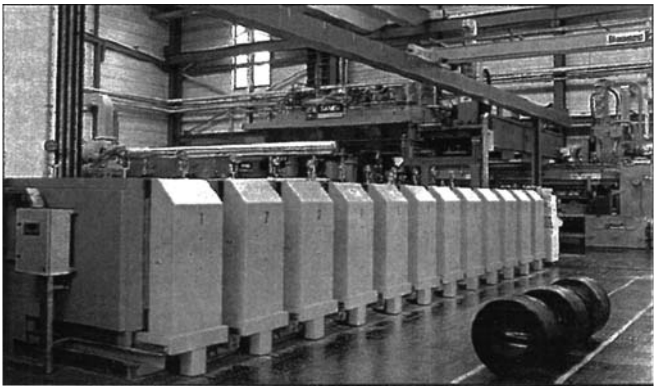


Fig. 26 Multichamber, single-cell drawer oven. Source: Ref 13

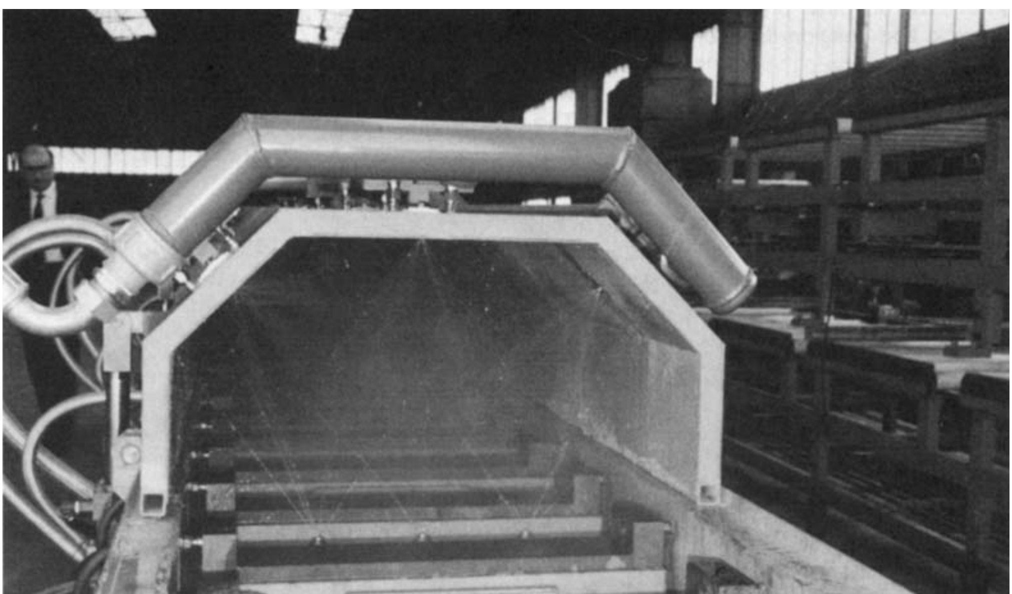


Fig. 27 Special water-spray quench system for profiles. Source: Ref 14

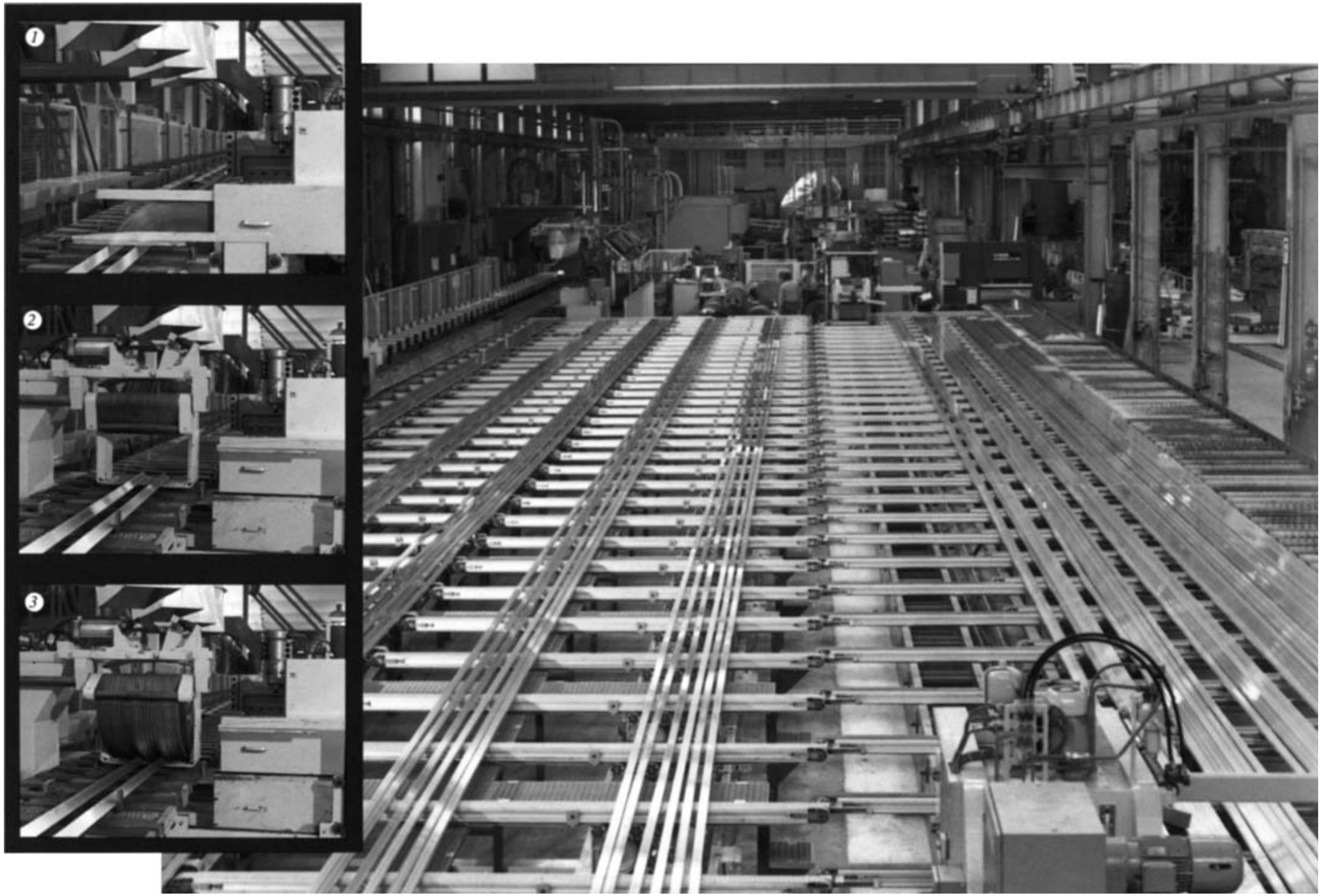


Fig. 28 Runout equipment showing hot saw and puller clamp. (1) Hot-shaping saw. (2) Puller with clamping blades opened. (3) Puller with sections gripped. Source: SMS Engineering Inc.

Fig. 29 Double-puller system and flying hot saw. (1) Double-puller system. Source: SMS Engineering Inc.

Fig. 30 Stretcher tailstock. (1) Stretcher headstock. Source: SMS Engineering Inc.

Fig. 31 Saw with hold-down device and discharging belts. (1) Saw, table with driven rollers, and transport for section ends. (2) Adjustable saw contact for exact positioning of the bundled sections. (3) Saw with section contact and discharging belts. Source: SMS Engineering Inc.

Fig. 32 Automatic section stacker. (1) Section stacker depositing in section basket. Source: SMS Engineering Inc.

graphite (no soiling), and vertical positioning of the sections on the first crossbelt by lowering the whole runout track. A finely tuned conveying system ensures both fully automatic operation and careful transport of sensitive sections.

Figure 28 also shows how the sections are transported from the runout table to the automatic stretcher line. Figure 30 shows the stretcher headstock and tailstock designed for gentle handling of the sections. Television cameras monitor the functioning of the stretcher; self-adjustment to the required section length allows fully automatic operation, and laminated clamping heads reduce deformation of the profile ends. A collecting table for sections in the form of a stationary cross-belt conveyer ensures proper bundling of the sections. Finally, the bundles of sections are gently passed on to an elevating-saw roller table and transferred further on rollers as shown in Fig. 31.

Due to constant demand for rising productivity and cost effectiveness for the future, greater automation continues to grow in the extrusion industry. Demands for cutting and stacking sections have been satisfied. One of the most modern saw systems, which includes a mainly undertable finish saw, a work table for cutting to length, conveyance of the sawn section to the stacker, and many additional features, is shown in the inset photos to Fig. 31.

In connection with the saw system, the section stacker is designed to stack sections based on the "first in-first out" principle, as shown in Fig. 32. This system is also equipped with a conveyer to transport the baskets filled with sections from the stacking area to the aging furnace, a conveyer for the return transport of emptied baskets to the stacker and to arrange stack unloading, and return conveying of the spacers downstream of the aging furnace.

Integrated System

The performance of an aluminum extrusion plant depends largely on its auxiliary equipment. With the advances in press control, significant improvements have been made in auxiliary operations as discussed in the previous section. The productivity of an extrusion plant, as shown in Fig. 33, is dependent on three major systems, billet heating and length control, extrusion press, and handling system, which control both downtime and scrap. Press performance is also dependent on proper die and tooling heating system. In addition to properly designed die and tooling, fast and efficient heating is a critical consideration in the life of the die, press performance, and finally, productivity. Productivity control includes the following:

- Use of the correct size of billet with optimum billet temperature using log heating and hot log shear with taper quench
- Use of the correct die and tooling temperature to reduce avoidable downtime
- Control of the exit speed and temperature with automatic double puller systems
- Reduced handling damage and labor cost by providing an automatic handling system from runout to the stacking, followed by aging

Press manufacturers not only install the press now but also provide complete installations for everything from heating of billets to cutting the cooled, stretched product. This development has been particularly successful in aluminum extrusion plants. Omav S.p.A. (Ref 16) installed in 1993 in Germany a "no-man" handling system. The handling system is automatically set, according to the setting data coming from the press PC. Starting from this point, the PLC automatically runs each extrusion on the cooling table.

The duration of the working cycle can be optimized by the press manufacturer who provides all the auxiliary equipment because the efficiency of a plant depends heavily on the operation of the auxiliary gear. The economics of the process are of primary importance, and the automatic operation of the complete working cycle for different press programs includes the operation of both the press and the auxiliary equipment in order to minimize the dead-cycle time in an extrusion cycle.

The operations carried out on the exit side of the press in aluminum extrusion have been studied in great detail because of the enormous increase in the production of sections. An important point in the design of an extrusion plant is the transport of the delicate sections without damage.

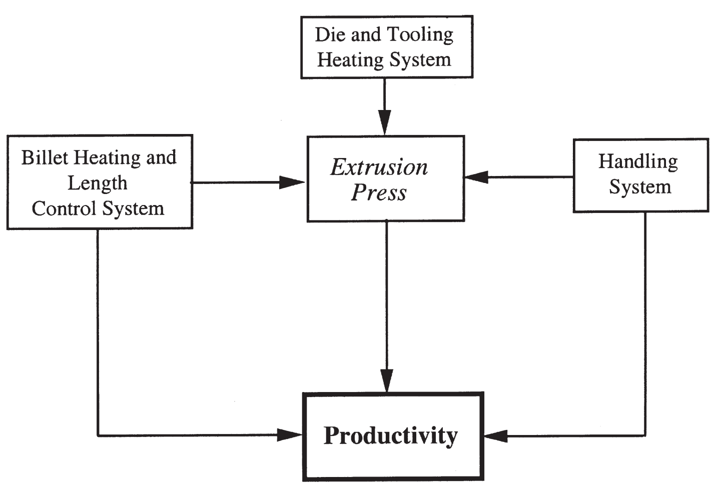


Fig. 33 Functional block diagram of productivity control system

The equipment used in an integrated aluminum extrusion system from log heating to age ovens includes the following:

- Log heating systems (induction or gas fired) with integrated log shear
- Induction shock heater/taper water quench
- Hot billet scalper for indirect extrusion of aircraft alloys
- Multicompartment/multichamber, single-cell die ovens
- Air and water, separate or combined, quenching systems
- Single- or double-puller based on customer requirement
- Stretchers with automatic handling system
- Profile saws and gaging systems
- Stacking systems
- Aging ovens

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CHAPTER **4**

Extrusion Die and Tooling

Extrusion delivery, cost, and quality are three important factors in a competitive market. To meet quality requirements, the performance of the extrusion die is critical. Die performance impacts product quality, productivity, recovery, and product design. The demands made on profiles for tolerances and on dies for die life and trial runs are becoming greater and greater. The application of extruded profiles in the world is changing every year. The uses of extruded aluminum profiles in the architectural, automotive, and high technology industries are increasing. Tolerance and finish quality therefore, must be maintained. This is why the aluminum extrusion industry has made huge demands on extrusion die technology to make integrated shapes with critical tolerances. The extrusion performance is the one thing that counts for a die. Effective use of die technology enhances the ability of an extruder to meet customer needs.

Extrusion performance can be affected by three major factors, mainly, the number of billets used scrap, the die life, and the extrusion speed. The objective of die manufacturers is to optimize these factors. This is possible using modern high technology equipment, high quality die steel, and advanced heat treatment processes to produce dies with high tolerances. Die makers must concentrate on quality, flexibility, and reliability in order to best ensure customer satisfaction, the ultimate goal of the die manufacturer. It is also important to remember that the use of the latest manufacturing technologies is necessary in order to be able to produce a die at a faster rate with a competitive price.

Aluminum extrusion die production involves a complex mixture of design (using computer aided design, CAD, systems) and machining (using computer numerical controlled, CNC, and electrical discharge machining, EDM processes. Now the market is moving toward computer aided industrial design (CAID) and computer aided industrial machining (CAIM) to produce reproducible dies. With the use of CAD to CAM and CAIM, many extrusion die manufacturers in North America and Europe are handling dies and tooling needed for both micropresses and larger presses. Extrusion die design and manufacturing is unique for each individual die manufacturer. In addition to die design and manufacturing, die correction is a very important aspect of extrusion, including modifying the dies and communicating with the die makers.

Advances in die design and technology in the aluminum extrusion plant can be followed through the successive proceedings of the Aluminum Association and the Aluminum Extruders Council's International Extrusion Technology Seminars. Nagpal (Ref 1) listed the benefits of CAD of extrusion dies, which reduces the skills required for design and manufacture, reduces the number of die corrections, improves die life, and yields higher productivity. Capturing the design principles and rules of thumb by using a computer can improve the efficiency of die design. Programs for CAD/CAM equipment can design with consideration for shrinkage, critical tongue, deflection, bearings, and layout. The systems can integrate the design and manufacturing of the dies. A great amount of research has been done on the use of computers in design and manufacture of extrusion dies and tooling. Some of the information, including formulas to calculate pressure applied to various types of flow and bearing length, is available in Ref 1-11.

Die design practices have changed to take into account the evolving concepts of flow control such as the single bearing die (Ref 12). Machado (Ref 13) developed the zero bearing, that is the minimum possible bearing length technology to increase the production speed and minimize die repair. The use of the piastrina (literally, "pocket around the shape") in the cap of a hollow die has been developed (Ref 14). In the last few years, a large number of research and technical papers have been presented and published on die design and technology (Ref 15). In conference proceedings (Ref 15), many subjects concern aluminum extrusion dies, including die technology, computer design, finite element analysis (FEA), die bearings and metal flow, die bearing surfaces, design systems, and treatments, hollow dies and special die designs. Hard coatings for the die bearings have been presented.

For the beginners in aluminum extrusion technology, it is very important to understand the fundamentals of extrusion die technology. The fundamentals will never change. Once the fundamentals are understood, it is easy to go further and further in the technology development.

This chapter discusses the terminology and function of extrusion dies and tooling, the types of dies, the fundamentals of die design, manufacturing, rectification, and material, and the surface treatments of die bearings and tribology in extrusion dies.

Terminology and Functions of Extrusion Dies and Tooling

Direct Extrusion

Soft and Medium Grade Alloy Extrusion. In hot extrusion of aluminum alloys, flat-face dies are generally used. The definition of a flat-face die is explained in the section "Bearing Length" in this article. Extrusion dies and tooling determine the performance and economics of the aluminum extrusion processes. There are fundamental differences between the configurations of dies and tooling used for softer alloy extrusions. Figure 1 shows the die and tooling configurations for soft and medium grade alloys (the 1100 series, 3000 series and 6000 series) and their extrusion with conventional direct extrusion processes. The functions of the individual tools are shown in Table 1. The following types of solid-shaped and hollow-shaped dies and tooling are normally used for softer alloy extrusion:

Solid-shaped dies and tooling

- Feeder plate with diverging cavity in front of the flat-face die for solid-shaped extrusion
- Straight cavity (welding pocket) in front of the die opening

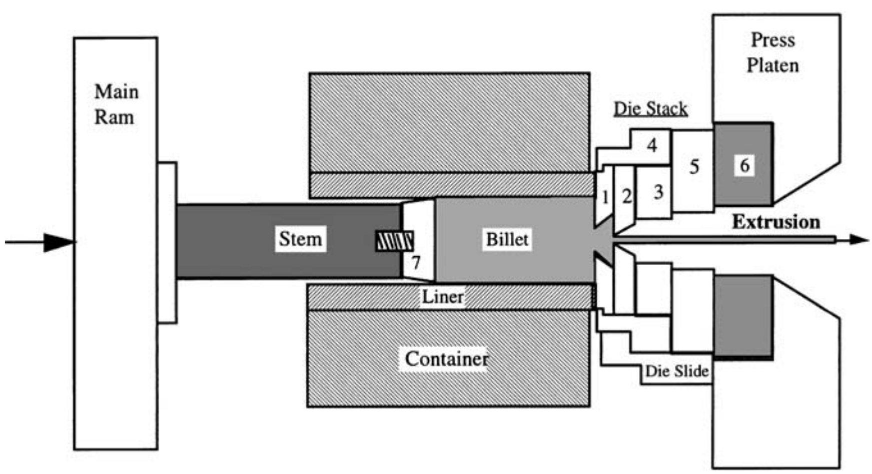


Fig. 1 Tooling configuration in direct extrusion process with feeder plate die for softer alloy. 1, feeder plate; 2, die; 3, backer; 4, die ring; 5, bolster; 6, pressure pad; and 7, fixed dummy

- Stepped cavity in front of the die opening (equal bearing die)
- Housing-type die (die and die ring together)
- Fixed expandable-type dummy pad

Hollow-shaped dies and tooling

- Porthole
- Bridge
- Spider

Hard Alloy Extrusion. The direct process is commonly used for the extrusion of soft, medium, and hard aluminum alloys. Figure 2 shows

Table 1 Functions of the individual tools used for extrusion of soft and medium grade alloys with conventional direct processes

Tool	Function
Die	Makes the shape of extrusion
Die holder/ring	Holds the die with feeder plate and backer
Die backer	Supports the die to prevent collapse or fracture
Bolster	Transmits the extrusion load from die to the pressure ring
Pressure ring	Transmits the extrusion load from bolster to press platen and also prevents bolster deflection
Die carrier/slide	Holds the complete die set (die ring and bolster) in the press
Bridge/spider/porthole die	Special die to make a hollow shape with welding joint along the length of the shape
Feeder plate	Sits in front of die to balance the metal flow and also to make a continuous extrusion
Liner	Protects the life of an expensive and huge container from thermal and mechanical stresses
Stem	Fitted with the main ram to push the billet through the container/liner
Dummy pad	Protects the life of the expensive stem that is fitted or floating in front of the stem

Source: Ref 16

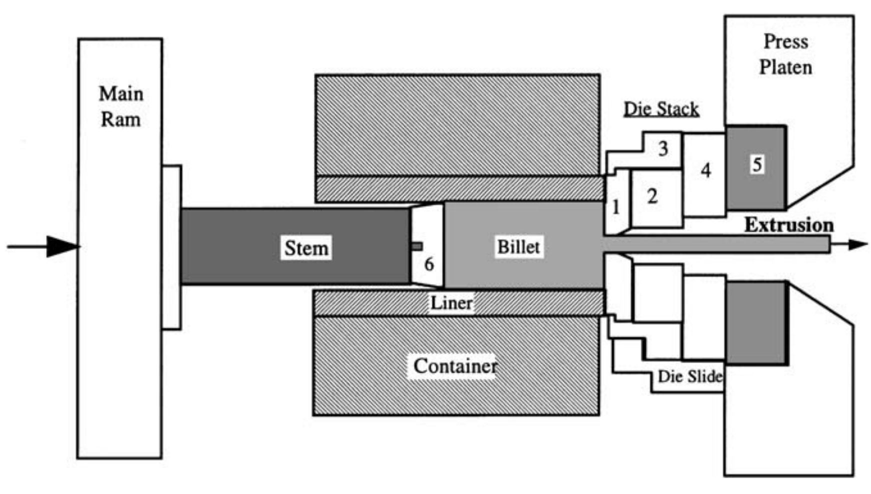


Fig. 2 Tooling configuration in direct extrusion processing with a solid die for harder alloy. 1, solid die; 2, backer; 3, die ring; 4, bolster; 5, pressure pad; and 6, floating dummy

the die and tooling configuration for extrusion of the hard alloys (the 2000-series, 7000-series, and some 5000-series alloys), using a solid die without feeder plate and loose dummy and making each extrusion separate. The dies and tooling used for harder alloy extrusion are as follows:

Solid-shaped dies and tooling

- Solid flat-face die with higher thickness and larger die bearing (small choke in front of the bearing)
- Pocket die (under trial and implementation)
- Loose solid dummy

Hollow-shaped (seamless type) dies and tooling

- Solid die to give the outer hollow shape
- Piercing or fixed mandrel through a hollow stem to produce the inside shape of extrusion
- Loose hollow dummy

Indirect Extrusion

The indirect process is normally used for extrusions of the harder alloys when shape is critical. The tooling configuration is different in the indirect process from the configuration in the direct process. The schematic of the die and the tooling configuration is shown in Fig. 3.

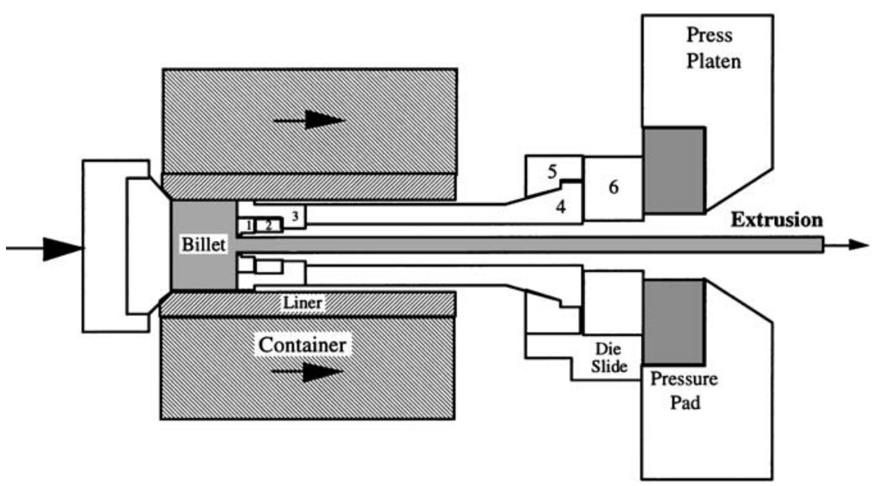


Fig. 3 Tooling configuration in indirect extrusion processing for extrusion of the harder alloys. 1, die; 2, backer; 3; die holder; 4, die stem; 5, stem holder; and 6, bolster

Die Design

Die design and die making are the most important and demanding aspects of the entire extrusion process. Die design is influenced by many factors including press procedure and maintenance, understanding of the section or profile and its tolerances, and alloy characteristics. The skill and resourcefulness of the individual die designer and maker are vital to the production of efficient extrusion dies. Many years of experience lie behind the design and manufacture of aluminum extrusion dies with increasing complexity of shape, thickness of section, and quality of surface. Some of this experience is captured in empirical design rules, but extrusion die design is still dependent on personal judgment, intuition, and experience. No two dies of the identical design, material, hardness, and surface finish are truly identical. A close working relationship between designer, die maker, press operator, and die corrector is needed to check tolerances and production performance.

Three basic goals apply to all extruding operations. They are providing for relative ease of metal flow, dimensional stability, and desirable surface finish. The principle of extrusion is quite simple, but many process factors, including die design and modification, equipment adjustment, alloy selection, temperature, and lubricant and extrusion ratios, are major determinants for successful runs of specific shapes. Deformation of the die under pressure and its expansion under high temperatures also must be considered in the die design. The basic considerations of die design are to determine the following factors:

- The number of die openings based on the shape and size of the profile, and the nature of the existing tooling
- Location of die opening with respect to the billet axis
- Orientation of the openings around their centroids to match the handling system
- Determination of the final die openings based on thermal shrinkage, stretching allowance, and die deflection (both die and deep tongues)
- Optimization of bearing lengths to increase productivity

To start with the design of a die, the designer needs fundamental information regarding the geometry of the shape, alloy to be extruded, size of the press, billet size, runout required by the customer, support tooling like backer or bolster to be used, the weight of extrusion per unit length, and so on.

After looking through the customer profile drawing, the die designer decides the type of die needed, that is, solid, hollow, or semihollow. If it is hollow, the designer can select the best port, bridge, and welding chamber configuration to get high productivity. Examples of hollow dies are shown in Fig. 15–20. If the needed die is a solid, the designer can choose from flat-face, feeder plate, recess, and single-bearing type dies (Fig. 9–13). For a single-opening die, design seems simple compared to that for a multihole die. The next step is to determine the layout of each hole and number of holes.

Die Layout

The geometric layout of the openings within the die face is determined by a number of factors, such as the following:

- Proper clearance, C, between the die opening and the container wall, and also proper distance, D, between the openings (Fig. 5)
- Balanced metal flow to avoid any distortion of the shape
- Ease in die design and manufacture
- To avoid overlapping and scratching a particular part of the extrusion on the runout table

A minimum clearance between the die opening and the container wall is required to avoid the flow of the oxide skin of the billet surface into the extrusion, in the case of the direct extrusion. At the same time, the minimum distance between two openings of a multihole die must be adequate to provide proper strength to withstand the pressure applied by the billet. Sufficient strength in the die may avoid cracking and deflection in the die.

Basically, there are two major methods of layout for multihole dies; these are radial and flat layouts. In radial layout, the major axis of each shape lies along a radius, as shown in Fig. 4, giving each portion of

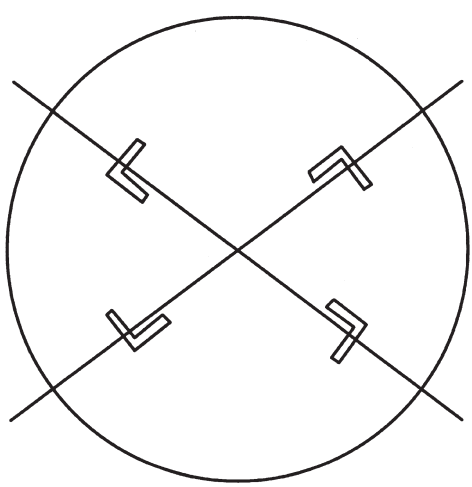


Fig. 4 Radial layout of a multihole die

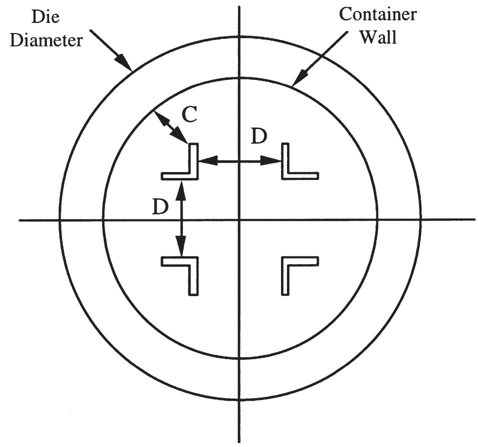


Fig. 5 Flat layout of a multihole die

bearing surface the same relationship to the center of the die. The advantages of radial layout include uniform layout, bearings, metal flow, and easy die correction. The disadvantages include difficulty in controlling twisting and handling on a runout table. Due to the handling difficulty, radial layout is not in use in the aluminum extrusion industry.

In flat layout, the major axis of each shape is at right angles, or parallel, to a radius (Fig. 5). The main advantage of flat layout is the ease of handling on a runout table for higher productivity. The disadvantages include difficulties in die correction, due to nonuniform die bearing, and in controlling uniform extrusion lengths on the runout. With advanced die design technology, die correction is less difficult these days. Milling machines are used to modify the die bearing in order to quantify the correction for the proper feedback to the die vendor.

The metal flow through a multihole die is very complicated. The flow is dependent on many variables such as shape, number and layout of die openings, extrusion temperature, and section thickness. Some fundamental rules are applied by the die designers to get more even flow through the die. For a single hole die, the center of gravity (CG) of the die opening should be close to the die or billet center. For a multihole die, the CG of the shape should more or less coincide with the CG of the segment of the billet that feeds that particular hole. The orientation of the opening with respect to the CG is dependent on the designer's knowledge and experience. Figure 6 is an example of a better orientation of an angle profile than the orientation shown in Fig. 5. Figure 6 also shows a flat type layout.

Number of holes in the die is determined by many factors, and some of them are existing tooling to fit the number of holes, handling ease and facilities on the runout, length, profile dimensions, and metal flow.

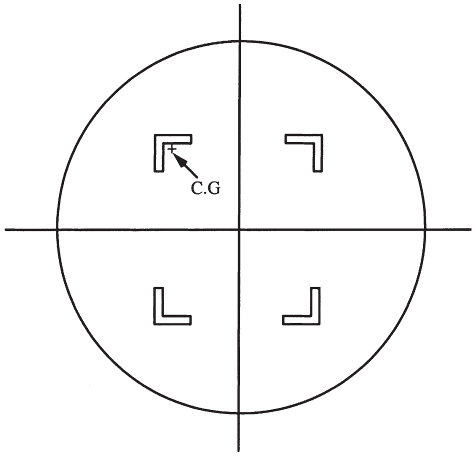


Fig. 6 Orientation of a shape around its center of gravity (CG)

Bearing Length

The schematic of a solid flat-face die configuration is shown in Fig. 7. The bearings of a die are of utmost importance. The function of the bearing is to control size, shape, finish, and speed of extrusion. The bearing also determines the life of the die. Friction at the die land is the controlling factor for retarding the metal flow. The length of bearing at any location of the die opening depends upon the extent to which the metal flow must be retarded at that point. Basically, three parameters determine the dimensions of the die bearing to control the metal flow:

- The distance of the opening from the center of the billet
- The section thickness at that location
- The pocket shape and size

In the direct extrusion process, the frictional resistance at the billet-container interface slows down the metal flow near the billet surface. The center of the billet thus moves faster than the periphery of the billet. To balance the flow, bearing length must be inversely proportional to its distance from the center of the billet. The thinner the section, the slower the flow, due to the small die opening. Similarly, to balance the flow in the thinner section, the bearing length needs to be smaller, and vice versa.

Sharp changes in bearing may cause streaks, due to uneven flow of the metal or to inadequate filling of the die opening. Variations in bearing lengths at the junction points must be properly blended to prevent streaking. Three different types of blending processes are shown in Fig. 7.

Sometimes fine adjustment to the die is necessary for correcting or changing the rate of metal flow by controlling the bearing width (b1–b4) and length (l1–l4) (Fig. 7). The treatment of bearing surfaces at the front and back of the die aperture is known as choke or relief, respectively, as shown in Fig. 8. For extrusion of hard (2000-series and 7000-series) alloys, the front of the bearing is generally choked (Fig. 8a) at an angle up to 3°. This slows the metal flow and consequently fills out the die aperture to give better dimensional stability. Increasing the relief angle at the back or exit side of the bearing (Fig. 8b) to as high as 7° increases the speed of metal flow by decreasing the original bearing length. Choke and relief are normally produced using electrical discharge machining (EDM) to quantify.

The single-bearing die is a modified version of the recess die. In a recess die, there is a single-stage cavity, whereas in a single-bearing die, there are multiple stages of cavity in a converging manner. Figure 9 is a schematic of a three-stage single-bearing die. By controlling the area of the cavity, the flow of aluminum is balanced, keeping the same bearing

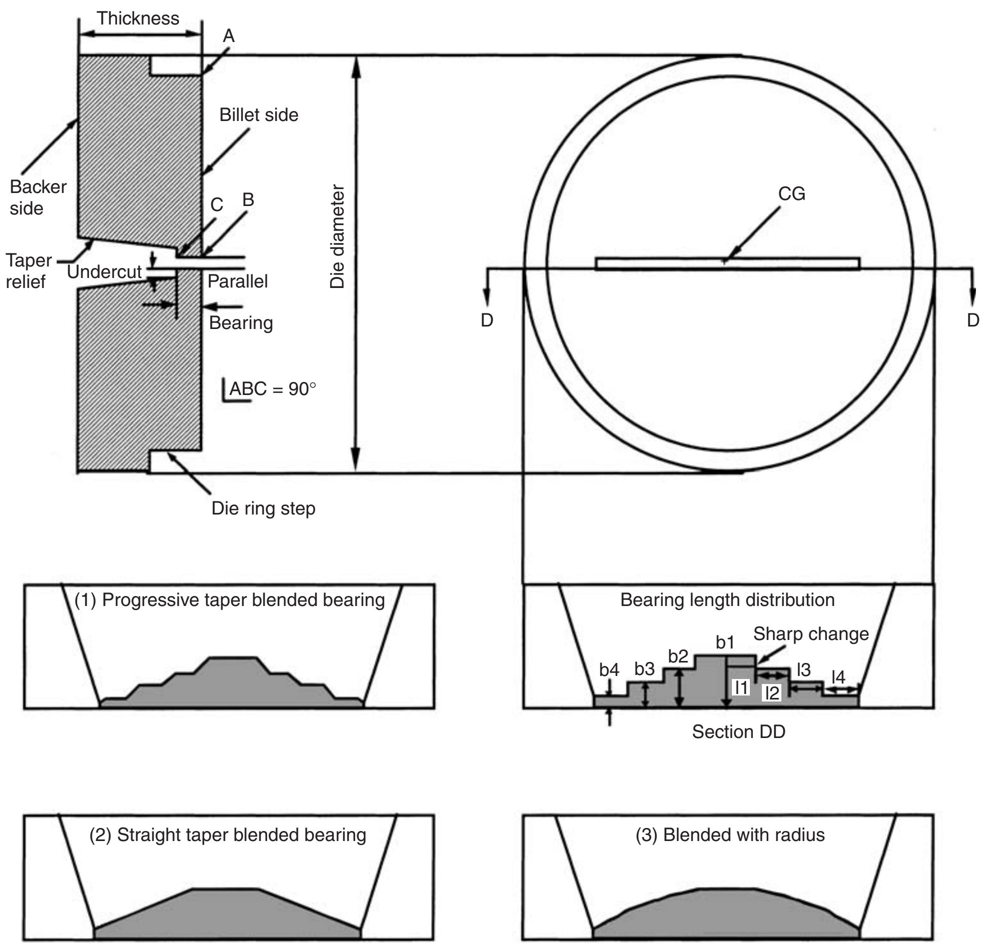


Fig. 7 Solid flat-face die configuration

over the die opening. Single-bearing (or constant-bearing) dies, developed by Rodriguez (Ref 12), offer the advantage of allowing aluminum to be easily pushed through the die at higher production rates.

The increase in extrusion speed in single-bearing dies can be explained by using the volume constancy relation that is given by:

$$A_C V_R = A_{Cm} V_{Cm} = A_E V_E \quad \text{(Eq 1)}$$

where A_C is the area of the container bore, V_R is the ram speed, A_{Cm} is the mean area of the stepped cavity (which is approximately given by $A_{Cm} = (A_1 + A_2 + A_3)/3$, V_{Cm} is the speed of flowing metal through the

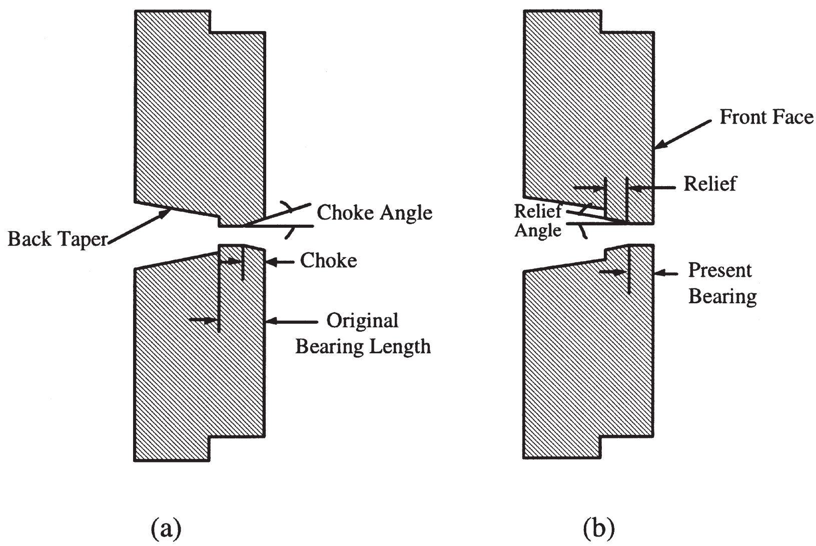


Fig. 8 Choke and relief in die bearing. (a) Choke at front of bearing. (b) Increased relief angle at the back or exit side of the bearing

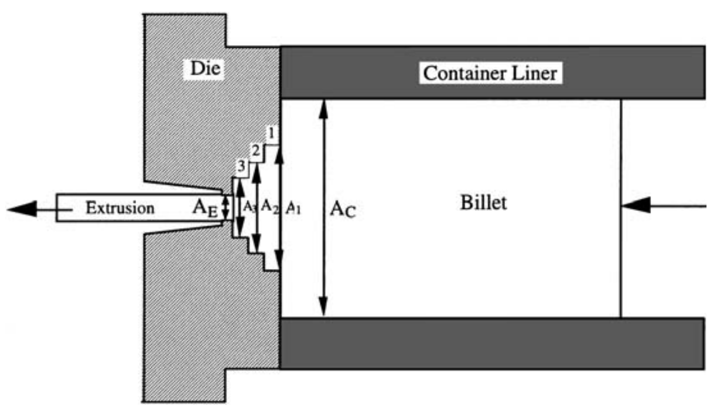


Fig. 9 Schematic of extrusion through a three-stage single-bearing die

stepped cavity, A_E is the final area of the extruded rod or shape, and V_E is the speed of extrusion.

The speed of extrusion is given by:

$$V_E = \frac{A_{Cm} V_{Cm}}{A_E} \quad \text{(Eq 2)}$$

For a fixed area of extrusion, V_E is proportional to the area of the cavity as well as to the speed of the metal flowing through the cavity.

Feeder Plate Dies. The large type feeder plate die, also called the housing die, is a solid die designed to produce a shape larger than the billet size. The outside diameter of the die is the same as the outside diameter of the die ring and fits with the regular feeder plate or recess type dies as shown in Fig. 10. The circumscribed circle diameter (CCD) of the opening for the feeder plate should be smaller than that of the billet diameter. The volume of aluminum inside the welding chamber looks like a rectangular slab to be extruded through the die opening to balance the flow with the center and rest of the extrusion as shown in Fig. 10.

The regular feeder plate die set has three components whereas a recess type die set has two components as shown in Fig. 11. Design of both feeder plate and recess dies is based on the same principle, putting a welding chamber in front of the die opening. Depending on the shape and size of the extrusion, the die maker will choose either a feeder or recess type die.

Figure 12 shows an example of a recess type die being used in the aluminum extrusion industry. Figure 13(a) is an example of a feeder plate die showing the weld chamber. The die set consists of the feeder plate, flat-face die, and a backer (Fig. 13b) sitting behind the die.

Extrusion through a feeder plate or recessed die is of two stages (Fig. 14). In the first stage, the billet is breaking down from the container area to the area of the recess or feeder plate openings. In the final stage, material is

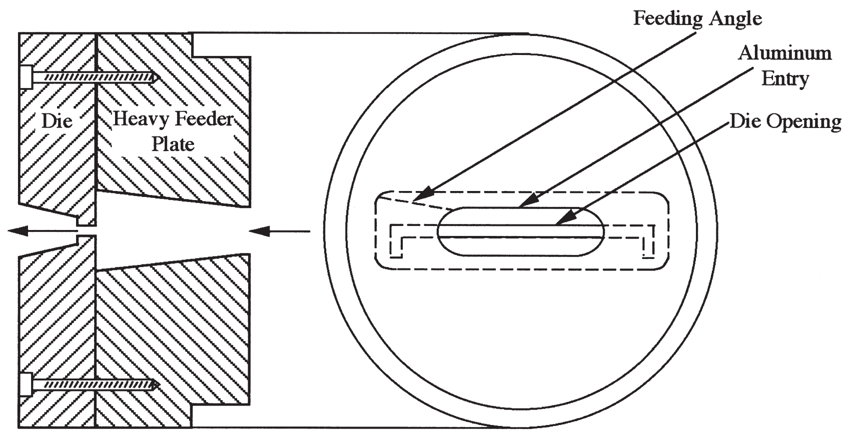


Fig. 10 Schematic of a heavy feeder plate die without backer and die ring

breaking down from the feeder plate or recess area to the actual extrusion area. The volume constancy relation is given by:

$$A_C V_R = A_F V_F = A_E V_E \qquad \text{(Eq 3)}$$

$$V_E = \frac{A_F V_F}{A_E} \qquad \text{(Eq 4)}$$

where A_F is the area of the cavity in the feeder plate or recess, and V_F is the material speed through the feeder plate or recess.

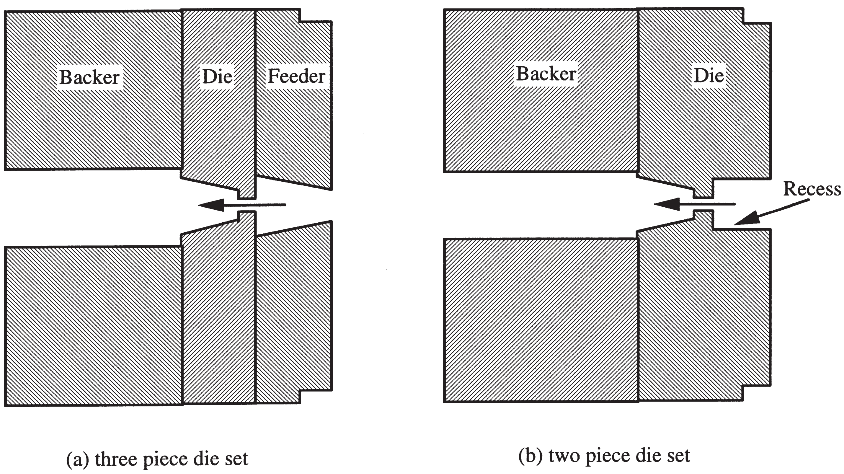


Fig. 11 Comparison of feeder and recess dies

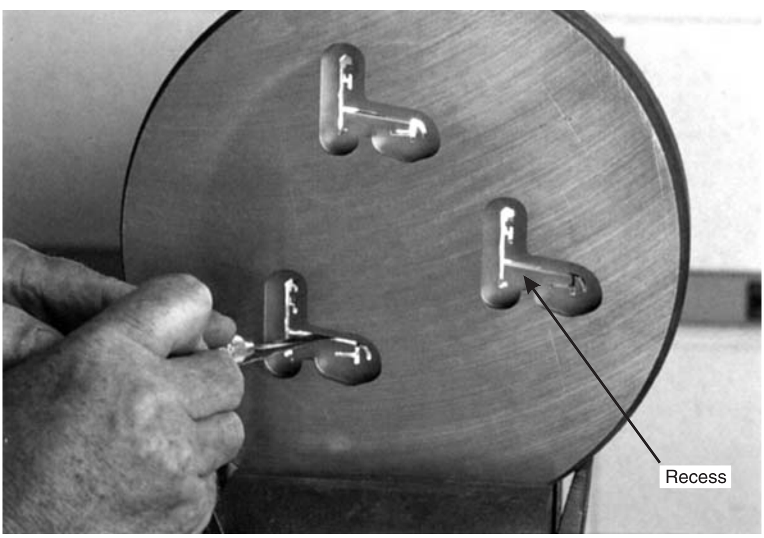


Fig. 12 Recessed die. Source: Cardinal Aluminum Co.

For the same extrusion area, A_E, $A_{Cm} > A_F$, and $V_{Cm} > V_F$. The speed through the single-bearing die is higher than that of the feeder plate die. Since the shape of the cavity in the single-bearing die is of the converging type, the speed of the material flowing through the cavity is higher than the speed for the diverging type feeder plate.

Hollow Die. A few examples of hollow dies are shown in Fig. 15–20. In Fig. 15, the different components of a porthole die are shown. Figure 16 is an example of a porthole die to make a critical shaped extrusion. In Fig 17(a), a recess has been provided on the entry of the mandrel to speed up flow through the outer periphery compared to flow through the

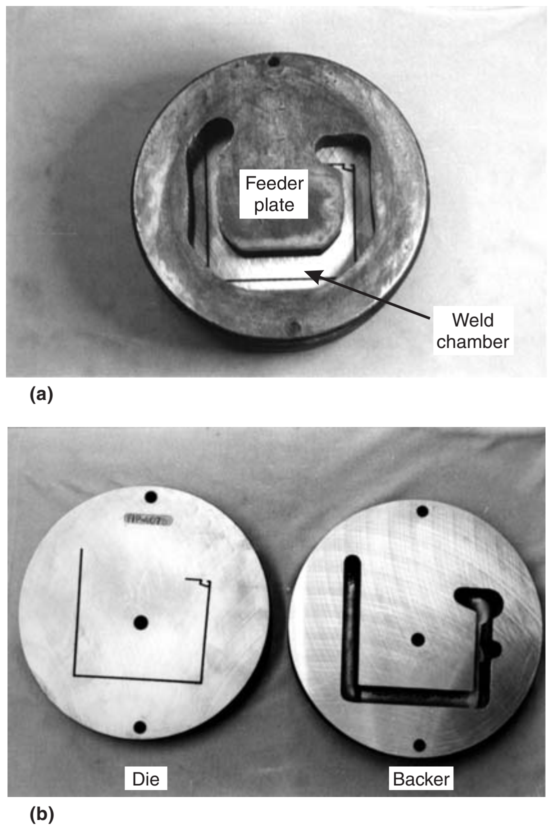


Fig. 13 Feeder plate die. (a) Complete die set with backer sitting behind die. (b) Die and backer

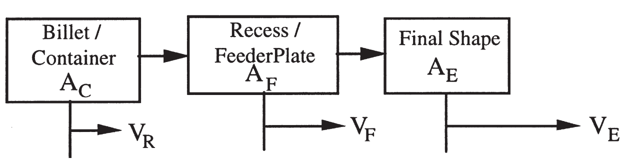


Fig. 14 Control volume of a feeder plate die

center of the die. In Fig. 17(c), a recess on the top of the mandrel has been provided to balance material flow in the critical wing of the shape (Fig. 17b). Figure 18 is a typical design showing the distribution of port areas to balance the flow through the die.

Figure 19(a) is an example of a porthole die with four equal ports of unequal web thickness. This design did not perform well in the press. The mandrel shifted in relation to the cap due to the crack developed in the four bridges as shown. The reason for cracking could be due to the higher deflection of the bridge due to lower stiffness because *Y* is smaller than *X* in the mandrel web. Another point to be noticed in this design is that pockets around the shape (two stages) have been provided (Fig. 19b) instead of the regular welding chamber. Figure 19(c) shows a typical example of a mandrel bridge that has a sharp radius on the top. Records indicate that this type of mandrel develops cracks compared to the mandrel with a much bigger radius on the bridge as shown in Fig. 20.

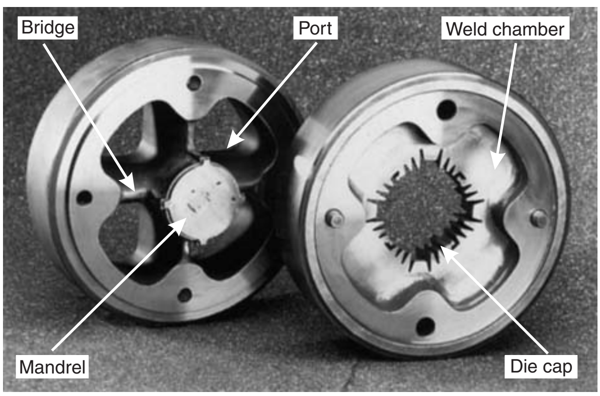


Fig. 15 Porthole die. Source: Exco Extrusion Dies

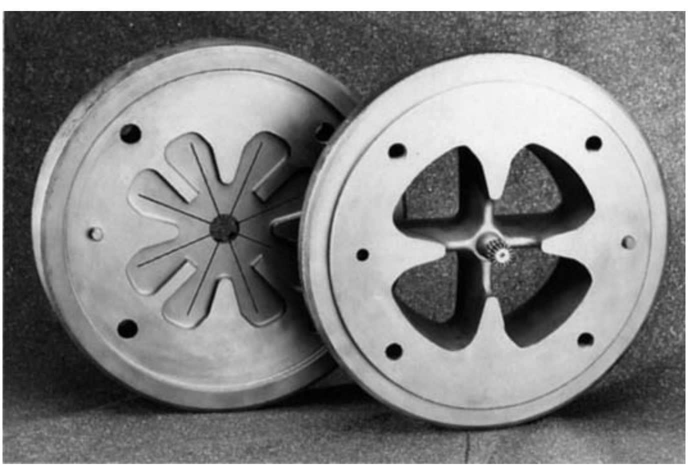
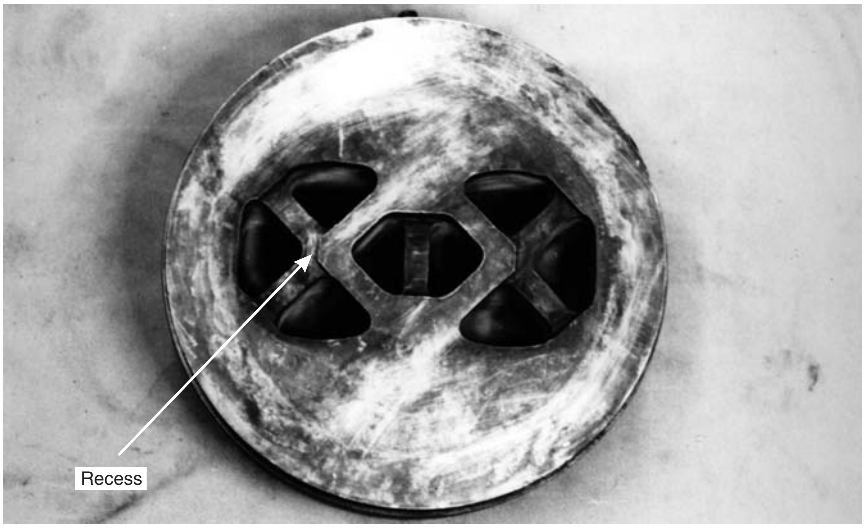
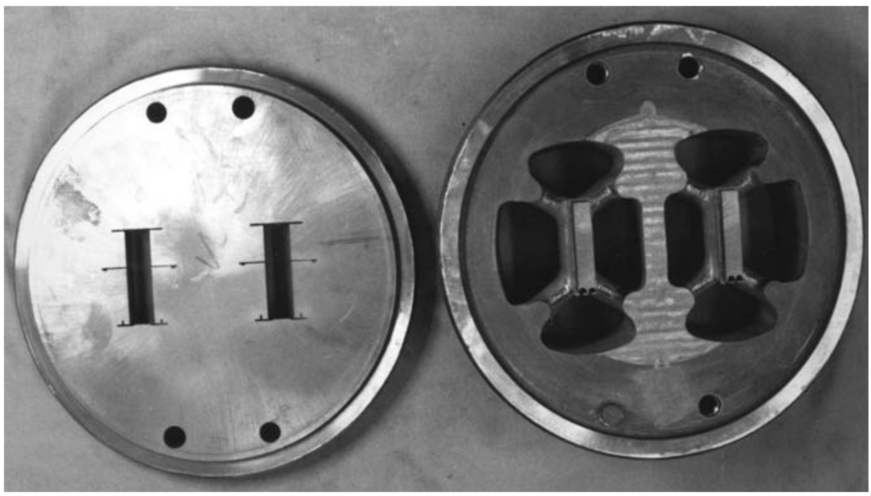


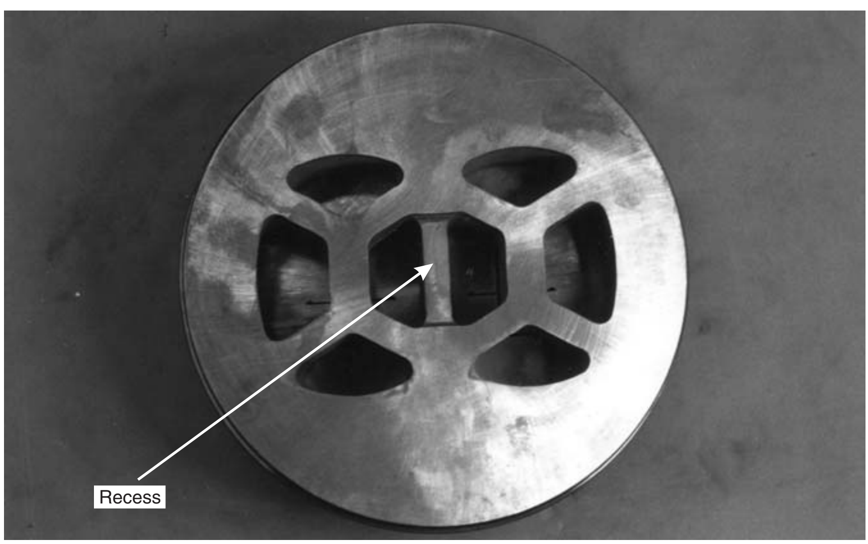
Fig. 16 Porthole die of a critical shape. Source: Exco Extrusion Dies



(a)



(b)



(c)

Fig. 17 Recess in the mandrel of a multihole porthole die. (a) Recess on entry of mandrel. (b) Inside view of the mandrel (right) and cap showing (left) the location of the critical wing of the shape. (c) Recess on top of mandrel. Source: Florida Extruder International, Inc.

Figure 20 is an another example of a tapered-type porthole die to make a square, thin-walled hollow shape. In the mandrel face, an example of choke is provided to slow down the metal entry at the center of the die compared to the outer periphery.

There are many varieties of hollow die designs in the aluminum extrusion industries. Examples of both solid and hollow dies are shown to provide the beginner with the idea of actual die and different features in the designs.

Flow of metal through a hollow die is much more complex than that through a solid die. In the case of a hollow die, the extrusion is taking place in three different stages. In stage one, metal flows from the billet to the mandrel port. In stage two, the metal flows from the port into the weld chamber. In the final stage, metal flows from the weld chamber to the gap between the mandrel and cap (die) to get the final hollow shape. The weld chamber includes the total volume between the top of the bridge of the mandrel and the cavity in the die cap.

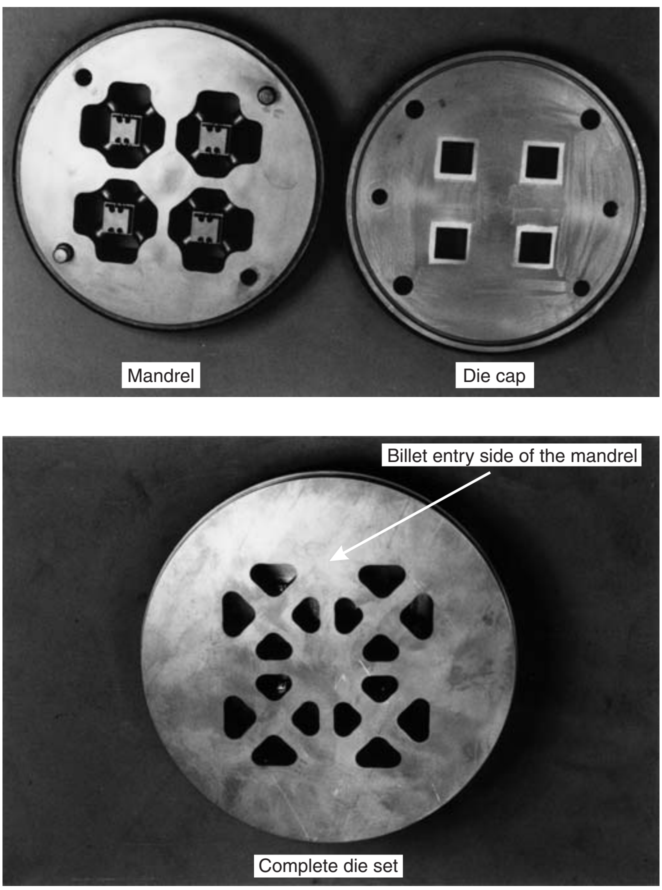


Fig. 18 Distribution of port areas to balance flow through a multihole hollow die

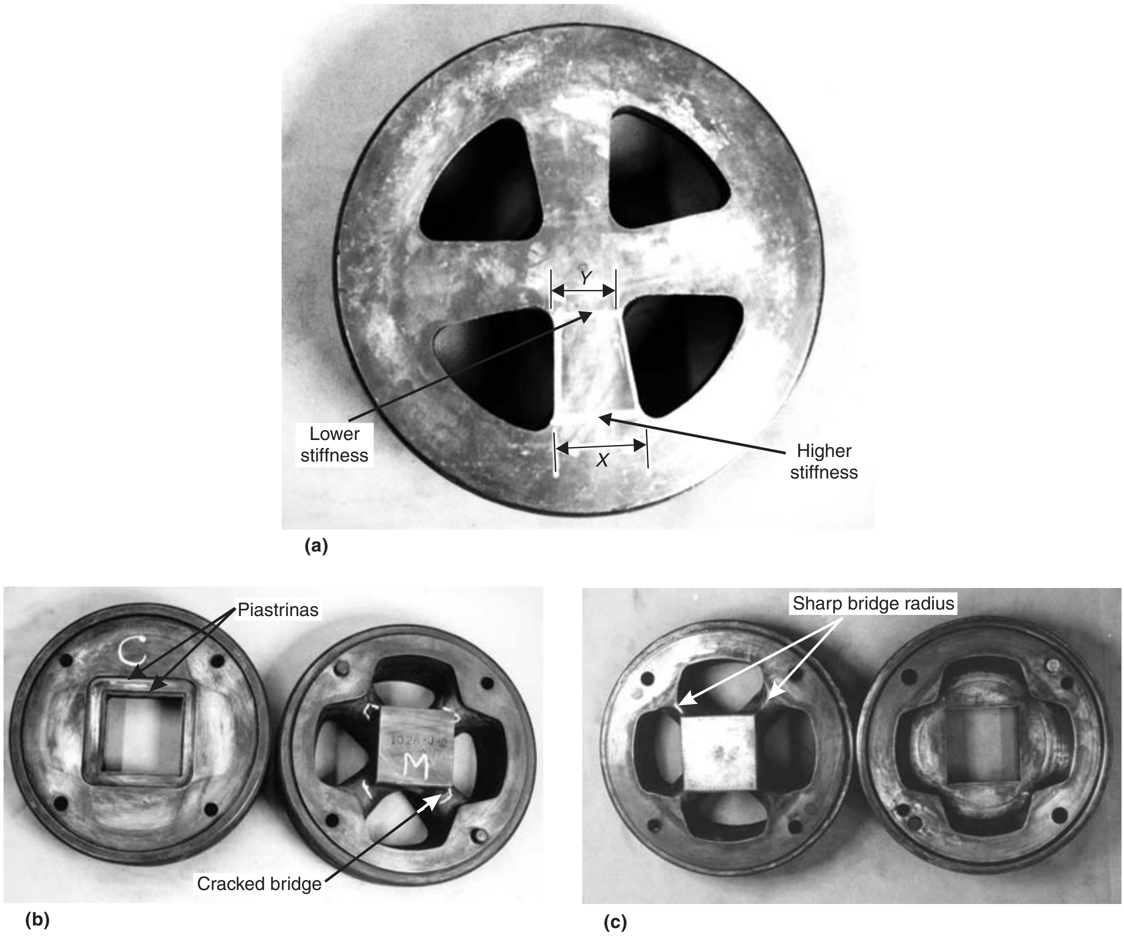


Fig. 19 Two different designs of porthole dies for the same shape. (a) Die showing variation of bridge thickness in a mandrel. (b) Piastrinas in a die cap. (c) Equal bridge thickness with sharp bridge radius in the mandrel of a porthole die of a second design. Source: Florida Extruder International, Inc.

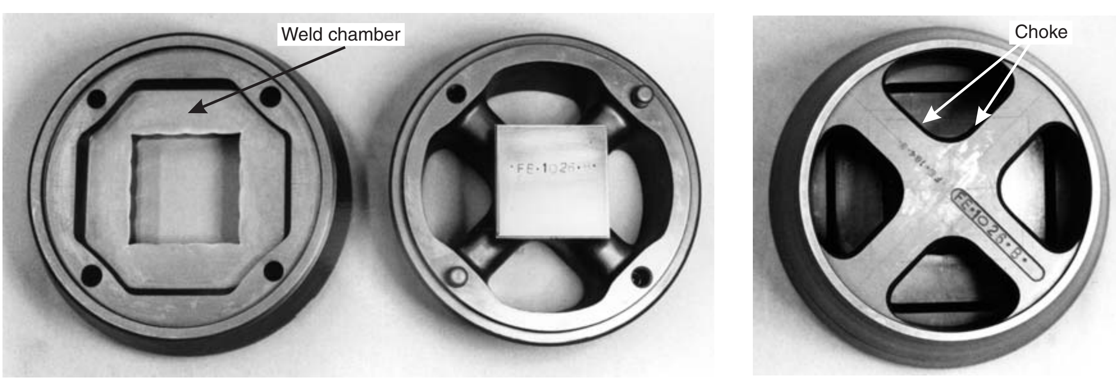


Fig. 20 Choke in a mandrel with equal bridge thickness of a single-hole hollow die. Source: Florida Extruder International, Inc.

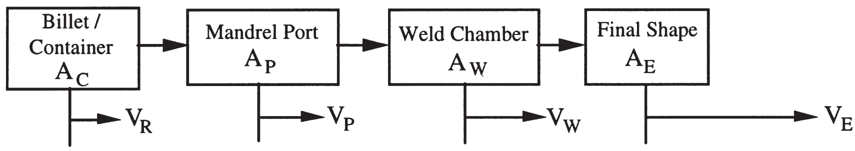


Fig. 21 Control volume of porthole hollow die

The volume constancy relationship as shown in Fig. 21 for a hollow die is given by:

$$A_C\, V_R = A_P\, V_P = A_W\, V_W = A_E\, V_E \quad \text{(Eq 5)}$$

where A_P is the area of the port in the mandrel, V_P is the material speed through the mandrel port, A_W is the area of the weld chamber, and V_W is the material speed through the weld chamber.

Die Making

Die making involves many steps and processes starting with receipt of a profile drawing from the customer to the shipment of a die. The steps and processes are shown in the flow diagram (Fig. 22). Two distinct areas require consideration in die making. In the first area, the die must be manufactured based on economic and extrusion productivity. In the second area to be considered, die manufacture must provide for maintaining the highest quality and reliability. Modern technology allows the die manufacturer to reduce the number of steps gradually. A comparison of traditional methods with the most advanced automatic method of die manufacturing is shown in Fig. 23.

Die Correction

Once manufactured, the die is sent to the press for testing and production, or for testing only, depending on the critical features of the extrusion. Despite the introduction of CAD/CAM and CNC in the design and manufacture of aluminum extrusion dies, the shape and finish of the product may not be accurately predictable. If the produced shape is successful in the first trial, production continues with proper checks and measures. If the extrusion does not succeed, the die needs to be corrected based on the report of the test run along with the front piece of the extrusion. Die corrections or maintenance could be required due to many reasons, such as improper metal flow, dimensional variation, surface finish, and any interference with runout table. However, die correction procedures require considerable practical experience. There are many ways to correct the same problem based on the skill and experience of the die corrector. It is important that the die corrector be present at the press to see the test run. The presence of the die corrector at the press will provide the information about the press, billet and die variables. This information will help the die corrector to rectify the die quickly or to relay some information to the die manufacturer if any major changes need be made. Luis Bello (Ref 17) discussed the fundamentals and application of how to correct extrusion dies, providing many examples and much information for solid, hollow, and semihollow dies.

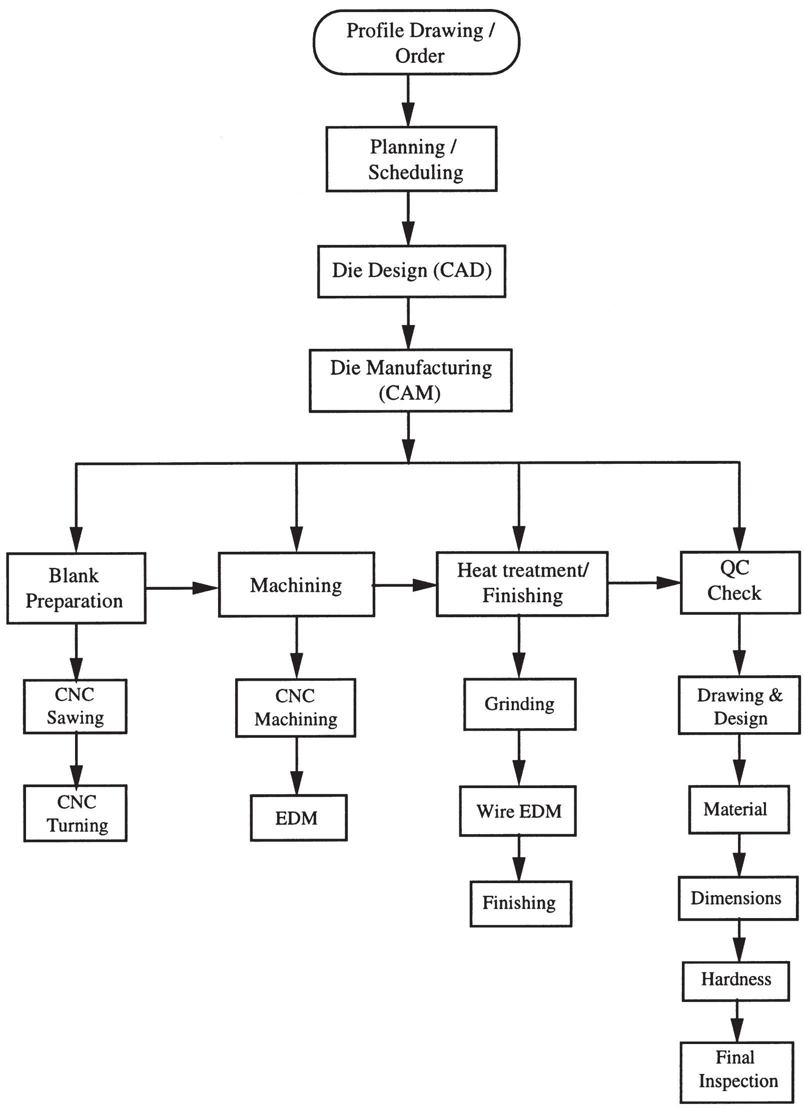
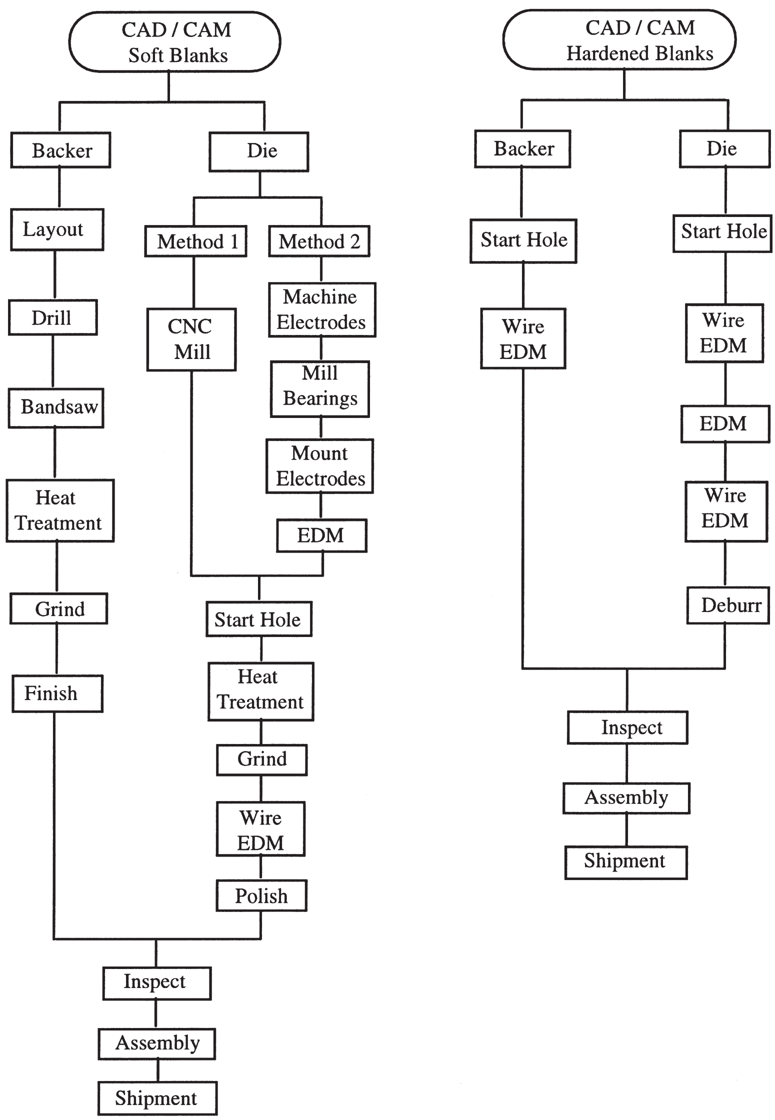


Fig. 22 Die manufacturing steps and processes

Factors for Consideration in Die Correction

Many factors affect the running of a die at the press. These factors need to be considered when correcting extrusion dies:

- Die temperature
- Billet temperature with respect to container temperature



(a) Traditional Methods (b) Advance Method

Fig. 23 Comparison between traditional and advanced methods. Source: Autotool

- Taper billet heating
- Change of extrusion speed
- Press alignment and adjustment
- Deflection of die stack
- Rotating the die to change position
- Use of lubricant
- Use of canister guide

In addition, problems associated with the press can include the following: improper tool stack, flatness of the pressure ring, improper sealing of the die with the container liner, a washed out container liner, and worn out dummy pads. To correct any type of die, solid or hollow, it is important that the die corrector be familiar with the press or presses that he works dies for.

Solid Die

Correction of a solid die requires either modification in the pocket or the feeder plate or modification of the bearing length from the front or exit side of the die. The proper method of correction should be by using a milling machine instead of flexible grinder, an old carbide-tipped method. A milling cutter is used to do the machining on the hardened steel. The amount of modification done using the milling machine can be measured and recorded for further communication with the die designer or manufacturer.

Correction may also be associated with dimensions or the wall thicknesses of the section. Similarly, the die corrector should communicate this information to the die manufacturer to change the program in the wire EDM.

Hollow Die

The correction of a hollow die is very complex compared to that of a solid die, because the aluminum is flowing through three stages, as shown in Fig. 21. There are many variables associated with hollow dies such as ports, depth of bridge, and the weld chamber cavity. The correction of hollow dies could be due to twist, angularity, split corners, a convex wall, a concave wall, and an uneven wall.

To correct the flow on a hollow die, examine the port first before working on the bearings. Ports control the volume of metal, which needs to be balanced in relation to the cross-sectional area of the extrusion that each port is feeding.

Die Materials and Surface Treatment

Selection of Die Material

In the process of manufacturing an aluminum extrusion die, the selection of a die material and its specific properties are critical factors. Since the aluminum extrusion process is a hot working process in the average range of 1050 °F, the most frequently used die material worldwide is the well-established hot die steel AISI H13 (Ref 18). The performance of the extrusion die is normally limited by typical material-related failure mechanisms. In aluminum extrusion, the most common die failure mechanisms are hot wear, plastic deformation, and cracking. In order to offer good resistance against these failure mechanisms, the die material should have the following properties:

- High hot hardness (hot yield strength)
- High tempering resistance
- Good wear resistance (response to nitriding and thin hard coatings)
- Good toughness

Newly developed precipitation-hardening die steel reduces die-making time compared to that for H13 steel by combining hardening and nitriding treatments. The new steel ALEX has been commercially introduced for making aluminum extrusion dies. A significant increase in die life can be achieved.

Surface Hardening and Treatment

The surface quality of extruded products depends on many factors. One of the most important is the wear mechanism on the bearing surface of the extrusion die. Adhesive wear is especially detrimental since it causes the characteristics of harmful crater wear on the bearing. A wide variety of surface treatments have been experimentally applied by extruders to improve wear resistance and, thus, to reduce the tooling costs.

Various methods of die nitriding, such as plasma, fluidized-bed, and nitrocarburizing, are available. The advantages of each are discussed in Ref 20 to 22. Statistical analysis of production data shows an improvement in die life for both nitrocarburizing and nitriding processes (Ref 22). Surface treatments to prevent die wear are of critical concern for improved die life and affect extrusion surface quality. Several treatment methods and mechanisms are available.

Adhesive and abrasive wear mechanisms are common failure modes for aluminum extrusion dies. Janoss (Ref 23) has given an overview of different coatings used in extrusion dies and tooling to reduce die wear, improve tool life, and improve productivity in aluminum extrusion. Pye (Ref 21) has reviewed surface modification techniques for preheated H13 extrusion dies and emerging technologies. He has compared deposition materials and different methods that offer good potential for wear resistance. Sundqvist et al. (Ref 24) tested different surface coatings and substrates for extrusion dies for wear resistance and friction when sliding against aluminum at high temperatures in a block-on-cylinder setup. Different coatings tested included nitriding, chemical vapor deposition (CVD), and pressure vapor deposition (PVD) coatings. The results indicate that adhesion between the aluminum and the coating is a key factor in causing wear. TiC, TiN, and VC coatings had lower friction coefficients and lower rates than both uncoated and nitrided tool steels. Mew and Guyoncourt (Ref 25) verified from their laboratory tests that a PVD coating of chromium nitride deposited on a nitride substrate gave the best results. The prediction trial confirmed the results, and the product had a better surface finish. Kelley et al. (Ref 26) evaluated plasma spray technology as an interesting alternative for die surface enhancement. Evaluation of the alumina (Al_2O_3) coating on the H13 die steel, including alumina wear performance and interphase bonding, is provided. The prospect of using ceramic coatings for aluminum extrusion dies is discussed.

Tribology in Extrusion Dies

The tribology (friction and wear processes) in die bearings is dependent on many factors, including temperature rise in the die, extrusion speed, shape and geometry of die, die bearing length and surface condition, and materials properties of the die steel and the extruding alloy. Because the temperature rise in the die bearing has a direct effect on the other factors, temperature is an important factor for die wear or change of friction condition in the die bearing or vice versa. Schey (Ref 27) gives a useful review of die wear inference in metal forming operations.

Thedja et al. (Ref 28) have studied the tribological processes in the die land to determine its influence on the accuracy of shape and the surface quality of the extrusion. They examined the tribological processes during the extrusion of AA6063 alloys and discussed the relationship between the periodic adhesive layer buildup and detachment on the die bearing face, and how the friction in the die land influences the surface quality of the extrusion. The process of dynamic formation and periodic removal of the adhered layer of aluminum may result in adhesive wear on the die bearing.

Wear in an Extrusion Die

A tribological effect, die wear is defined as the progressive loss or removal of material from a die surface. Wear has important technologic and economic significance because it changes the flow and shape of the material and die interfaces. Finally, it affects the process, size, shape, and quality of the material flowing through the die. Wear generally alters the surface topography and may result in severe surface damage. Wear is usually classified as adhesive, abrasive, corrosion, fatigue, erosion, fretting, or impact wear.

In direct extrusion, the process becomes complicated due to high pressure and relative velocity between billet and container and also between die and extrusion material, combined with adhesive and abrasive action including sudden temperature fluctuations and prolonged exposure to high temperatures. Dies are the most severely loaded. In extrusion of a long section, the die softening temperature may be reached. Tongues deform, and the orifice may open up. Dimensions are lost. Abrasive wear is more gradual but is, again, much accelerated at elevated temperatures. Such die wash is sometimes aggravated by adhesive wear.

Adhesive Wear. Since aluminum has a strong tendency to adhere on the steel surface, there will be development of the adhesive layer on the die bearing. The development of an adhesive layer on the die bearing surface is dependent on many factors: temperature developed in the die bearing, speed of extrusion, shape and geometry of the die, die bearing length, surface roughness parameters of the die bearing, and hardness of the bearing surface.

Of the above factors, the most important are temperature and speed of extrusion. Extrusion speed and temperature rise on the die bearing are directly related to each other. For the same billet temperature, temperature rise on the die bearing is greater at higher speeds due to increase in strain rate and increase in shear deformation (sticking friction) on the die bearing. When the temperature on the die bearing increases, the tendency for the development of an adhesive layer increases. Due to the increase of temperature, the adhesive layer begins to develop, and with the increase of press cycles, the adhesive layer slowly may cover the complete bearing area and become a thicker layer. The repetitive adhesive layers buildup, and detachment leads to die wear and contaminates in the extrusion.

Experimental Observation. It was observed by Saha (Ref 29) that after certain press cycles, severe surface damage (die wear) occurred on the die bearing of a hollow die (tapered seal type) as shown in Fig. 24 to make a thin-walled square tube with screw bosses from 6063 aluminum alloy. The die was properly heat treated with nitrided surface treatment on the die bearing. Significant washout or die wear was observed when

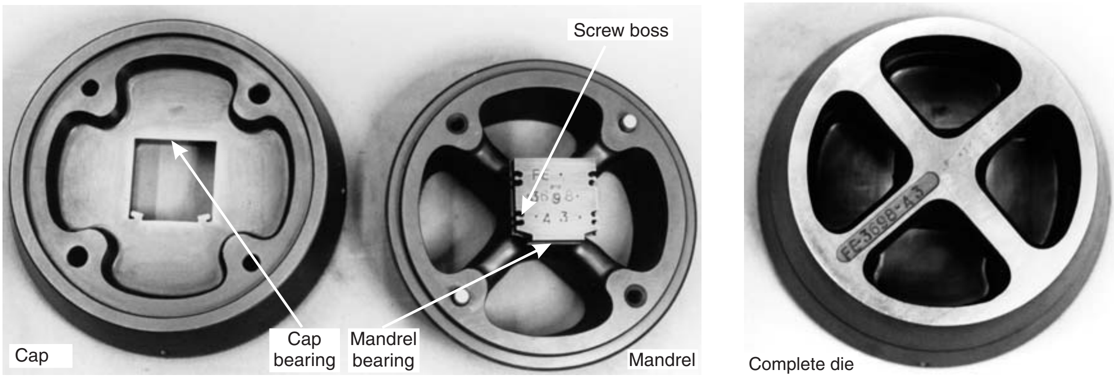


Fig. 24 Photograph of tapered-seal hollow die. Source: Florida Extruded International, Inc.

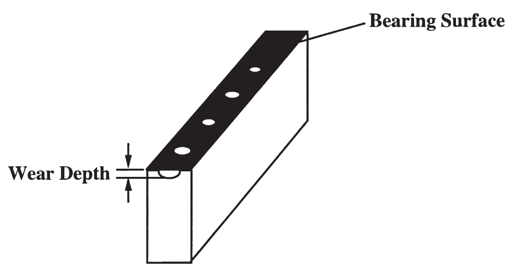


Fig. 25 Wear depth on the die bearing

more billets were extruded through the same die. Washout was also due to the use of a higher extrusion velocity. Thedja et al. (Ref 30) found the die wear begins on the delivery edge of the die bearing and continues in the opposite direction of the extrusion. In the present work, washout or wear spots started at the leading edge and finally propagated at the middle of the die bearing as shown in Fig. 25. More wear spots were observed on the mandrel bearing surfaces compared to the bearing surfaces of the cap. According to the design of a hollow die, additional heat is greater on a larger bearing area. Wear spots appeared to be different on the bearing surface, having gaps or discontinuities.

Wear measurements on the die bearing surfaces of tapered-seal hollow dies have been conducted by Saha (Ref 29) to determine the effect of different press cycles (the number of billets run). Tests have been conducted under two different extrusion conditions:

- Two different billet lengths (for constant billet temperature and ram speed)
- Two different ram speeds (for constant billet temperature and billet length)

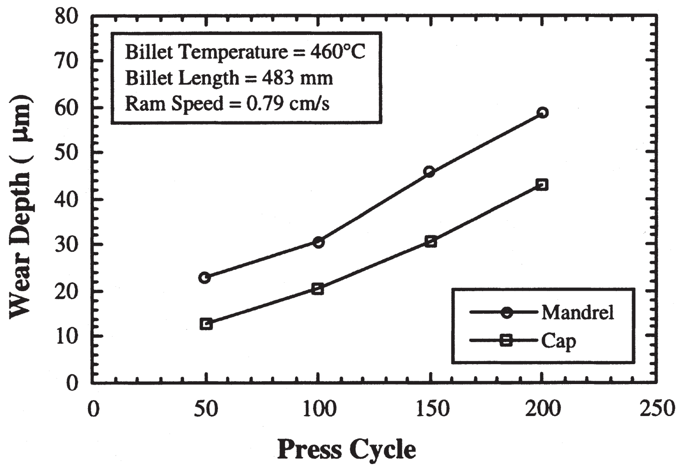


Fig. 26 Variation on wear depth on the mandrel and cap bearing with press cycle

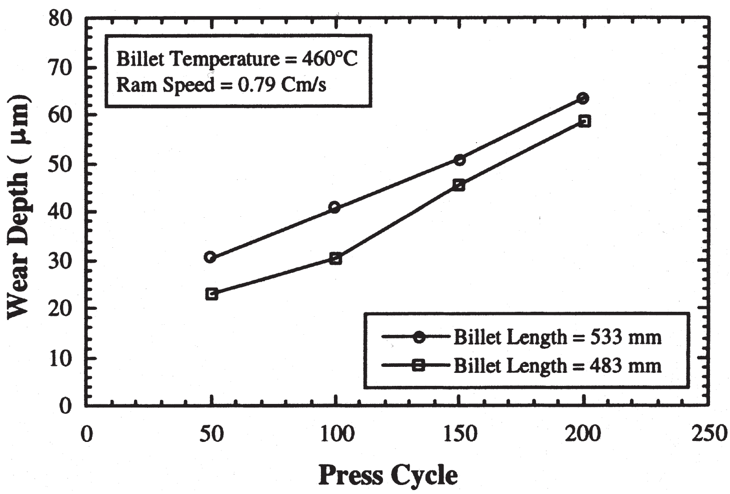


Fig. 27 Variation of wear depth with press cycle for two different billet lengths

Dies used in the tests had identical quality (the same die steel with the same heat treatment, including nitriding) supplied by the same die manufacturer.

To measure the amount of die wear, measuring the maximum depth of the wear spot on the die bearing surface of the mandrel or cap was the chosen method. This is shown in Fig. 25. Each point in the plots shown in Fig. 26 to 28 is the average of three identical tests.

Figure 26 shows the variation of depth of wear on the mandrel and cap bearing for different cycle times. Wear depth increases with the increase of press cycles (number of billets run). More wear spots were

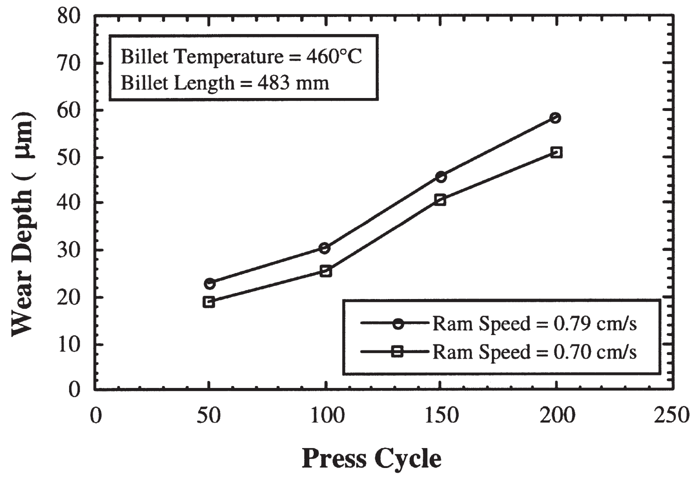


Fig. 28 Variation of wear depth with press cycle for two different ram speeds

found on the mandrel surface compared to that of the cap. In reality, more heat is generated inside the mandrel due to additional deformation and friction inside the mandrel area. It is observed that wear starts from the leading edge of the die bearing with respect to the direction of metal flow.

Figure 27 shows the variation of wear depth with press cycle for two different billet lengths. Wear depth increases with the increase of billet length. The longer the billet length is, the longer the time is for each extrusion cycle and the more localized temperature rise in the die bearing.

Figure 28 shows the variation of wear depth with press cycle for two different ram speeds. This shows that wear depth increases with the increase in ram speed. As ram speed increases, extrusion speed increases for the same extrusion die. The amount of wear depth may increase with the increase of exit temperature, which finally increases the temperature of the die bearing.

Change of Frictional Contact Area. A typical pattern of die wear is shown in Fig. 29. The present study involves some investigation of the performance of a hollow die used in the extrusion of a 6063 tubular shape. The die used in the process is a tapered-seal type hollow die. Figure 24 is a photograph of the die. Several wear spots are observed on both the mandrel and the cap bearing surfaces, respectively.

If A is the area of the wear spot on a surface of a die bearing, the total wear area will be given by:

$$A_{TW} = A_1 + A_2 + A_3 + \dots + A_n = \sum_{1}^{n} A \qquad \text{(Eq 6)}$$

The apparent area of the bearing surface after the wear, A_A, will be given by:

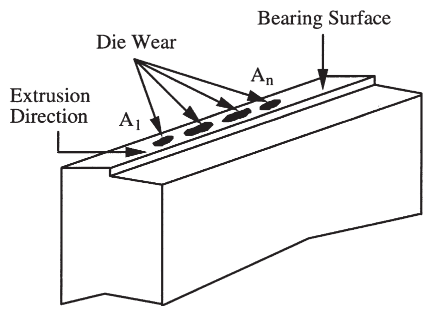


Fig. 29 Change of real frictional area after die wear

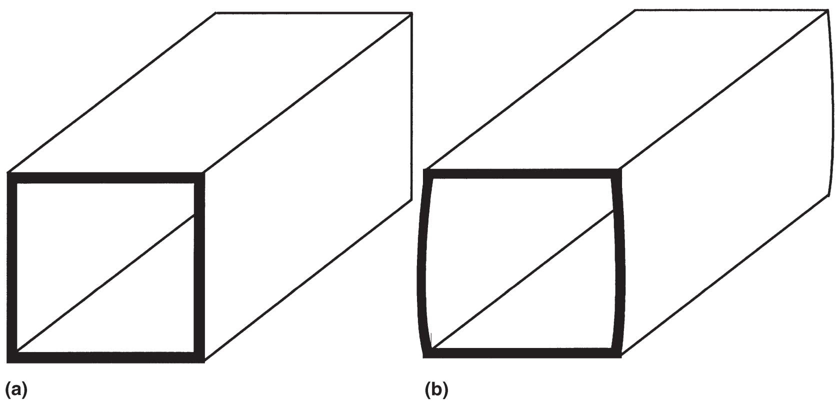


Fig. 30 Change of shape of the extruded aluminum alloy square tube (a) before die wear and (b) after die wear

$$A_A = A_O - A_{TW} \quad \text{(Eq 7)}$$

where A_O is the apparent area of the original bearing surface.

Because the apparent area of contact after the wear, A_A, is becoming less than A_O, die wear effectively reduces the frictional area of the die bearing. The present experiment shows that the mandrel bearing surface area has a greater number of wear spots than the cap of a hollow die. The effective change of frictional area varies in a different way on the mandrel and cap bearing, respectively, for each side of a square-shaped hollow die. As a result, there is relative sliding velocity between the inside and the outside layer of each side of the hollow square tube. Due to this variation in relative sliding velocity, the total metal flow between the gap of mandrel and cap is expected to change, and eventually the shape changes.

As mentioned, an interesting feature that was observed was that the change of the shape of the extruded aluminum 6063 alloy square tube before and after the die wear as shown in Fig. 30. Figure 30(a) shows a perfect square shape before any die wear takes place and Fig. 30(b) shows a convex shape on the two side walls. Each side wall has two screw bosses. Screw bosses are not shown in Fig. 30. The screw bosses are shown in the view of the die in Fig 24.

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CHAPTER 5

Billet Casting Principles and Practice

The extrusion process consists of four major components, hydraulic press, die, tooling, and billet casting. In the previous two chapters, extrusion presses, extrusion dies, and tooling have been discussed. Now it is important to discuss how the extrusion raw material (billet) is processed. Some of the fundamental aspects of billet casting are covered in this chapter to give an overview of the casting process, especially for the beginner in the aluminum extrusion technology. Billet quality directly controls or may affect extrusion productivity and quality. The profitability of the extrusion is derived from the cost of the billet. The cost of casting and the quality of the billet are two very important considerations for the extrusion producer. But the technology is changing and improving toward higher productivity and quality. The advances in the billet process, equipment, and technology can be followed through the successive proceedings of the Aluminum Association and the Aluminum Extruders Council's International Extrusion Technology seminars.

Principle of Billet Making

The functional block diagram of the billet-making process is shown in Fig. 1. Figure 2 shows the flow diagram of the basic steps of the melting and casting processes. There are many steps involved between the input of the raw materials to the final casting process. The direct chill (DC) continuous casting process developed in 1933 by W.T. Ennor is the method used today to cast aluminum extrusion billets. Figure 3 illustrates the principle of the DC casting process. Molten aluminum is poured into a shallow, water-cooled mold normally of a round, cross-sectional shape. When the metal begins to freeze in the mold, the false bottom in the mold is lowered at a controlled speed, and water is sprayed on the surface of the freshly solidified billet as it comes out of the mold.

A recent trend is toward using larger DC casting machines equipped with programmable-logic control systems (Ref 1). By the use of sensors and programmed logic, the automated systems can now control a multitude of casting parameters. The water-cooled mold, used in a hot-top casting machine, is a complex assembly that is not easily changed.

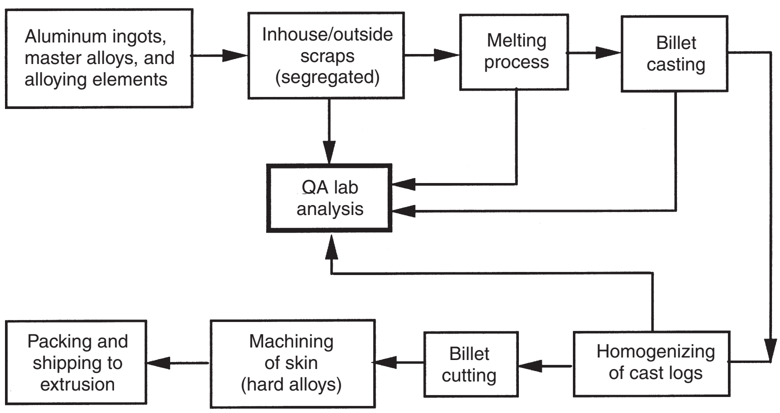

Fig. 1 Functional block diagram of the billet-making process

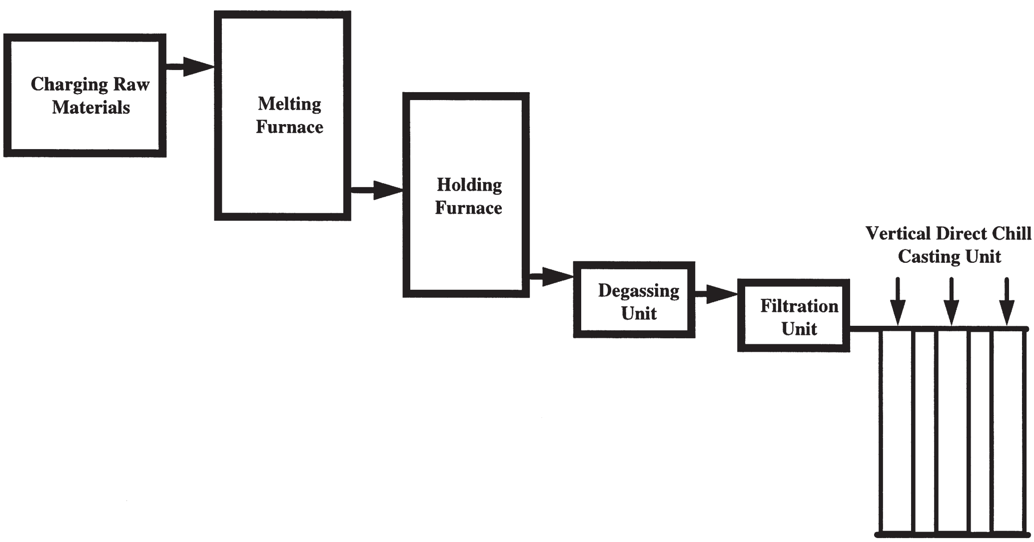

Fig. 2 Functional block diagram of melting and casting processes

Different alloys and billet sizes, however, require different molds. A modular mold system can greatly increase the capabilities of an existing casting machine. The modular design permits a rapid change of mold components. This design permits casting at different speeds and billet sizes in the same machine (Ref 2). Wagstaff hot-top casting systems were developed over a decade ago (Ref 3).

In billet casting, molten metal flows through a transfer and distribution system. Refractory liners, belonging to different components of that system, must satisfy diverse criteria such as reactivity, maintainability, and disposability. New materials (high-temperature fused silica and low-density fused silica) are being evaluated as long-term alternatives to the refractory ceramic-fiber product (Ref 4).

There are several advantages to the DC casting system, especially for hard alloys such as 2000 and 7000 series systems, compared with other techniques, such as tilt-mold casting:

- Has minimum metal segregation
- Can produce large ingots
- Flexible to cast with varying speeds
- Minimizes cracking in hard alloys
- Transfers molten aluminum slowly and uniformly with a relatively low temperature to avoid many problems

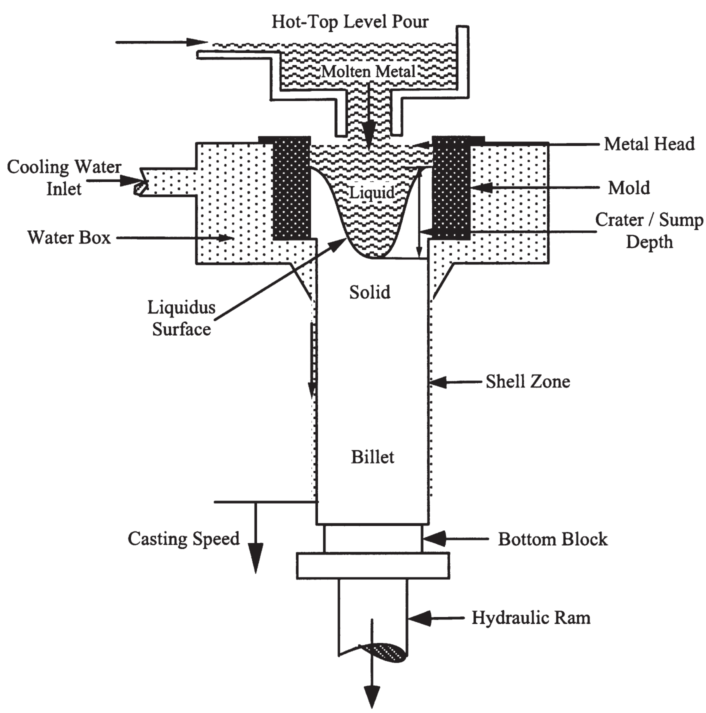

Fig. 3 Principle of DC billet casting

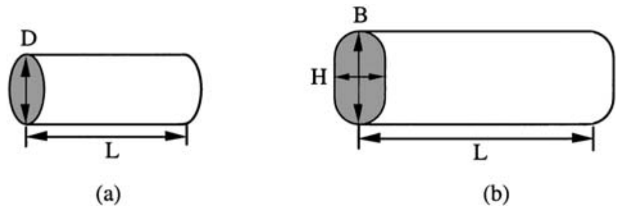

Fig. 4 Shapes of aluminum alloy billets

Billet Shape. Aluminum extrusion ingots are cast in round-shaped continuous lengths (logs) up to 160 in. (4064 mm), and billets are then cut from the cast log to the desired length as shown in Fig. 4(a). Round billets have two dimensions, diameter, *D*, and length, *L*. The length of the billet is determined from the product size and the press capacity. For wide extrusions, the rectangular/oval-shaped billet (Fig. 4b) is used for a rectangular container. Rectangular billets have three dimensions, major axis, *B*, and minor axis, *H*, of oval cross section, and length, *L*. The ratio of *B* and *H* is normally 2 to 1 or 2.5 to 1.

Casting Practices

Casting Variables

The principal variables of aluminum billet casting that influence production performance are the following:

- Pouring temperature
- Casting speed
- Type of mold
- Metal head
- Rate of water flow

Pouring Temperature. The molten metal temperature in the furnace should be kept as low as possible to prevent gas pickup and the formation of oxide. Metal should reach the casting unit 50 °F (28 °C) above the liquidus temperature of the alloy being cast. The liquidus and casting temperatures for some common aluminum wrought alloy systems are shown.

Alloy system	Liquidus temperature, °F (°C)	Casting temperature, °F (°C)
Al, AlMn	1220 (660)	1270 (688)
AlMg, AlMgSi	1202 (650)	1252 (680)
AlCuMg, AlZnMgCu	1184 (640)	1234 (670)

Casting Speed. Casting speed is one of the most important variables in the DC casting process. The billet sizes and the kinds of alloys determine

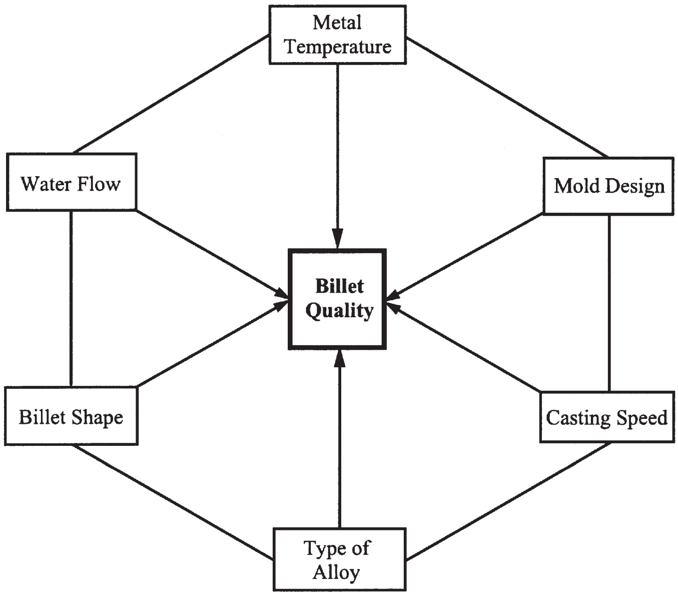

Fig. 5 Effect of principal variables on billet quality

casting speeds. The typical casting speeds in a vertical semicontinuous casting process for a 6063 alloy are 5.1 in. (130 mm)/min for 7 in. (178 mm) diameter and 3.9 in. (100 mm)/min for 9 in. (230 mm) diameter, respectively.

Types of Molds. Mold materials requirements include factors such as lightness, good machinability, and good thermal conductivity. Aluminum alloys 6061 and 5052 are suitable mold materials. The cooling system of a DC mold is designed so that the cooling water first comes in contact with the mold wall and then passes on to the surface of the billet as it comes out of the mold. Based on this DC casting principle, various types of molds have been designed. Some recently developed and popular molds are discussed in the section "Vertical Casting System."

Metal Head. The metal head is the distance from the bottom of the mold to the liquid metal surface and is usually kept at a depth of at least 2 in. (51 mm) as shown in Fig. 3.

Rate of Water Flow. During DC casting, approximately 432 btu/lb (1 MJ/kg) of heat must be transferred from the ingot. The temperature and the rate of water flow must be adjusted so that the water will wet the entire surface of the ingot being cast and cascade down its surface. The water must be prevented from bouncing off the ingot surface.

In summary, the overall production performance and quality of DC cast billet are influenced by the factors that are connected with a closed-loop chain as shown in Fig. 5.

Charge Material

Aluminum and other alloying constituents necessary for the alloy make up the furnace charge. The charge materials consist of three major components, high purity aluminum ingots, alloying elements and master alloys, and in-house process scraps. Virgin aluminum directly from the reduction cells or remelt ingots made from the virgin aluminum are sometimes used. The choice of using the high-purity aluminum ingot is a management decision to maintain high-purity billet quality within the cost limits.

The alloying elements with low melting points, such as magnesium and zinc, are usually added to the molten aluminum as pure metals in the form of bars. Alloying elements with high melting points, such as silicon, manganese, nickel, copper, and chromium, are added in the form of master alloys or hardeners. Hardeners are generally made separately by melting high-melting-point elements with aluminum in the form of small ingots or bars. When hardeners are added in the charge during melting, the alloying elements are mixed with the molten aluminum without overheating the metal. Hardener chemistry is tightly controlled.

Scraps from previous operations are added to many charges by a proper segregation process. Uses of the proper scrap in controlled amounts in a particular charge are important factors that can affect quality. The use of purchased scrap in an aluminum extrusion cast house is a common practice to keep an extruder in the competitive market. McHale and Sites (Ref 6) wrote a useful procedure that explains how to handle purchased scraps, including specifications established for vendors with quarterly rating systems, internal scrap samplings, handling and inspection procedures, and the charging of purchased scrap.

Melting and Holding

The selection of the furnace to be used for melting aluminum and making alloys depends on the type and size of the casting. For billet casting operations, large, refractory-lined stationary reverberatory melting furnaces are used. Two single-hearth furnaces are operated alternately. One furnace is used for charging raw material and melting, and the second one is used for holding and casting (Fig. 2). The current trend is to use tilting rather than stationary holding furnaces to feed the DC casting operation. The tilting furnace has a fully open front with a single door to facilitate stirring, skimming, and cleaning of the hearth. After aluminum and alloying elements are melted together in a suitable furnace, the piece is transferred to the holding furnace. Tilting furnaces now are equipped with an interactive mode, accessed by pressing an individual control button, or a fully automatic control system, including the flow of aluminum with the control of the furnace tilt angle. The melt is stirred from the bottom upward in order to avoid excessive agitation and breaking of the oxide skin surface. The melt is then skimmed of surface oxides.

Fluxing and Degassing

Fluxing is a chemical treatment of molten aluminum. The chemical compounds are usually inorganic salt mixtures. Fluxing also includes the treatment of aluminum melts by inert or reactive gases to remove solid or gaseous impurities. In aluminum melting, oxide formation and nonmetallic impurities are quite common. Impurities may appear in the form of liquid and solid inclusions that persist through melt solidification into the casting billet. Fluxing of the melt facilitates the accumulation and separation of such undesirable constituents from the melt. Fluxing is temperature dependent. The temperature of molten metal needs to be kept higher before adding the fluxes to the melt. At high temperatures, the fluidity of both aluminum and the fluxing agent is likely to be very high to provide good contact between the melt and the fluxes as well as better reactivity. Cover fluxes, cleaning fluxes, drossing fluxes, and refining fluxes are considered to be the four principal types of fluxes used for aluminum alloys.

To maintain a good quality billet, metal treatment to degas and remove inclusions is an important consideration in billet casting. Like the extrusion industry, metal treatment technology is advancing toward quality improvements and excellence. New filtration materials, modeling of mechanisms, and experimental data gathering all contribute to improvement of metal treatment (Ref 7). In-line gas fluxing systems remove 61 to 66% of the hydrogen and decrease inclusions by more than 65%. Improved billet quality can increase extrusion speed (Ref 8). A model of gas fluxing with a cylindrical rotor delineates the most important parameters for efficiency. Data are available to confirm 61% hydrogen and 67% particulate removal (Ref 9).

Hydrogen gas is the only gas with appreciable solubility in both liquid (approximately 1.4 ppm) and solid (approximately 0.12 ppm) aluminum. In solid aluminum, hydrogen is detrimental, causing porosity in castings and chances of blistering in the extrusion and also during subsequent heat treatment of extruded shapes of hard alloys. There are many potential sources of hydrogen in aluminum, such as furnace atmosphere (fuel) charge materials, fluxes, external components, and metal/mold reactions. Dissolved hydrogen can be reduced or removed by proper degassing. There are many ways the degassing could be done, such as gas purging, tablet-type flux degassing, and mechanical mixer degassing. Degassing is a big concern in billet casting as well as a major subject in casting. More detailed information about the sources of hydrogen and different degassing systems are discussed in Ref 10.

The metal flowing from the holding furnace to the DC casting machine is first refined in the treatment unit as shown in Fig. 6. Figure 7 shows the schematic of the SNIF rotary degassing system. It removes dissolved hydrogen and nonmetallic impurities by means of a spinning nozzle, which distributes a fluxing gas in the melt in the form of small

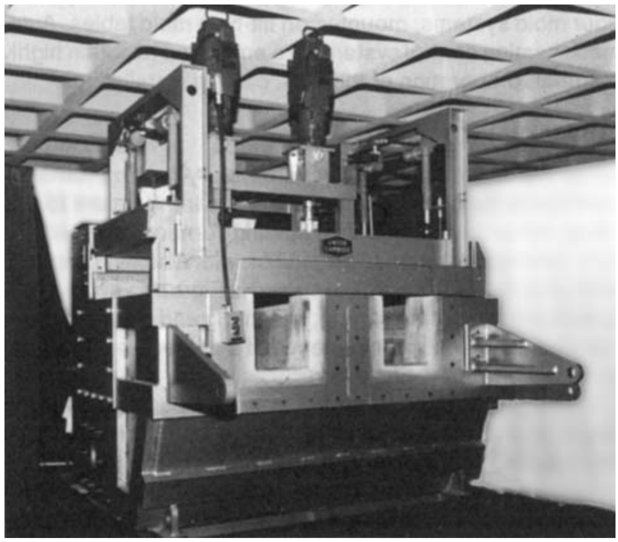

Fig. 6 SNIF degassing system. Source: Ref 1

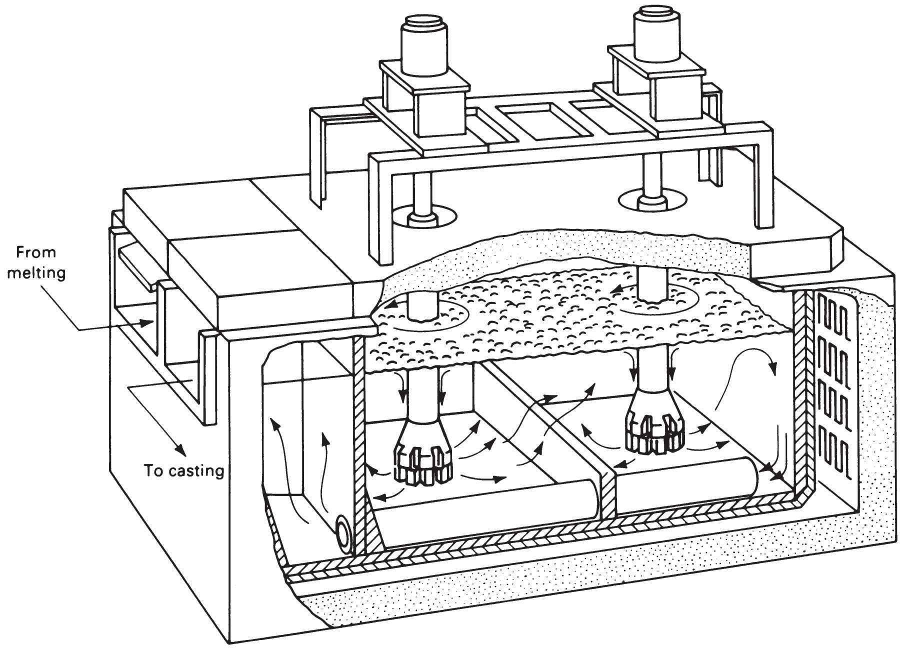

Fig. 7 Schematic of spinning nozzle in SNIF degassing system. Source: Ref 10

gas bubbles. The gas is usually an inert gas (argon) or a mixture of argon and chlorine. For safety reasons, an exhaust processing system must be strictly provided for the chlorinating process. Chlorine is the most efficient gas for degassing molten aluminum.

Grain Refining

In aluminum billet casting, the goal is to get a fine equiaxed grain structure. The different type of grain structure is shown in Fig. 8. The type and size of grains formed in billet casting are determined by many factors, including alloy chemistry, solidification rate, and the addition of grain refiner. Grain refiner improves the casting process by minimizing shrinkage, hot cracking, and hydrogen porosity. Finally, the cast grain refined billets result in extrusion with improved mechanical properties, response to thermal treatment, appearance of extrusion in chemical or electromechanical finishing, and increased resistance to surface tearing. The most widely used grain refiners are master alloys of titanium and boron or titanium and boron in aluminum. More detailed information about fluxing and grain refinement is discussed in Ref 10. A commitment to excellence requires standardization, that is, quantitative methods of measuring the quality of processes and materials. One extruder has designed a companywide program to evaluate the quality of grain refiners (Ref 11). The addition of rare earth elements is proposed as a method to improve grain refiner efficiency (Ref 12).

A typical example of a photomacrograph of transverse cross sections of the ten 7016 alloy billets showing the billet surface and internal grain structures is shown in Fig. 9. A band of large grains can be observed at

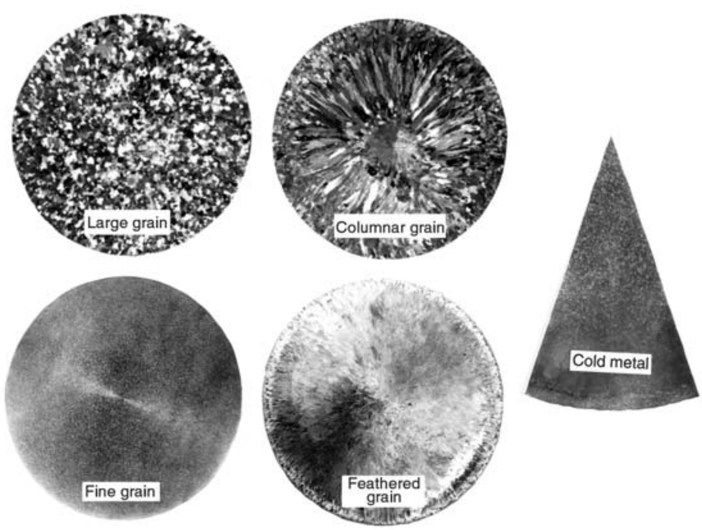

Fig. 8 Different grain structure formed in billet casting

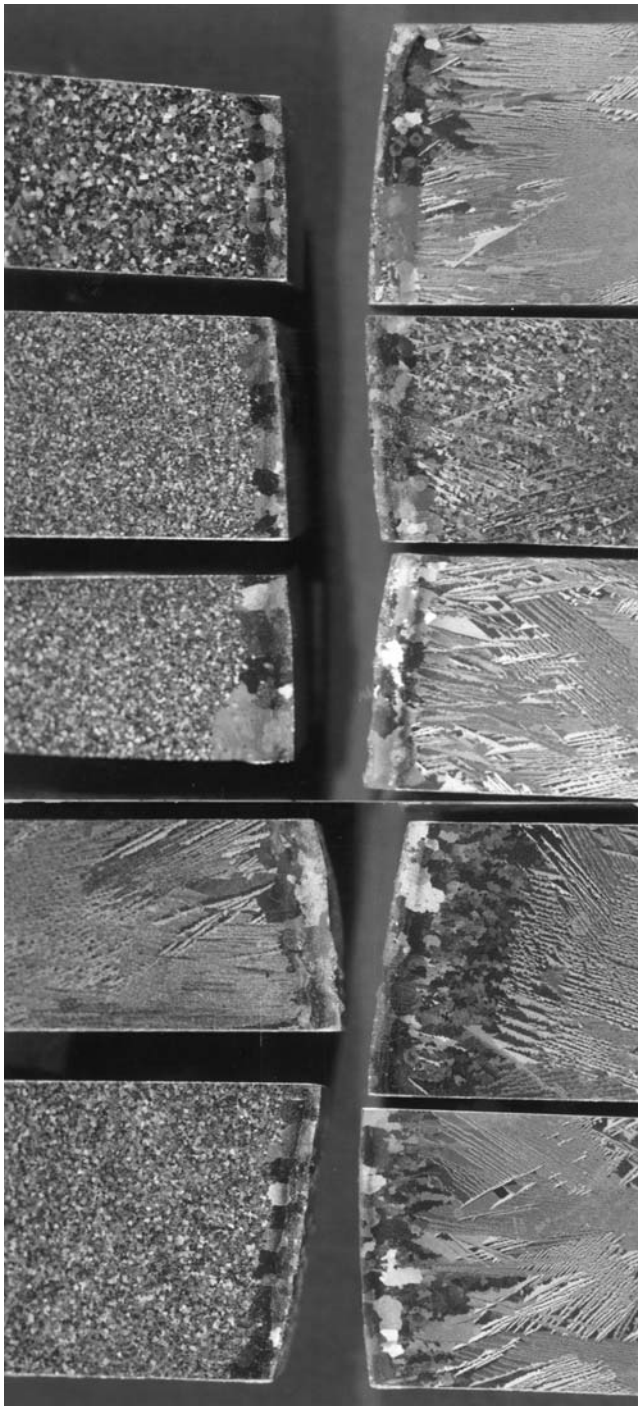

Fig. 9 Effect of grain refiner on grain structure (magnification 1.2×)

the surface regardless of the casting mold (either graphite or composite) that was used. Determination of the actual liquated zone becomes difficult because the depth of liquation varies within the band of large grains. It is quite significant that the billet cast using a Ti grain refiner has a fine equiaxed grain structure compared with the casting without the grain refiner having a coarser, feathered grain structure.

Filtration System

Aluminum alloys have a high tendency toward oxidation and contain nonmetallic inclusions. Inclusions could cause deterioration of physical, mechanical, and electrical properties of the alloy. Filtration is the heart of quality of the billet. Filtration is an on-line process that occurs just before the molten metal goes to the casting unit for pouring into the mold. In filtration, the molten metal flows through the porous filtering devices, and the inclusions are trapped by the filtration system. The selection of filter material is an important issue. Filter material must satisfy strength, refractoriness, thermal shock resistance, and corrosion resistance so that it performs its purpose. There are various types of filters used in the casting process, such as metal or fiber glass screen, rotary degassing, bed filters, bonded particle filters, cartridge filters, and ceramic foam filters. In casting, filter selection will depend on ease of use, economics, space constraints, auxiliary metal treatment capabilities, desired filtration efficiency, and end-product application. Ceramic foam filters are commonly and successfully used in the current process. Ceramic foam filters were developed by Selee Corporation to filter molten aluminum in 1974. Now ceramic foam filter technology is the primary and preferred method to filter commercial aluminum alloys throughout the world. There are several types of solid-phase inclusion (Ref 10) in molten aluminum alloys:

- Oxides (Al_2O_3, MgO)
- Spinels (Mg_2AlO_4)
- Borides (TiB_2, VB_2, ZrB_2)
- Carbides (Al_3C_4, TiC)
- Intermetallics ($MnAl_3$, $FeAl_3$) (expected and desired in fine distribution and considered inclusions if present in large primary phases)
- Nitrides (AlN)
- Refractory inclusions

Selee ceramic foam functions as a deep-bed filter where the bulk of the inclusion particles retained are smaller than the pore size opening and, therefore, retained through the depth of the filter structure as shown in Fig. 10.

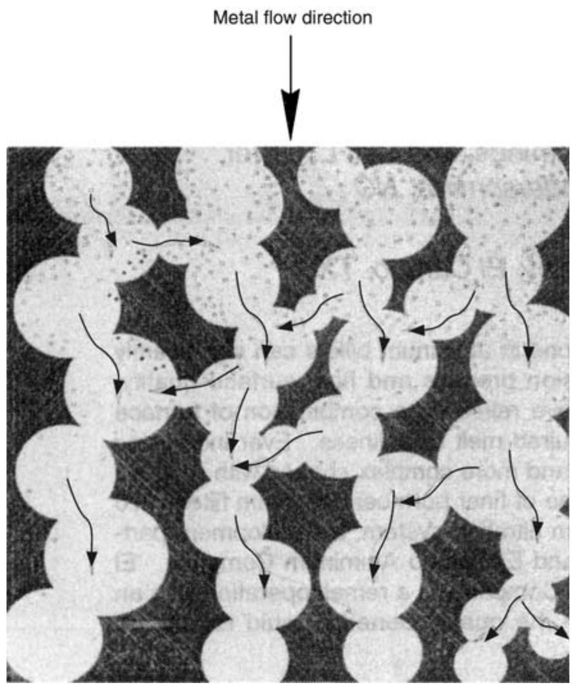

Fig. 10 Schematic of the Selee ceramic foam filter mechanism. Source: Ref 13

Vertical Casting System

The hot-top level pour casting system is the recent trend to replace the earlier downspout tube and float systems of metal flow control. In level pour units, liquid metal flows directly from the furnace launder via a large distribution pan made with special asbestos-free refractory material into the water-cooled molds as shown in Fig. 11. In the distribution, when the equilibrium condition is reached, there is a minimum fluctuation in the metal level of the distribution pan, and turbulence is greatly eliminated. Oxides remain at the top of the metal pan, and the flowing aluminum feeds individual molds to form billets by underpouring. The number of molds for a given casting machine depends on many factors, including machine platen size, the mold cooling water system, and the capacity of the hydraulic driving unit.

Developments continued in the design of molds to obtain a billet surface of optimal quality. The latest developments in mold design have been directed toward the reduction of heat transfer through the cooled mold wall so as to improve the surface and subsurface of the billet quality, including the extrudabilty of the billet. Common mold designs now available in the billet casting industries are AirSlip (United States), Air Veil (Germany), and Showa Process (Japan). In addition, most of the large aluminum producers have developed their own billet casting mold systems.

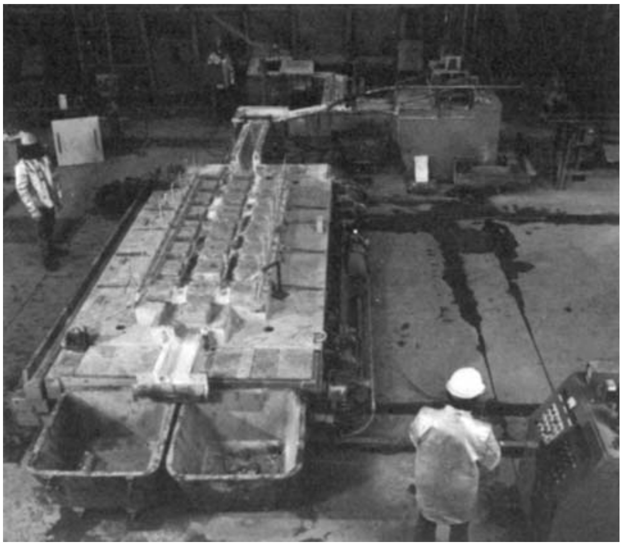

Fig. 11 Hot-top level pour system. Source: Ref 1

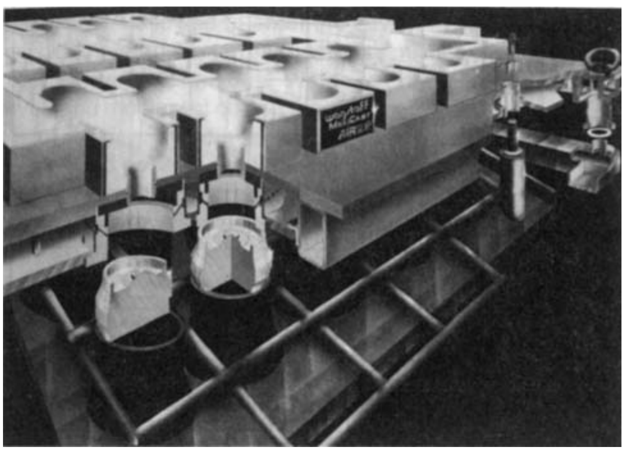

Fig. 12 MaxiCast hot-top system with AirSlip molds. Source: Ref 3

MaxiCast hot-top concept is shown in Fig. 12. The AirSlip (Ref 14) mold technology was introduced in 1983 and added as an option to the MaxiCast equipment to produce excellent surface and microstructure properties. The AirSlip technology uses a short mold length with a permeable graphite ring as the casting interface. During the cast, a process gas with minute amounts of oil form an air bearing, which insulates and separates the molten metal from the mold. This air bearing generates a smooth outside billet surface with minimum subsurface segregation (liquation). In general, the mold length increases as the billet diameter increases or the casting speed decreases. With the air bearing principle, a given mold diameter can accommodate a rather wide range of casting

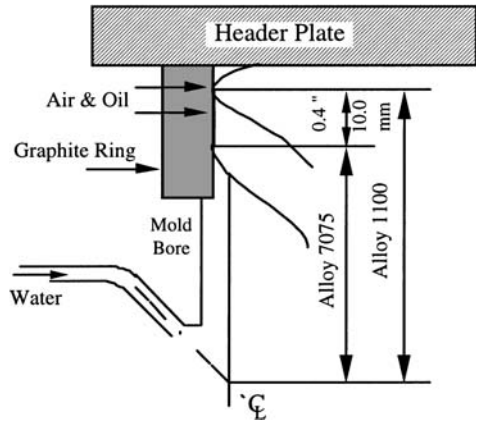

Fig. 13 Principle of AirSlip mold. Source: Ref 3

Fig. 14 AirSlip as-cast 2017 billet surface. Source: Ref 3

speeds and freezing range variations compared with other mold technology (Fig. 13).

A wide range of alloys is being produced commercially with AirSlip technology, including alloys from 1100 to 7150. Surface appearance is influenced by the composition being cast (Ref 14). A typical example of 412 mm (16.5 in.) AirSlip as-cast 2017 billet surface is shown in Fig. 14. AirSlip casting technology offers an important advantage to produce both small and large diameter billets. The shallow liquation (oxide) zone on the billet outer surface means that less material needs to be scalped on an indirect extrusion billet. The inverse segregation zone is restricted to 1 mm (0.04 in.) for all alloys. Brock and Avery (Ref 15) discussed the successful production of high-strength aluminum alloys (2000 and 7000 series), especially for the aircraft industry, using the MaxiCast system.

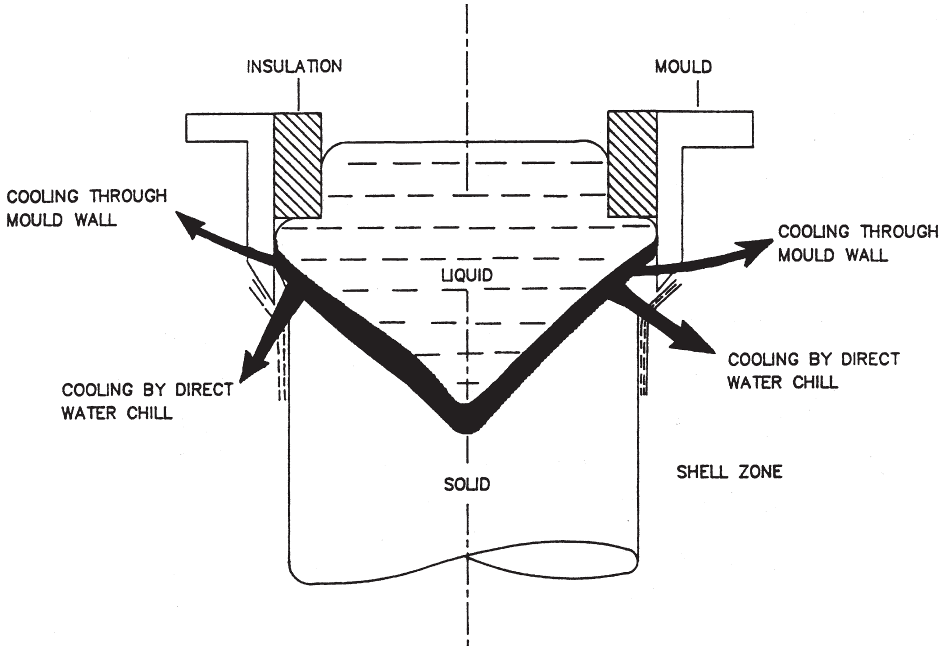

Fig. 15 Modular insulated mould system. Source: Ref 2

Auchterlonie et al. (Ref 2) described another successful modular mold system used for casting aluminum billets with wide varieties of alloys and billet diameters with rapid table and mould change features. A typical insulated modular mould system is shown in Fig. 15. The cooling through the mould wall is reduced by the insulation, which is present. As a result, this system provides smooth billet surface with a thin shell and uniform microstructure.

Horizontal Casting System

Vertical semicontinuous casting produces most of the extrusion billets today. In 1989, one Japanese company successfully developed high-speed horizontal continuous casting of 6063 alloy billets in 7 in. (178 mm) and 9 in. (230 mm) diameters. Casting speeds are nearly tripled compared with those of conventional DC casting. Whatever process of billet making is used, worldwide market requirements of aluminum alloy billet quality are of the utmost importance. The quality requirements for billets have concentrated on chemistry, dimensional tolerances, billet surface quality, shell zone, and billet homogenizing. Figure 16 shows a view of a horizontal continuous casting line developed in Japan (Ref 16). The sequence of operation in a horizontal casting system is shown in the flow diagram in Fig. 17.

During casting, the liquid region in the billet head near the mold is called the sump. The depth and shape of the sump greatly influence the

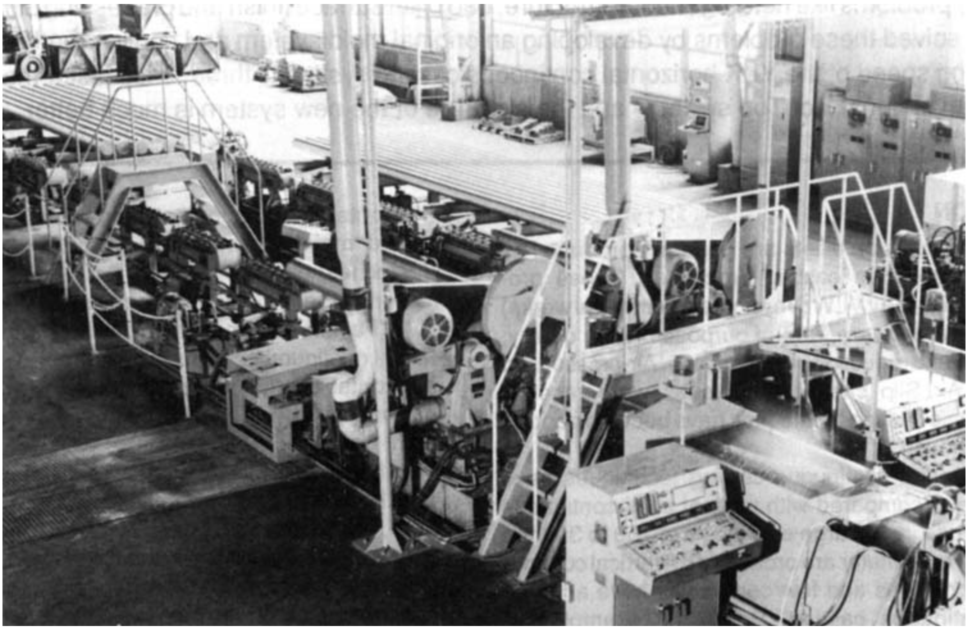

Fig. 16 View of horizontal casting line. Source: Ref 16

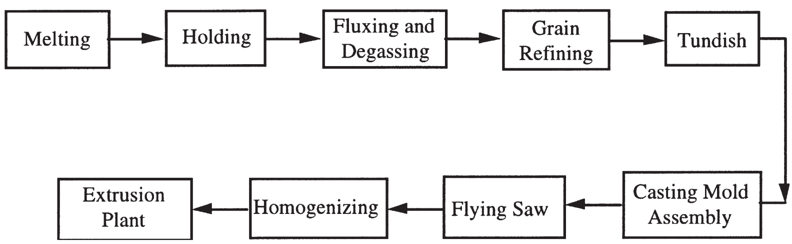

Fig. 17 Flow diagram of horizontal casting system

billet structure and the formation of center cracks in the billet. The sump depth is determined by the casting speed, cooling condition, and the mold system, which means it is dependent on the heat transfer during solidification. In the Wagstaff AirSlip (Ref 14) technology, lubricant and compressed gas exist between the mold wall and the solidified shell. The heat conduction through the mold wall decreases, and heat is extracted in the direction of casting. When the sump depth becomes half of the billet diameter, a good surface finish is obtained. Figure 18 shows the sump shape in a continuous horizontal casting of 6063 billet. Arase et al. (Ref 16) found a correlation between casting speed and sump depth. Sump depth increases with the increase of casting speed. The macrostructure of the 9 in. (239 mm) diameter billet is shown in Fig. 19. It is homogeneous and consists of fine granular grains.

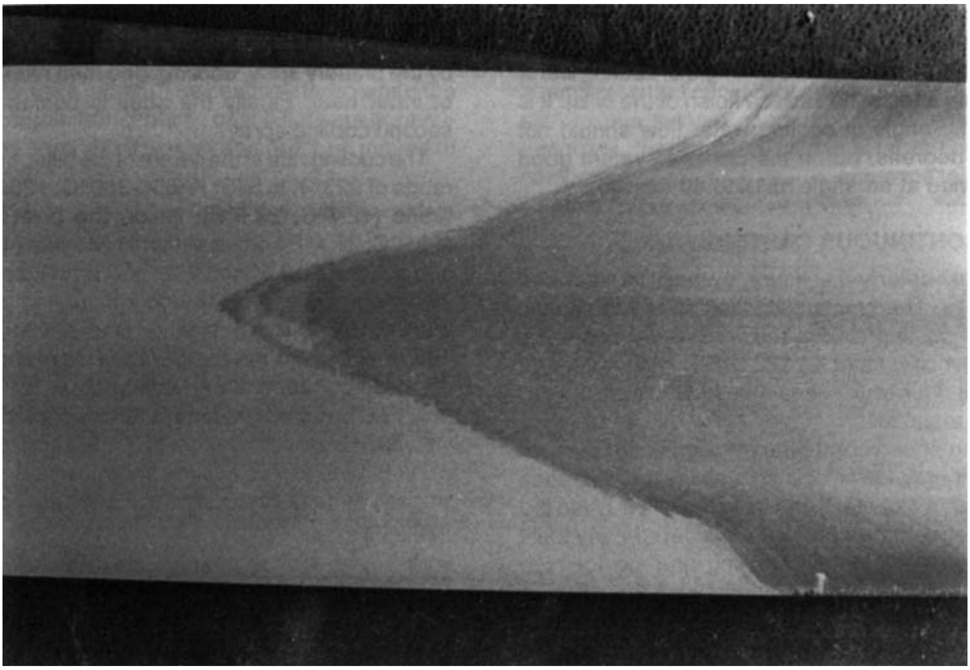

Fig. 18 Sump shape and depth of 6063 billet. Source: Ref 16

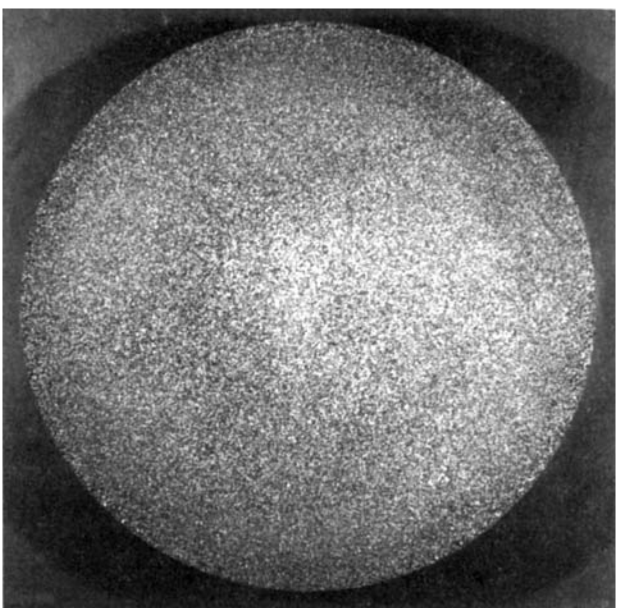

Fig. 19 Macrostructure of a 6063 billet. Source: Ref 16

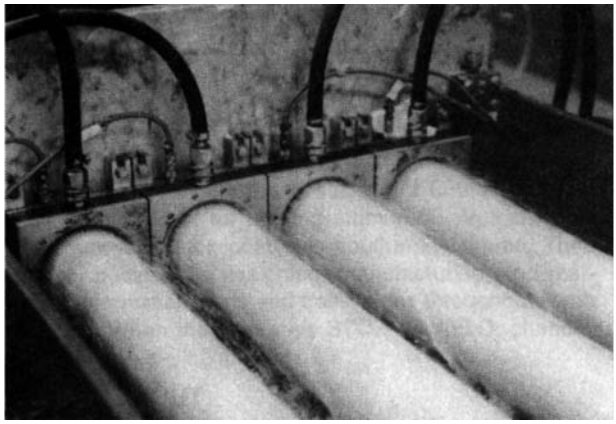

Fig. 20 Continuous horizontal casting of billet. Source: Ref 17

In Austria, a horizontal DC casting technology (Ref 17) was also developed to produce foundry ingots, forging rods, bus bars, and extrusion billets, including a flying billet saw and continuous homogenizing. This small-scale horizontal DC casting process is shown in Fig. 20. The horizontal casting process has the flexibility to produce oval-shaped billets for rectangular container extrusion for a wider section with the same horizontal caster.

Homogenization of Billet

Cast billets or logs are usually homogenized before extrusion. The as-cast condition gives a product of unsatisfactory quality and has a lower workability for the following reasons (Ref 18):

- Grain-boundary and dendritic cell segregation, low-melting-point eutectics, and brittle intermetallic compounds reduce the workability of the metal.
- Supersaturated solutions of finely dispersed precipitates of the alloying components (e.g., Al_6Mn, AlFeMn, and Mg_2Si) increase the high-temperature flow stress and, thus, reduce the workability.
- Certain alloying elements, including manganese, iron, and zirconium, either in solution or as finely dispersed precipitates, retard recrystallization. This effect is of particular significance in the extrusion of AlMgSi(Mn) alloys for color anodization and also if the extrusion effect is to be used.
- Precipitated Mg_2Si in AlMgSi alloys during cooling after continuous casting reduces the hardenability of the extruded sections and impairs the finish of bright-finish alloys.

- Grain-boundary segregation (i.e., variations in the concentration of dissolved alloying elements) results in a streaked texture after anodizing.
- Heterogeneous grain- and cell-boundary precipitation give structural markings and, in unfavorable dispersions, reduce the quality of the finish of bright-finish sections.

These effects can be partly or completely eliminated by heat treatment homogenization of the cast billets. However, the purpose of the billet heat treatment varies according to quality and economic requirements and can involve dissolution, precipitation, or uniform distribution of the alloying components. The choice of homogenization, heterogenization, or a combined heat treatment depends on each individual case.

Homogenization comprises three major steps, heating billet logs with a particular rate, holding a constant temperature for a certain time, and cooling with a proper cooling rate. In the homogenization cycle, the cast logs are held at an elevated temperature for a specific time span. At elevated temperatures, diffusion is enhanced, and any concentration gradients within the alloy are diminished. The controlling factor in the homogenization of an alloy is thus the diffusivity of the respective alloy elements present at the homogenization temperature. The higher the homogenization temperature is, the faster homogeneity can be obtained and, thus, the more efficient this practice becomes in terms of industrial throughput. The homogenization temperature, however, should not exceed the lowest melting point phase temperature in the particular alloy, which results in localized melting. This melting could cause microstructural damage of a type that cannot be repaired subsequently. This damage consists of excessive void formation, segregation, blistering, and cracking. Cooling of logs after homogenization is very important to get the good microstructure to improve the productivity as well as the final mechanical properties of the extrusion.

Dahl et al. (Ref 19) studied the effects of cooling rate and microalloying with manganese (Mn) on the precipitation of Mg_2Si in 6063 alloys during cooling from homogenization temperatures. The amounts of Mg and Si in solid solution, and hence the amount of Mg_2Si precipitated, are highly affected by the cooling rate from the homogenization temperature. As expected, decreasing the cooling rate was found to increase the precipitation of Mg_2Si and decrease the amount of Mg in solid solution. A fast cooling rate showed the opposite result. Mn additions up to 0.027% have no effect on Mg_2Si precipitation.

Log cooling after homogenizing has begun to play an important role in homogenization. Mahoney (Ref 20) presented an improved method, which increases the cooling rate and uniformity of cooling for the entire load of logs. He also described the design details, performance, and sequence of operation.

Jackson and Sheppard (Ref 20) described the microstructural changes that occur within 7*xxx* alloys during homogenization. They studied the effect of homogenization heating rate, hold time, and cooling rate upon structure.

Reiso et al. (Ref 22) found lower mechanical properties in extruded sections from billets that were water quenched after homogenization compared with billets that were air cooled after homogenization from full-scale industrial extrusion experiments of an AlMgSi alloy. They also found that the mechanical properties of the billet section from the water-quenched billets are much higher compared with those from the air-cooled billets.

Oka et al. (Ref 23) studied the effects of homogenization and microstructure on the productivity of round-tube extrusion. Anderson (Ref 24) did an excellent review on physical metallurgy and extrusion of 6063 alloy. He covered the important aspects on chemistry, heat treatment, casting considerations, homogenizing process, billet reheating, extrusion process, and aging cycle.

Cook and Musulin (Ref 25) developed a model of airflow within a homogenizing furnace using a finite volume computer code and studied the effects of variations in homogenization on microstructure and subsequent processing. Variability in homogenizing furnaces can result in inadequate homogenization or, in some cases, excessive homogenization. One of the examples of high-temperature homogenization on microstructure of 7.95 in. (202 mm) diameter 6063 billet is shown in Fig. 21.

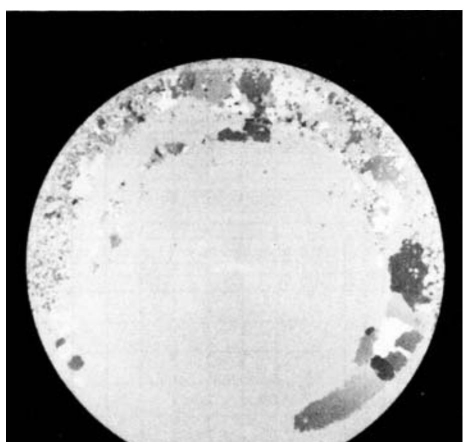

Fig. 21 Grain growth in high-temperature homogenization. Source: Ref 25

Garcia and Hertwich (Ref 26) described the continuous homogenizing system installed with the continuous horizontal casting unit. The continuous furnaces have only one layer compared with the multilayers in batch furnaces. The billets move continuously through the furnace by means of a walking beam system. In continuous type homogenizing, every billet receives exactly the same temperature and time for the heat treatment. With a batch furnace, however, some dispersion in the heating and holding time is unavoidable between the hot side and the cool side of the load.

Improved operating efficiencies of log homogenizing furnaces have been the demand of many extruders. Alabran (Ref 27) discussed the methods of minimizing heat loss, maximizing the fan motor control, fuel efficiencies for direct fired burners, and adjustable baffle techniques. He also mentioned case histories of a homogenizing furnace survey that described fuel consumption and methods to improve the heat transfer rate by controlling air flow.

Typical values for billet heat treatment parameters of some aluminum alloys are given in Table 1.

Billet Scalping. Scalping of the billet means the machining of the liquated skin of the billet generally for harder alloys and also for wider sections of softer alloys where the circumscribed circle diameter (CCD) of the die is very close to the container bore. For harder alloy extrusions, especially for the indirect process where there is no relative displacement between billet and container, the machined billets are being used. Generally, the skin surface of harder alloys are much harder than those of softer grade alloys. It is always recommended to use the machined billets for harder alloy extrusions, for the best quality of extrusion, especially in the aerospace industries.

Table 1 Typical values for billet homogenizing of some aluminum alloys

Alloy	Homogenizing temperature, °F (°C)	Holding time (min), h
1060	1040–1076 (560–580)	6
1100	1076–1112 (580–600)	6
2014–2024	896–914 (480–490)	12
5052	1022–1040 (550–560)	12
5083, 5086	968–1004 (520–540)	12
5454, 5456	1022–1040 (550–560)	12
6061	1040–1058 (560–570)	6–8
6063	1040–1076 (560–580)	6
6101	1040–1076 (560–580)	6
6463	1040–1076 (560–580)	6
7001	860–896 (460–480)	12
7075, 7079	878–896 (470–480)	12

Casting Defects

The objective of the DC casting process is to produce quality billets of uniform chemistry, fine metal structure, and strength. The common problems or defects associated with DC casting billets are as follows:

- Cracking and splitting
- Segregation
- Bleeding
- Cold shutting
- Porosity
- Grain growth

Cracking and Splitting. In the solidification system, metal starts freezing from the outer skin to the center of the mold because the outer skin is being cooled by the water flow. After the outer shell has contracted upon freezing, the inner metal tries to contract as it freezes. Because of the difference in the contraction from the skin to the center of the ingot due to the difference in temperature gradient from skin to the center, internal thermal stresses develop. The internal stress causes cracks (Fig. 22) when these stresses exceed the tensile stress limit of the alloy being cast. Alloys most likely to crack or split are AlCuMg, AlZnMgCu, and, sometimes, AlMgSi. Slower casting with lower possible temperature minimizes this problem.

Segregation. Ingot structure is one of the origins of streak defects in aluminum extrusion. Surface segregation or a shell zone present in the

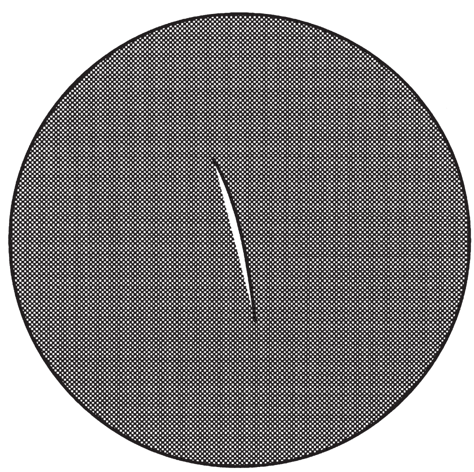

Fig. 22 Schematic showing the center crack

billet microstructure as shown in Fig. 23 could occur during the early stages of solidification during DC casting and are located in the billet peripheral zone.

In inverse segregation, the high concentration of lower melting temperature constituents is found at the outer surface of the billet. The main factor causing the inverse segregation is the shrinkage of the alloy during solidification. During solidification, the liquid metal at the center of the billet, which has a high concentration of low-melting temperature constituents, is forced by the pressure of the metal above it to fill the gaps left in the solidified metal at the outer portions of the billet due to shrinkage. In aluminum alloys, the solidification shrinkage is about 6%. Inverse segregation is present at the surface of practically all extrusion billets to some degree, and a typical example is shown in Fig. 24. The depth of this region is normally 100 to 200 μm and contains coarse, iron-rich intermetallic and can be solute rich in magnesium and silicon.

Bleeding. Bleeding is a casting defect named to describe a flow of molten metal along the solidified outer billet surface. It is the result of remelting through the thin solidified shell of the billet and is caused by hot liquid metal at the center. Normally, bleeding is due to casting at higher speeds.

Cold Shutting. Cold shut in the billet surface appears as a wrinkle on the outer billet surface. The wrinkle may be as deep as 0.125 to 0.25 in. (3.2 to 6.4 mm). Cold shuts result from casting at relatively slow speeds followed by rapid cooling. In DC casting, the billet must be cast at a fast

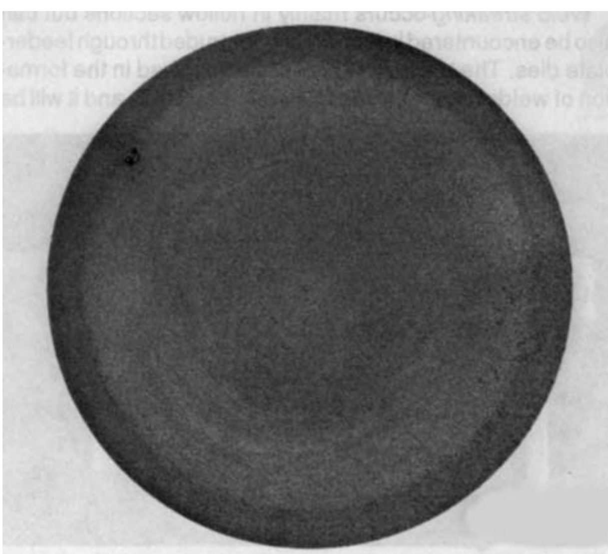

Fig. 23 6063 anodized billet showing shell zone. Source: Ref 28

speed to avoid cold shutting but cast slowly enough to avoid splitting, bleeding, and liquation. Liquation is applied to the process where the elements with low melting point ooze to the outside surface of the billet. Liquation occurs by the same process as inverse segregation in combination with freezing and partial remelting of molten aluminum with the cold mold surface.

Porosity. A typical example of porosity found in a 6463 billet is shown in Fig. 25. Photomicrographs are prepared from the billet cross sections taken in three different positions of the billet near the left surface, center, and right surface, respectively.

Another example of a 6063 billet showing the relative gross porosity, including underlying blisters, had significantly larger voids (Fig. 26). It is also evident that there is no great amount of second phases in the liquation zone compared with the internal structure shown in Fig. 27. Figure 27 shows the fine triple-point porosity.

Grain Growth. Figure 28(a) shows evidence of selective grain growth that is slightly different from Fig. 28(b). In both cases there is evidence of growth in the columnar grains along the circumference of the 3105 billet. Other billet slices taken from the same cast do not show this selective grain growth (Fig. 28c), even after a second homogenization treatment. It is significant that the problem of nonuniform grain growth is transient and may be related to the location of the cast log from which this billet was obtained. This also indicates a difference in the casting condition, depending on the location of the log.

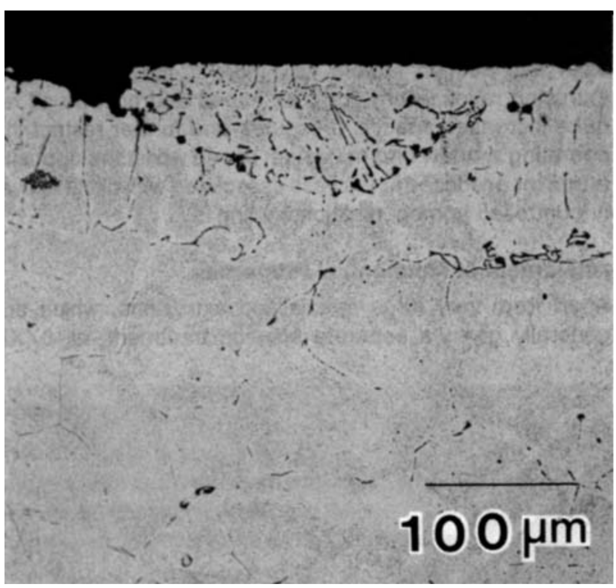

Fig. 24 Inverse segregation in 6.7 in. (171 mm) 6063 billet. Source: Ref 28

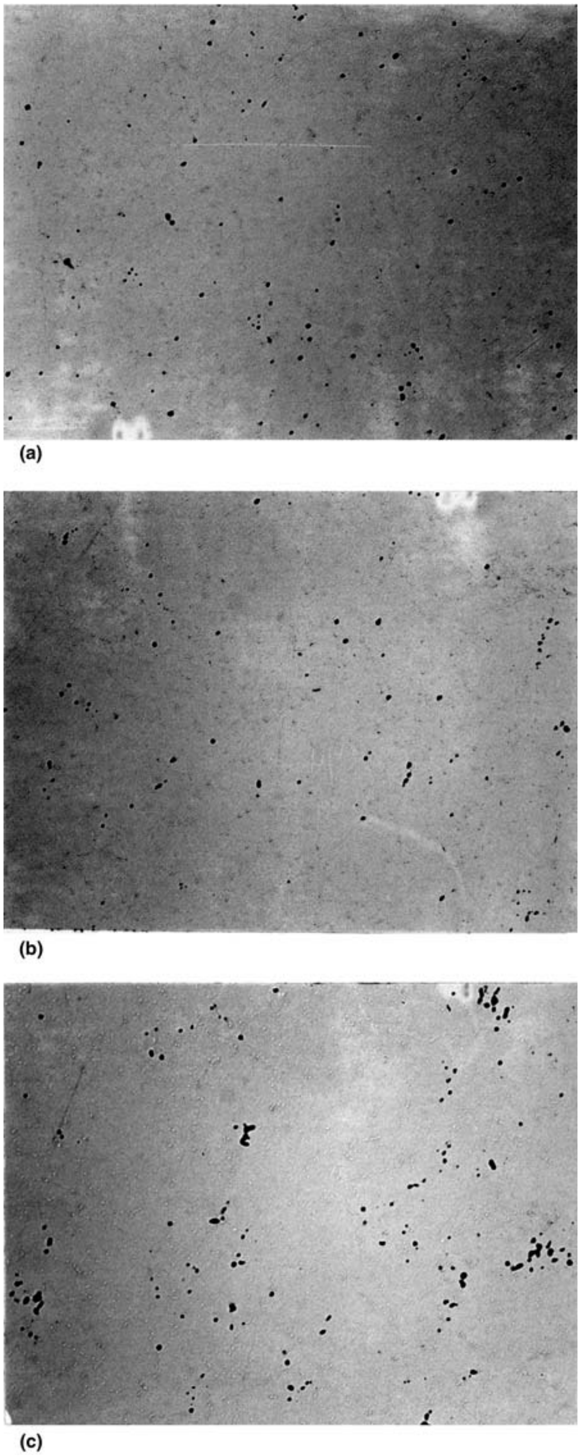

Fig. 25 Porosity in 6463 billet at three different positions (magnification 50×). (a) Left surface. (b) Center. (c) Right surface

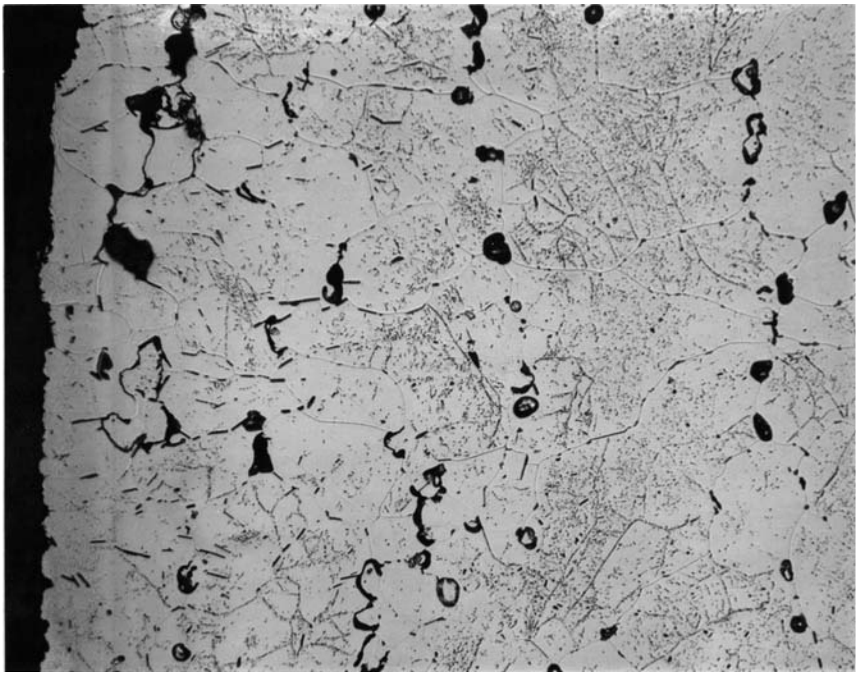

Fig. 26 Micrograph of a 6063 billet cross section at the edge with gross porosity (magnification 200×)

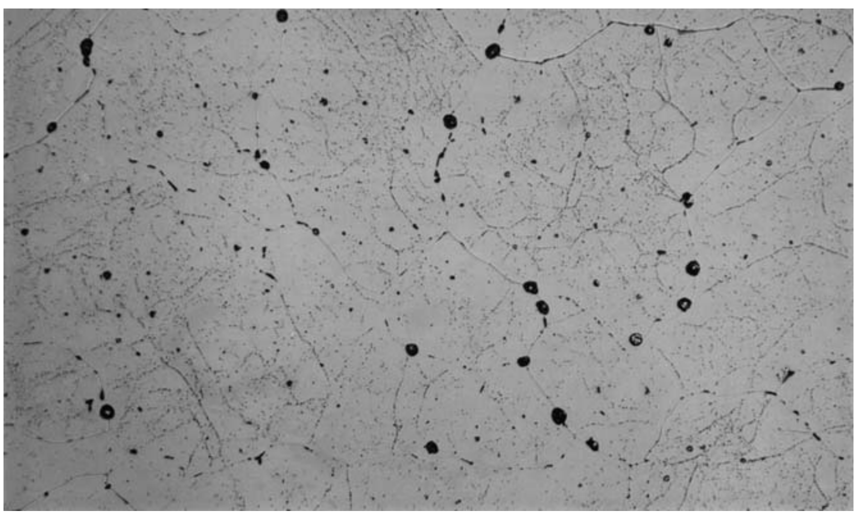

Fig. 27 Micrograph of a 6063 billet near the center with triple-point porosity (magnification 200×)

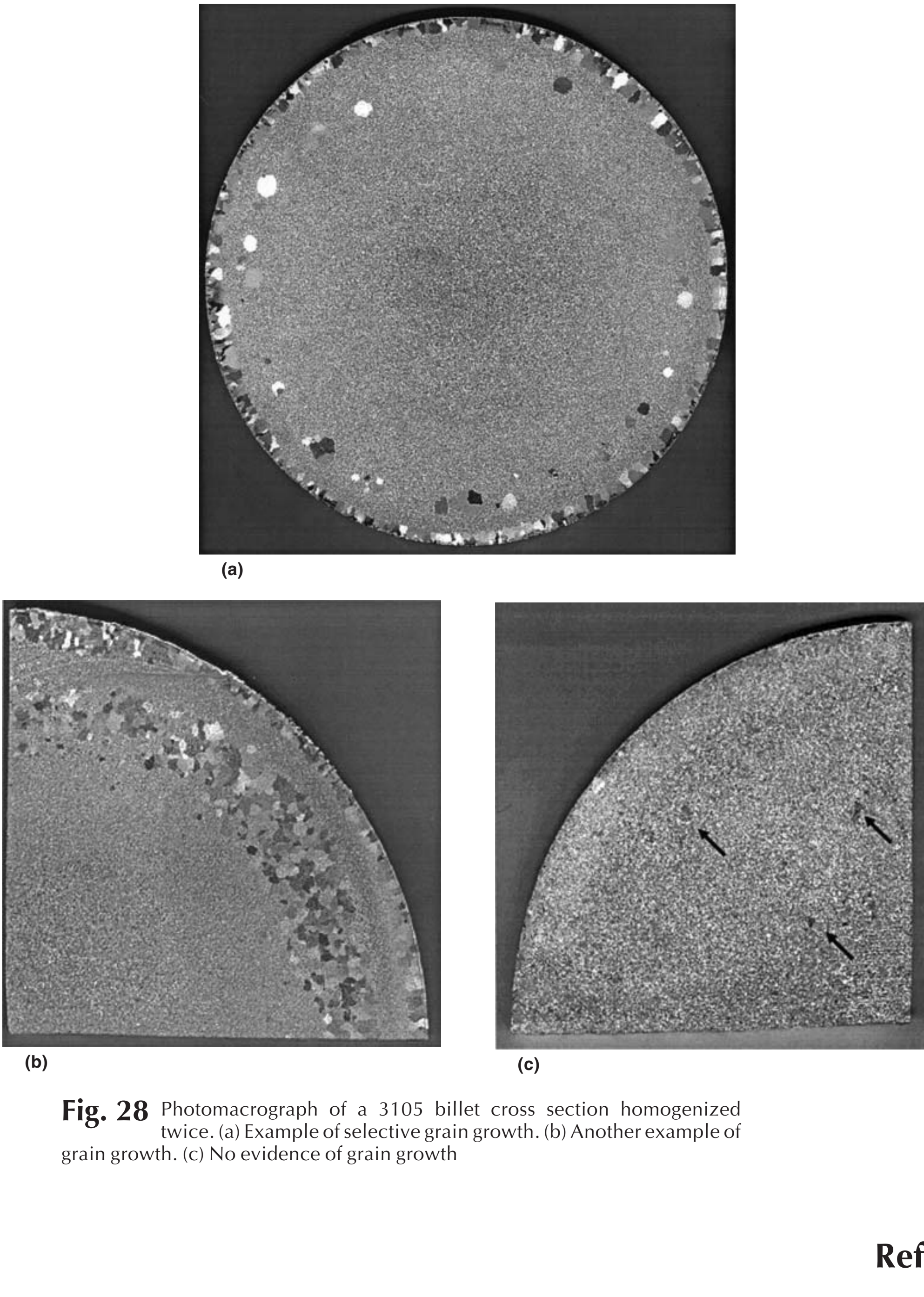

Fig. 28 Photomacrograph of a 3105 billet cross section homogenized twice. (a) Example of selective grain growth. (b) Another example of grain growth. (c) No evidence of grain growth

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CHAPTER 6

Extrusion of Soft- and Medium-Grade Alloys

Extrusion of aluminum alloy shapes represents the most advanced technology in terms of alloy making, press design, tooling, and die design. The billet chemistry determines the type of alloy and its applications. The 6000-series alloys are widely used based on their having the best technical and economic characteristics, including ease of extrudability into hollow and complex shapes, simplicity in heat treatment, good electrical conductivity, satisfactory mechanical properties, good surface finish quality, high corrosion resistance, and good weldability for a wide variety of applications. Several million tons of 6000-series alloy extrusions are produced every year. Applications include bars and rods to intricate shapes such as door and window frames, automobile trim, building structures, electrical bus bars, heat exchangers and so on. For bright finish applications required for automobile trim, alloys such as 6463 or 6763 made from high-purity aluminum (99.8%) with very low iron (Fe) content are used.

Because it is easy to work with 6000-series alloys, development of many derivatives of 6000-series alloys continues in order to fulfill the requirements of different customer applications throughout the world. Some 6000-series alloys have a higher level of alloying elements to achieve higher strength for structural and semistructural applications. In general, 6061 (Al-Mg-Si-Cu) and 6082 (Al-Si-Mg-Mn) are the most common alloys offering higher mechanical properties for structural applications. The 6061 alloy has improved toughness, an important factor in specific structural applications. These alloys respond very well during quenching and aging heat treatment and have reasonable properties

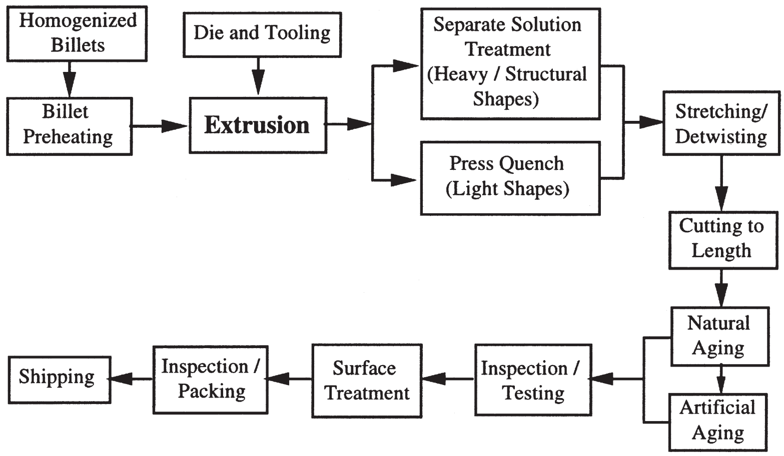


Fig. 1 Basic process of soft- and medium-strength heat treatable aluminum extrusions

in welded joint areas. In terms of corrosion and finishing, both 6061 and 6082 are excellent. They are also good for hot or cold impact forging from extruded stock.

The medium-strength alloys are classified into two different alloying combinations, Al-Zn-Mg and Al-Mg. The first, Al-Zn-Mg, is a heat treatable alloy, whereas Al-Mg is not heat treatable. Over the last 30 years, Al-Zn-Mg alloys (7020, 7005, 7003, and similar) have been used particularly for railway rolling stock bodies, load-bearing structures, and welded structures. These alloys respond well in solution heat treatment if the extrusion comes out of the press a little over 400 °C (752 °F), they have a low quench sensitivity, and they maintain good mechanical properties, even in weld-affected regions. These alloys are not recommended for extrusion of complex shapes. The alloys have a tendency for exfoliation and stress-corrosion cracking, which can be minimized by compositional and process control. The Al-Mg alloys (5052, 5154, 5254, and 5454) are also considered to be in the group of medium-strength extrusion alloys. These alloys are also corrosion resistant.

Soft- and medium-strength heat treatable aluminum extruded sections for commercial and industrial uses are generally made using the sequence of steps shown in Fig. 1. For the non-heat-treatable 5000 series alloys, the final mechanical properties of the extrusions are obtained from subsequent cold-forming operations.

Alloys and Extrudability

Extrudability, which can be measured by the maximum extrusion speed, is one of the most significant factors influencing cost and efficiency of the

Table 1 Extrudability ratings of soft- and medium-grade alloys

Alloy designation	Type	Major alloying elements	Relative extrudability(a)
1060	Non-heat-treatable	Al (99.6)	150
1100	Non-heat-treatable	Al(99), Cu	150
3003	Non-heat-treatable	Mn, Cu	100
5052	Non-heat-treatable	Mg	80
5154	Non-heat-treatable	Mg	50
5254	Non-heat-treatable	Mg	50
5454	Non-heat-treatable	Mg, Mn	50
6061	Heat treatable	Mg, Si, Cu	60
6063	Heat treatable	Mg, Si	100
6066	Heat treatable	Mg, Si, Cu, Mn	40
6101	Heat treatable	Mg, Si	100
6463	Heat treatable	Mg, Si	100

(a) 50–150, easy to extrude; 30–50, moderately difficult to extrude. Source: Ref 5

extrusion process. Temperature and speed parameters, together with the state of stress in the deformation zone, mainly in the die region, play a significant role in improving extrudability of a given alloy. The most well-known and frequently cited work on extrudability of AlMgSi alloys was written by Mondolfo et al. (Ref 1, 2). A simple, practical method of extrudability testing is to vary extrusion ratios while holding other process parameters unchanged, the maximum extrusion speed without cracks being the measure of extrudability. Zasadzinski et al. (Ref 3) studied improved extrudability (as measured by maximum exit speed) through the control of deformation geometry and accurate selection of temperature and speed process parameters. The advantage of the approach is its practicality. They used an inexpensive method by changing the die design using a direct extrusion press and developed an algorithm for calculating the optimum temperature and speed conditions for a given extrusion.

Reiso (Ref 4) investigated billet preheating practices in an industrial environment for two different AlMgSi alloys to determine extrudability. It was shown that extrudability, as well as the mechanical properties and surface quality, may be significantly improved by using billet preheating practices different from accepted normal production practices. At high billet temperatures, a sharp increase in extrudability was recorded (30% and 60% for the two alloys investigated), and a further gain in extrudability was obtained by homogenizing the billets, followed by cooling into the normal temperature range, prior to extrusion. The obtained increase in the extrusion speed was found to be alloy dependent. Furthermore, the extrusions with the highest extrusion speeds also had better mechanical properties and improved surface quality compared with those from billets heated directly in the normal preheating temperature range.

The relative extrudability ratings of some soft- and medium-grade alloys are given in Table 1. The alloys are classified into three different groups according to their extrudability (Ref 5):

Table 2 Aluminum alloys commonly used for various extruded products

Extrusion shapes	Aluminum alloys
Tubes and pipes	1060, 1100, 2014, 2024, 3003, 5083, 5086, 5154, 5454, 6061, 6063, 6351, 7075
Architectural shapes	6063, 6061
Aircraft shapes	2014, 2024, 7075, 7178
Structural shapes	5083, 5086, 6061, 6063, 6351, 7004
Electrical bus conductors	6101, 1350

Source: Ref 6

- *I, Alloys easy to extrude:* pure aluminum, AlMn, AlMg1, AlMgSi0.5, and AlMgSi0.8
- *II, Alloys moderately difficult to extrude:* AlMg2-3, AlMgSi1, AlZnMg1
- *III, Alloys difficult to extrude:* AlCuMg, AlCuMgPb, AlZnMgCu, AlMg > 3% Mg

Alloys under groups I and II are considered to be soft- and medium-grade alloys. Alloys under group III have lower extrudability ratings that are discussed in Chapter 7.

The alloys generally used for the principal types of extruded aluminum products are listed in Table 2.

Product Shapes and Sizes

In the 6000 series, some alloys (e.g., 6063, 6101, and 6463) have higher extrudability ratings, allowing extrusion into very complex shapes (Fig. 2). Product shapes and sizes are defined by their geometric configuration. Based on the geometry, the following parameters are commonly used in defining the shapes and sizes of extrusions:

- Cross-sectional area of the shape
- Perimeter of the shape
- Diameter of the circle circumscribing the cross section of the shape

The circumscribing circle diameter (CCD), as shown in Fig. 3, is a commonly used term and a critical factor in designing and making the extrusion die as mentioned in Chapter 4. The CCD controls the following features of the extrusion:

- Dimensional stability of the shape
- Ingress of oxide and nonmetallic inclusions
- Metal flow at the end of extrusion

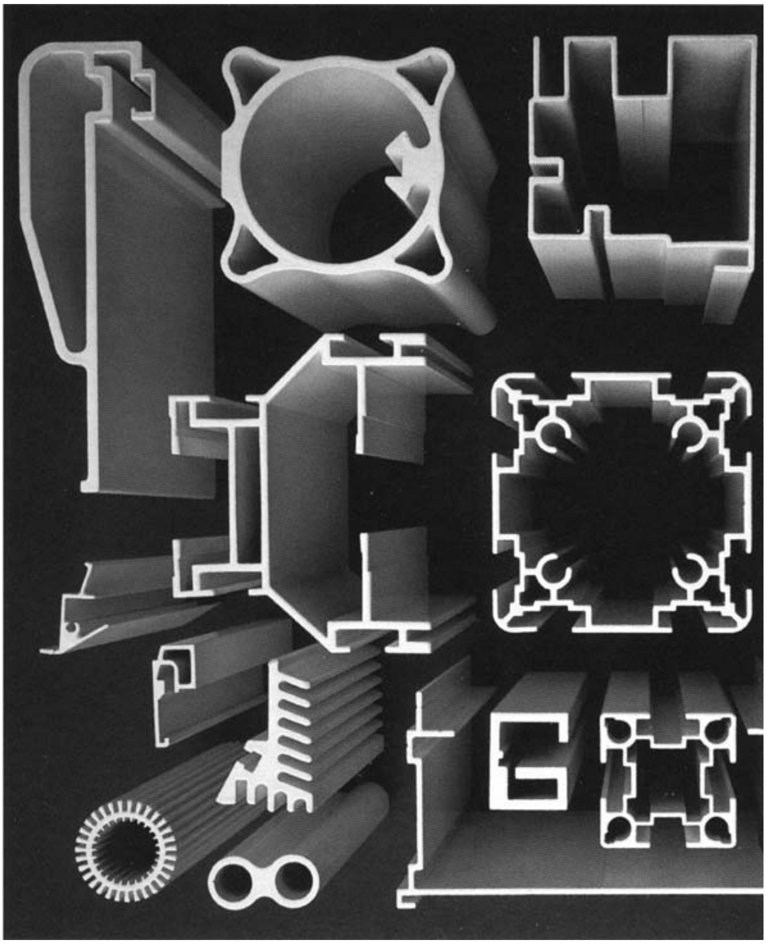


Fig. 2 Extruded aluminum shapes. Source: Cardinal Aluminum Co.

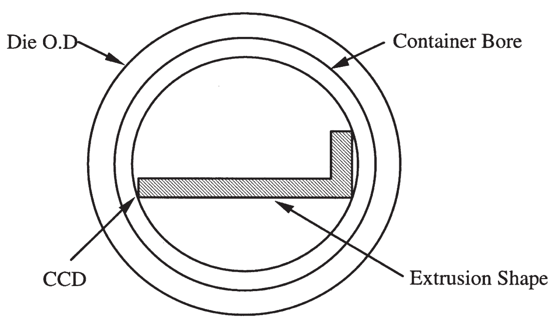


Fig. 3 Circumscribing circle diameter (CCD). OD, outside diameter

In the direct extrusion process, metal flows faster at the center than the periphery of the billet. Thus, the larger the CCD (Fig. 3) is, the more control is needed to match the metal flow in order to get dimensional stability. The greater the clearance between the CCD and the container bore is,

Table 3 Relationship between minimum wall thickness, circumscribing circle diameter (CCD), and press size for different soft- and medium-grade alloys

Alloy	Section type(a)	Minimum wall thickness, mm, at CCD: <25	<50	<75	<100	<150	<200	<250	<300	<350	<400	<450
Al99-99.5	A	0.8	1	1.2	1.5	2	2.5	2.5	3	4	4	5
AlMgSi0.5	B	0.8	1	1.2	1.5	2	2.5	2.5	3	4	4	5
AlMg1	C	1	1	1.5	2	2.5	2.5	2.5	4	5	5	6
AlMn	C	1	1	1.5	2	2.5	2.5	2.5	4	5	5	6
AlMgSi1	A	1	1.2	1.2	1.5	2	2.5	3	4	4	5	6
AlSi0.5Mg	B	1	1.2	1.5	2	2	2.5	3	4	4	5	6
AlZnMg1	B	1	1.2	1.5	2	2	2.5	3	4	4	5	6
	C	2	1.5	2	2	3	4	4	5	5	6	6
Press size, MN	…	10	10	10	10	25	25–35	35	50	50	80	80

(a) A, solid and semihollow sections; B, hollow sections with uniform wall thickness (including tube); C, hollow sections with varying wall thickness (one or more cavities in the section). Source: Ref 8

the higher the tendency will be for contamination from the skin of the billet or other sources to flow inside the extrusion toward the end of extrusion. The larger the CCD is, the thicker the butt required will be, to minimize waviness at the end of extrusion.

Shape Factor. Shape factor (Ref 7, 8) is used as a measure of the degree of difficulty regardless of classification into the different types of sections:

$$\text{Shape factor} = \frac{\text{Periphery of the section}}{\text{Weight per unit length}}$$

The shape factor increases with both complexity of the section and reduction of wall thickness. The shape factor affects the following:

- Production rate
- Cost of manufacturing
- Design of the dies and tooling

Laue and Stenger (Ref 8) defined and explained in more detail another term, *form factor,* for the degree of difficulty of a section. Form factor is calculated from data given in Table 3, whereby:

$$\text{Form factor} = \frac{\text{Diameter of the circumscribing circle}}{\text{Minimum wall thickness}}$$

Analysis of Useful Extrusion Parameters

In this section, some useful parameters and their relationships associated with day-to-day practices in the aluminum extrusion industry are discussed. This fundamental information could be very useful to the beginner, as well as to the person experienced in the extrusion industry.

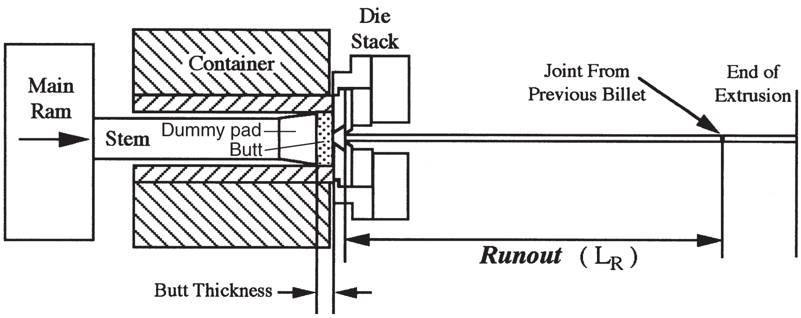


Fig. 4 End of extrusion showing runout and butt thickness

Extrusion Runout

Extrusion shapes of highly weldable alloys, such as 6063, are typically produced using a feeder plate die with a puller system, allowing continuous extrusion with higher productivity. Extrusion runout, as shown in Fig. 4, can be calculated either from the theory of volume constancy or by the actual weight measurements.

Volume constancy is defined as:

$$A_C \cdot L_B = A_E \cdot L_R \qquad \text{(Eq 1)}$$

where, A_C is the area of the container bore, and L_B is the effective billet length, given by:

$$L_B = \frac{\text{billet weight} - \text{butt weight}}{\text{weight per unit length of billet}} \qquad \text{(Eq 2)}$$

A_E is the normal area of the extrusion, and L_R is the runout length.

Therefore, the runout length is given by:

$$L_R = \frac{A_C \cdot L_B}{A_E} \qquad \text{(Eq 3)}$$

For a particular extrusion, the numerator of Eq 3 for the same container bore and billet length is constant. Therefore, the runout length is inversely proportional to the normal cross-sectional area of the product. This is an estimate based on the die print when the actual weight per unit length of the extrusion is not known. In reality, the actual area of the shape before stretching may change due to one or more of the following reasons:

- Contraction of flowing material just leaving the die bearing based on initial billet temperature and speed of extrusion
- Type and design of the die and support tooling
- Puller tension

- Thermal contraction in the cooling process on the table
- Chemistry of the alloy

Weight Measurements. In industry, the runout is calculated based on the weight of the billet, the butt, and the weight per unit length of the actual extrusion:

$$\text{Runout} = \frac{\text{billet weight} - \text{butt weight}}{\text{weight per unit length of extrusion}} \qquad \text{(Eq 4)}$$

Factors Affecting Runout. Variation of runout length has been noticed when running thin-gage 6063 alloy extrusions from the same die for the same billet length, temperature, and fixed butt thickness. The following factors can cause variation in runout length:

- Die deflection
- Extrusion ratio
- Speed of extrusion
- Number of billets run

Because of the high pressures and temperatures employed in extrusion, die faces tend to deflect. Such deflection of the die tends to close the opening, causing the profile to extrude undersized. It is observed from the variation of thickness across the profile that the deflection is greatest at the center of the die and diminishes toward the periphery. The amount of die deflection is a function of the temperature rise in the die, die design, and support tooling. The temperature rise in the die is influenced by the temperature rise in the billet during extrusion.

Saha (Ref 9, 10) studied extrusion of 6063 alloys and established that the maximum temperature in the billet during extrusion occurs at the corner or very close to the die exit. Because heat is transferring from the

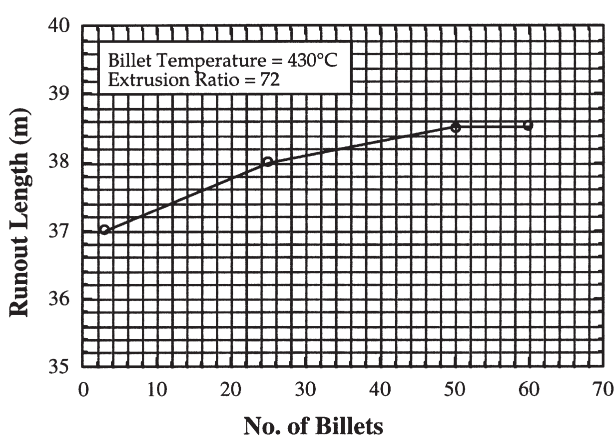


Fig. 5 Variation of runout length according to number of billets

billet to the die and tooling and, finally, to the atmosphere, the die takes a certain amount of time to reach the steady-state temperature for a given billet temperature, billet length, and extrusion ratio. At that point, the die will reach a certain hardness value. The higher the temperature rise in the die is, the lower the hardness of the die is due to the hot hardness relation of H13 hot die steel with the temperature. Due to the decrease in hardness, more deflection of the die is expected. One example of the variation in runout length due to the number of billets run is shown in Fig. 5.

It was observed that a reduction of wall thickness by 4.0% at the center of the profile will increase runout by 2.5%, according to the simple volume constancy relation (Ref 3).

Extrusion Pressure

The pressure required for extrusion is a function of many variables as discussed in the section "Extrusion Pressure" in Chapter 1. Higher extrusion ratios require higher extrusion pressure. Clearly, the parameter that determines whether the extrusion will succeed or fail to extrude is that the maximum pressure required must be within the press capacity.

Effect of Speed on Extrusion Pressure. Saha (Ref 10) experimentally studied the variation in extrusion pressure with ram speed for two different extrusion ratios. Extrusion pressure, P (from the main pressure gage of the extrusion press), for different ram speeds was measured at the same ram travel position, X, as shown in Fig. 6.

Figure 7 shows the variation in extrusion pressure with the ram speeds for two different extrusion ratios for the same 6063 billet temperature. As expected, the results show that extrusion pressure increases with the ram speed. It also shows that the higher the extrusion ratio is, the higher the extrusion pressure will be.

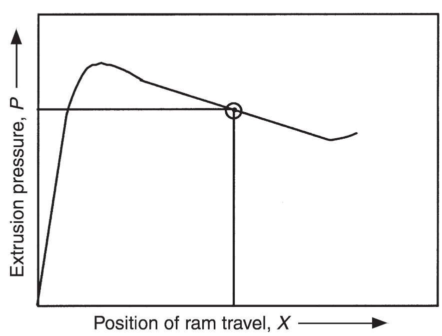


Fig. 6 Schematic showing pressures for different ram speeds collected at the same ram travel position

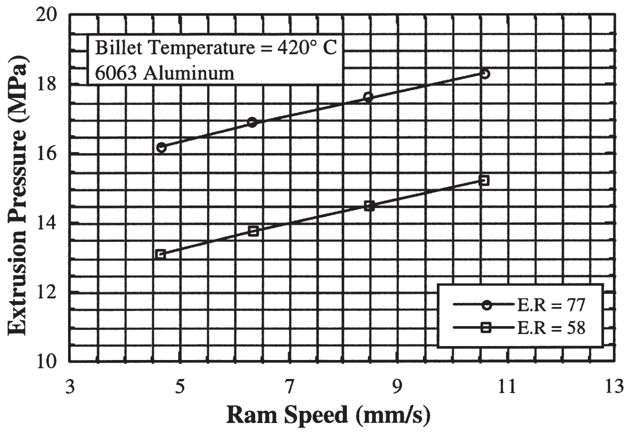


Fig. 7 Variation in extrusion pressure with the ram speeds for two different extrusion ratios

Ram and Extrusion Speed Control

Relationship Between Ram Speed and Puller Speed. Today, extrusion plants extruding 6*xxx* shapes at high productivity are using mechanical or automatic puller systems (single or double) for single or multihole dies. The pullers mounted on or above the runout table grip all the extruded sections together. The puller is close-loop linked with the press cycle, and it stops automatically when the press is stopped at any time during the extrusion process and, finally, at the end of each extrusion. The section is passed through the air or water-quenching system after it leaves the die by the puller system. There are many advantages to using a puller system:

- Mechanical pulling to reduce labor and to increase production
- Reduce the amount of scrap
- Helps control metal flow through the die
- Helps cut the extrusion in multiple lengths without stopping the press

Figure 8 shows the variables required to explain the relationship between ram speed and puller speed. The extrusion speed without the puller tension could be written as (shown in the section "Extrusion Speed" in Chapter 1):

$$V_E = V_R \cdot ER \qquad \text{(Eq 5)}$$

where ER is the extrusion ratio, which is defined by $A_C/n(A_E)$, V_R is the ram speed, and n is the number of holes in the die. Equation 5 could be used to estimate the puller speed for a given extrusion ratio and ram

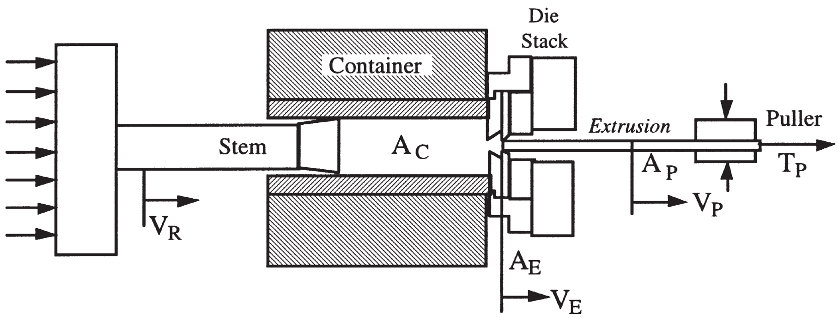


Fig. 8 Schematic showing the start of extrusion using a feeder plate die and a puller system

speed and to compare with the actual puller speed recorded from the electronic readout. The actual puller speed, V_P, may be defined as:

$$V_P = V_E + \Delta V_P \quad \text{(Eq 6)}$$

where ΔV_P is the increase in speed due to an increase in puller tension, and V_E is the exit speed of the material leaving the die without the puller. The increase in puller tension, T_P, means the increase in length (ΔL) of the extrusion and, finally, the increase in speed. From the volume constancy, it is written as:

$$A_E \cdot V_E = A_P \cdot V_P \quad \text{(Eq 7)}$$

where A_P is the final area of the extrusion after the puller tension is applied.

Combining Eq 5 and 7, puller speed can be written as:

$$V_P = V_R \cdot (ER)_m \quad \text{(Eq 8)}$$

where $(ER)_m$ is the modified extrusion ratio as defined by $A_C/n(A_P)$.

Factors Affecting Speed. It is observed in 6063 shaped extrusion that in the beginning of an extrusion, the extrusion speed increases slowly and reaches the steady state or uniform speed as shown in Fig. 9. The acceleration part of the speed curve shown is assumed to be linear, and the slope of the acceleration curve is given by θ. Saha (Ref 10) studied a fundamental relationship between the slope and some of the principal extrusion variables, such as extrusion ratio and the working billet temperature.

The extrusion speed and time measurements from start to finish with 6063 billet extrusion have been studied by Saha (Ref 10) to determine the effect of extrusion ratio and initial billet temperature in the acceleration regime of the extrusion speed versus the time curve as shown in

Fig. 9. A series of tests have been conducted with different dies of different extrusion ratios.

Extrusion Ratio (ER). A series of readings on acceleration time and steady-state or uniform puller speed were collected from the press for different extrusion ratios at the same billet temperature, billet length, and ram speed. Figure 10 shows the variation in extrusion speeds with extrusion times for four different extrusion ratios for the same billet length, billet temperature, and ram speed. It shows that extrusion speed increases with an increase of extrusion ratio according to the relationship shown in Eq 5. It also shows that the acceleration time increases with the increase of the extrusion ratio. That means the slope of the acceleration curve increases with the decrease of the extrusion ratio.

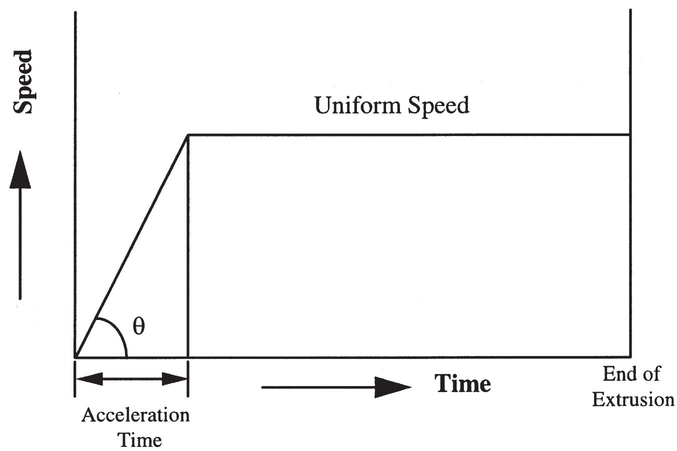


Fig. 9 Extrusion speed model

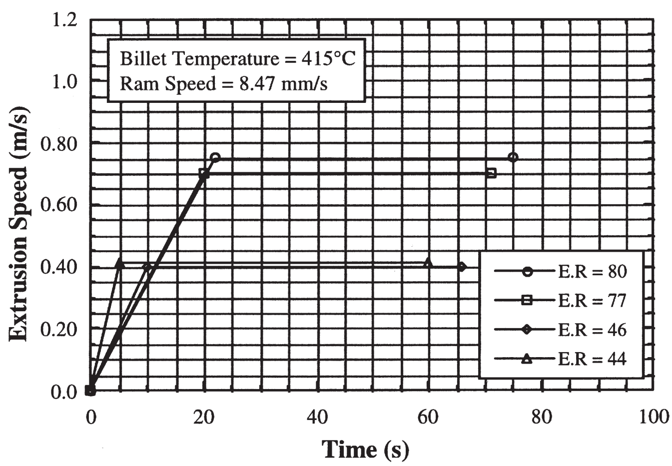


Fig. 10 Variation of extrusion speed with time for different extrusion ratios for the same billet temperature and ram speed

Initial Billet Temperature. Another series of tests were conducted to record extrusion speed, which is assumed to be equal to the puller speed, and the acceleration for the same billet length with different billet temperatures and the same extrusion ratio and ram speeds. Figure 11 shows the variation in acceleration time for the same extrusion ratio and ram speed with four different billet temperatures. The same results can be explained in a different way by showing the acceleration curve slope variation with different billet temperatures as shown in Fig. 12. It can be observed that the slope increases with an increase of billet temperature, suggesting the acceleration time reduces at higher billet temperatures.

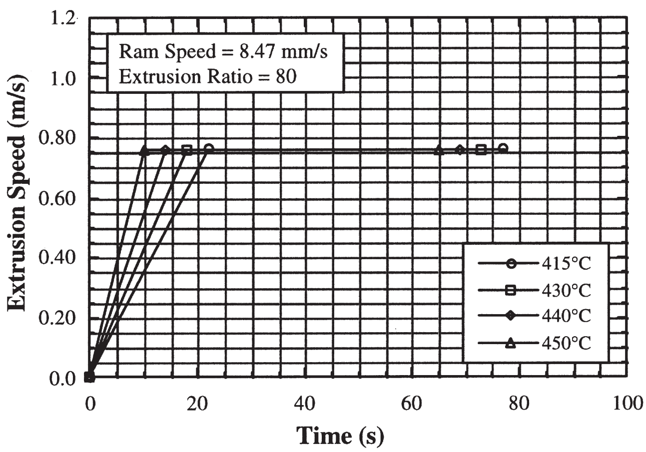


Fig. 11 Variation of extrusion speed with time for different billet temperatures for the same extrusion ratio and ram speed

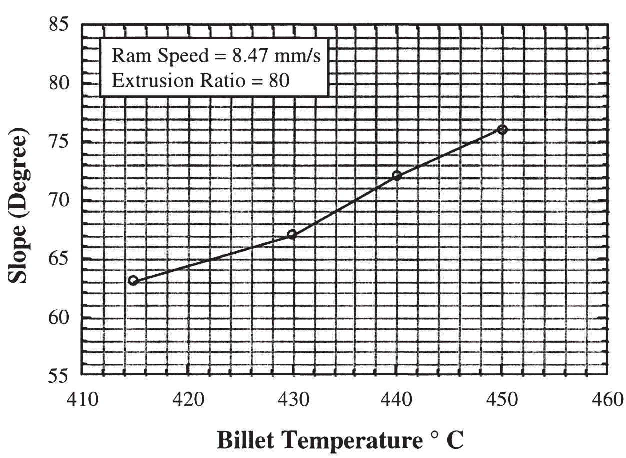


Fig. 12 Variation of slope of the acceleration curve with different billet temperatures for the same ram speed and extrusion ratio

There is, however, a limitation to increasing the billet temperature to reduce the acceleration time; as initial billet temperature increases, the extrusion temperature increases. Optimization of billet temperature can, therefore, be reached for the minimum acceleration time by checking the following:

- Whether the exit temperature lies within the solution temperature range to obtain the desired properties after heat treatment
- Whether the exit temperature reaches the hot shortness temperature range of the alloy being extruded

Factors Affecting Acceleration Time. It is important to know how to reduce acceleration time in order to reduce the total extrusion cycle time and increase productivity. This reduction can be accomplished by trial and error for each alloy and billet size by taking, for example, the following steps:

- Increasing the ram speed for the fixed billet temperature
- Reducing the extrusion ratio by increasing the number of holes in the die
- Adjusting the initial billet temperature for the fixed ram speed

Acceleration time could also be reduced by improving the extrudability of the alloy, either by making compositional adjustments or using an optimal homogenization process.

Butt Thickness Control

The runout length is controlled by billet butt thickness for a given billet length and a particular extrusion die. There are many problems and extrusion defects related to improper butt thickness. These problems are discussed in the section "Extrusion Defects" in this chapter.

Some of the common problems related to butt thickness are discussed in this section. It is noticed that for a feeder plate or a recessed die, a thicker butt draws aluminum from the pocket of the die in the first one or two billets run before the die achieves a temperature steady state, allowing preferred adhesion of aluminum into the pocket of the recessed die. The pocket has to have aluminum left from the previous billet to weld together in the next billet to get a continuous extrusion. Wide extrusions that become wavy toward the end of extrusion can be controlled by increasing the butt thickness.

As the billet reduces and approaches the selected butt thickness, material flows more radially towards the center of the billet because container friction is reduced to a minimum value as extrusion approaches completion. The frictional behavior in direct extrusion is shown schematically in Fig. 13.

In extrusion of soft-grade aluminum alloys, flare is a common problem. Improper sealing of the container liner against the face of the die may cause the billet to back extrude or flare between the gap of the die face and the container liner, as shown in Fig. 14(b). This may be due to one or more of the following:

- Aluminum buildup on the liner face or worn-out liner face
- Smaller die diameter compared with the outside diameter of the liner, causing indentation on the liner face over a period of time
- Improper sealing pressure

In the beginning of the extrusion, as shown in Fig. 14(a), the container liner is properly sealed with the die face due to the combined effect of sealing pressure and the frictional drag at the billet container interface. As extrusion proceeds, the billet becomes shorter, and the frictional drag drops, as shown in Fig. 14(b), coming to a minimum value while approaching the set butt thickness. In that position, the container seals with the die face due to sealing pressure only. At the same time, the rest of the billet is in a more plastic state due to the temperature rise in the billet, which allows a tendency to back extrude through any gap. In such cases, the flare can be avoided by temporarily keeping a thicker butt before replacing the container. However, flares could be avoided by taking some preventive measures, such as the following:

- Use proper size die diameter as shown in Fig. 14(c)
- Keep liner face clean
- Periodically check sealing pressure

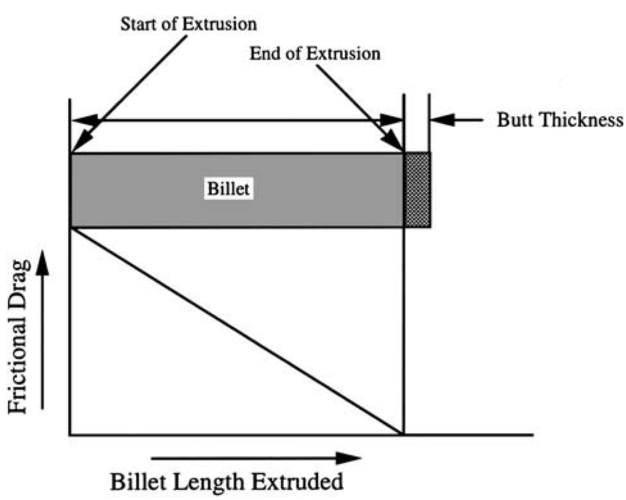


Fig. 13 Schematic of role of container friction in direct extrusion

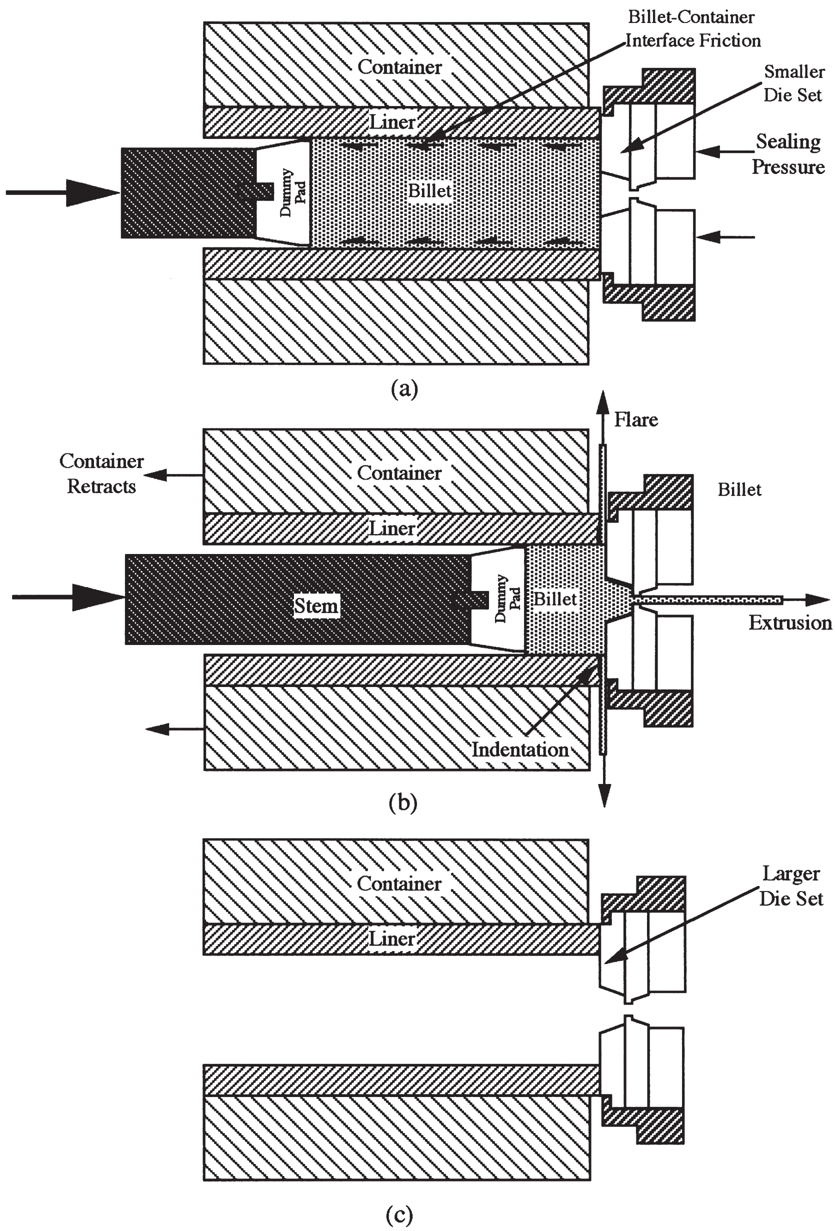


Fig. 14 Flare in direct 6063 alloy extrusion. (a) Beginning of the extrusion process. (b) As extrusion progresses, the billet becomes shorter, and the frictional drag drops. (c) Use of a die diameter of proper size can prevent flare.

Production Practice

Extrusion of Solid Shapes

Solid-shaped extrusions are generally made from soft- and medium-strength aluminum alloys, such as AlMgSi0.5, AlMgSi1, AlZnMg1, and some non-heat-treatable AlMg alloys. The extrudability of those alloys is given in Table 1. The sections are classified according to the difficulty to produce extrusions as shown in Fig. 15.

Laue and Stenger (Ref 8) classified and explained more about the extrusion of some soft- and medium-strength alloys, including AlMgSi0.5-0.8, AlMgSi0.5, AlMgSi1, and AlZnMg1 for sections, bright trim sections, structural sections, and other sections, respectively. Typical values of the extrusion parameters of some soft- and medium-strength alloys are given in Table 4 for guidance only. Actual billet temperatures and extrusion speeds vary with product complexity.

Structural Extrusions. The AlMgSi1 alloy, with the addition of manganese, is used for high-strength structural sections and color-anodizing architectural sections. The extrusion variables will be different for these two different applications. Because AlMgSi1 has a higher alloy content, the sections need to be cooled at a faster rate for structural

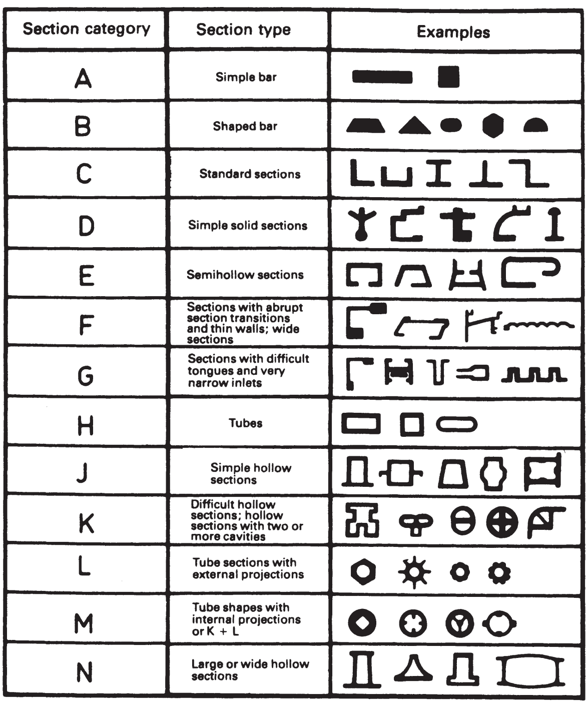


Fig. 15 Classification of aluminum extruded section. Source: Ref 7

sections in order to obtain maximum strength. For structural sections, a water quench from the exit extrusion temperature to a temperature greater than the solid solution temperature is recommended. Warping of a section may occur when it is quenched in water upon leaving the die, even with the puller system employed. The heavy structural sections with a lower extrusion ratio may not reach the solid solution temperature while leaving the die and, therefore, require a separate furnace solution treatment and water quench to satisfy the mechanical properties. The sequence of processes for structural heavy sections is shown in Fig. 16. A short natural age time period is normally employed to achieve optimal mechanical properties.

Extrusion defects in the back end of an extruded length may cause serious concern in the case of structural applications. The defect can generate longitudinal cracks in the direction of extrusion at much lower applied loads. Additional process controls can be applied for extrusion of structural shapes to minimize extrusion defects. Butt thicknesses of 10 to 20% are typical for critical sections, and etch tests to check any inclusions or defects at the back of the extruded section are recommended.

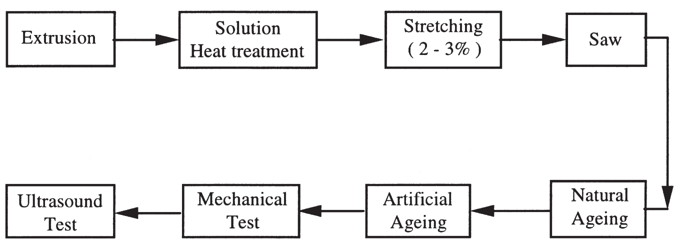


Fig. 16 Typical flow diagram of structural shape extrusion

Table 4 Typical values of billet temperatures and extrusion speeds of soft- and medium-grade alloys

Alloy	Type	Billet temperature °F	Billet temperature °C	Exit speed ft/min	Exit speed m/min
1060	Non-heat-treatable	788	420	164–328	50–100
1100	Non-heat-treatable	806	430	164–262	50–80
3003	Non-heat-treatable	842	450	98–230	30–70
5052	Non-heat-treatable	842	450	16–33	5–10
5154, 5254, 5454	Non-heat-treatable	860	460	20–49	6–15
6061	Heat treatable	806–932	430–500	16–82	5–25
6063	Heat treatable	896–932	480–500	115–262	35–80
6066	Heat treatable	797–860	425–460	66–115	20–35
6101	Heat treatable	896–932	480–500	115–262	35–80
6463	Heat treatable	896–932	480–500	115–262	35–80
7003	Heat treatable	824–977	440–525	16–69	5–21
7005	Heat treatable	824–977	440–525	16–46	5–14

Source: Ref 8

Extrusion of Tubes and Hollow Shapes

Tubes and hollow sections are typically extruded through a die that determines the outer shape of the tube or hollow sections, and a mandrel, located in the aperture of the die, determines the inside shape and section thickness. There are various methods to extrude hollow shapes in the industry based on the requirements of the product and the limitations of the alloy being extruded:

- *Seamless extrusion:* Makes use of a mandrel on the extrusion stem with either a fixed mandrel screwed to the stem (Fig. 17) or a moving mandrel controlled independently of the ram. This process is usually restricted to round tube or very simple hollow shapes and is not practical for thin-walled products.
- *Extrusions with welding joints:* A welding chamber die is used.

Welding Chamber Die Extrusion. Tubes and hollow sections of softer alloys are generally produced by the use of welding chamber-type dies. This type of die has a wide range of applications in the aluminum extrusion industry and is suitable for aluminum alloys such as AlMn, AlMgSi, and some AlMg and AlZnMg. Welding properties of some aluminum alloys for the production of tubes and hollow sections are shown in Table 5. The welding chamber process has some advantages, such as the following:

- Hollow sections can be extruded in a longer length.
- Very thin hollow sections can be extruded.
- It is useful in the extrusion of complicated sections for many industrial applications.

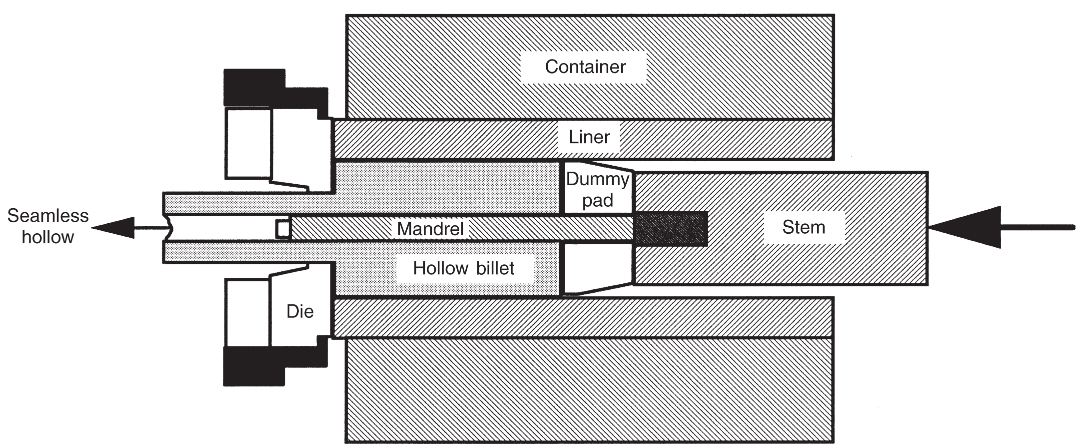


Fig. 17 Principle of seamless tube extrusion

Table 5 Welding properties of some soft- and medium-strength alloys

Alloys	Welding properties
Pure Al	Very good
AlMn	Very good
AlMg1	Very good
AlMgSi0.5	Good to very good
AlMgSi1	Good to very good
AlZnMg1	Good
AlMgSi0.8	Good to very good

Source: Ref 11

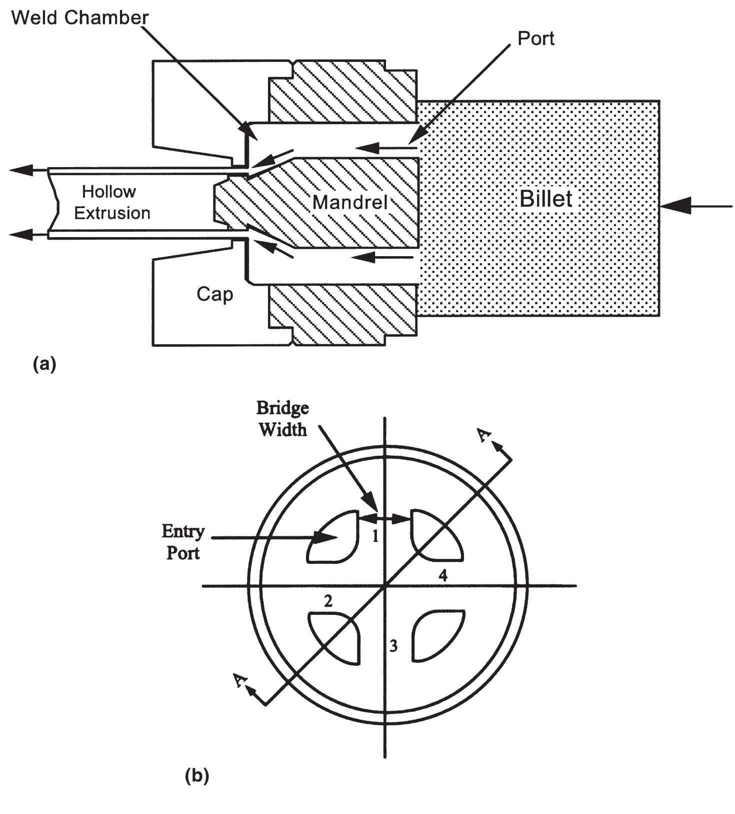


Fig. 18 Schematic of welding chamber (porthole) die hollow extrusion. (a) Cross section showing metal flow into port streams and around the mandrel. (b) Billet entrance face of the die set

Hollow sections in alloys (6063 are commonly used) that reweld together are extruded from solid billets with welding chamber dies (bridge, spider, or porthole). The metal is forced to flow into separate ports and around the bridges, which support the mandrel. The separate streams of metal that flow through the ports are brought together in a welding chamber surrounding the mandrel, and the metal exits from the die through the gap between the mandrel and the die cap as a hollow shape, as shown in Fig. 18. Because the separate metal streams are

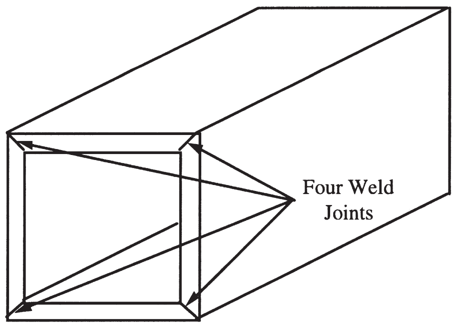


Fig. 19 Location of welding joints in a square shape

joined within the die, where there is no atmospheric contamination, a perfectly sound weld is obtained. Laue and Stenger (Ref 8) described some important points in extruding hollow shapes. In comparison with the extrusion of solid sections, hollow section extrusions present several technical peculiarities:

- Extrusion load becomes higher because metal has to overcome frictional drag in order to flow through the ports before reaching the welding chamber.
- The billet temperature must usually exceed 500 °C (930 °F) to facilitate flow through the ports and achieve a proper weld in the welding chamber. The container temperature should be relatively high and not less than 50 to 70 °C (90 to 126 °F) below the billet temperature, 450 to 470 °C (842 to 860 °F) for satisfactory extrusion and welding with thick-walled sections.
- Longitudinal weld marks can appear lighter than the rest of the section after anodizing because of metallurgical influences. Accordingly, special attention is required in die design to ensure preferred location of the welds (i.e., at the corners of the hollow sections, as shown in Fig. 19). The four longitudinal joints are shown at the corners of the tube.
- Small hollow shapes are produced using multihole, porthole-type dies where the number of holes is selected by considering the extrusion ratio of each hole, extrudability of the alloys, press size, and the CCD.

Productivity Control

Productivity is defined by the quantity of good extrusion produced per unit time. Basically, there are a number of ways to maximize productivity:

- Minimize the amount of avoidable scrap per each billet run for the same press speed, billet size, and runout length.
- Maximize the billet length to best utilize press capacity and runout table length.
- Optimize the speed, compensating for the temperature rise during extrusion.

Minimize Avoidable Scrap

Productivity can be controlled by minimizing the amount of avoidable scrap per each billet run for the same press speed, billet size, and runout length. Scraps could easily be avoided by controlling die performance, inspection on the runout table, hot saw length, combination of finish cut size, and handling systems. It is always recommended to check the recovery percentage at the beginning of each die run to determine the source of any problem and to correct it accordingly.

Maximize the Billet Length

Increasing productivity by maximizing the billet length to make the best use of the press capacity and runout table length for a fixed dead-cycle time of the press is always recommended.

Optimization of Extrusion Speed and Temperature

Optimization of extrusion speed and temperature is important to maximize productivity. The fundamentals of the optimization process are discussed in this section. Before increasing the speed of extrusion, it is necessary to optimize the billet temperature for a particular billet size, extrusion ratio, and the type of die. The purpose of determining the optimum billet temperature is to reduce the acceleration time, as shown in Fig. 11, without jeopardizing the maximum extrusion speed before the

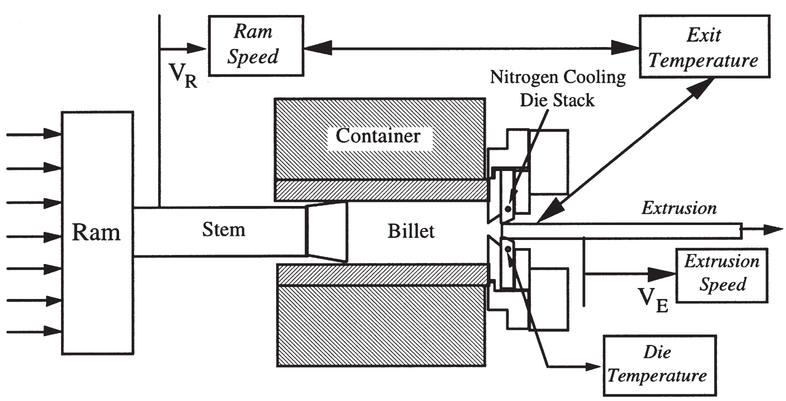


Fig. 20 Temperature and speed control extrusion

onset of speed cracking or hot shortness. Figures 20 and 21 illustrate the concept of optimizing speed and exit temperature to maintain the best quality of extrusion with maximum output. The extrusion press equipped with a closed-loop temperature measuring system for both the extrusion and the die can monitor the exit temperature at a given ram speed. The process can be augmented with a die stack equipped with a nitrogen cooling system. Every alloy has a temperature limit for the onset of incipient melting. For complete optimization, there are certain additional points to consider:

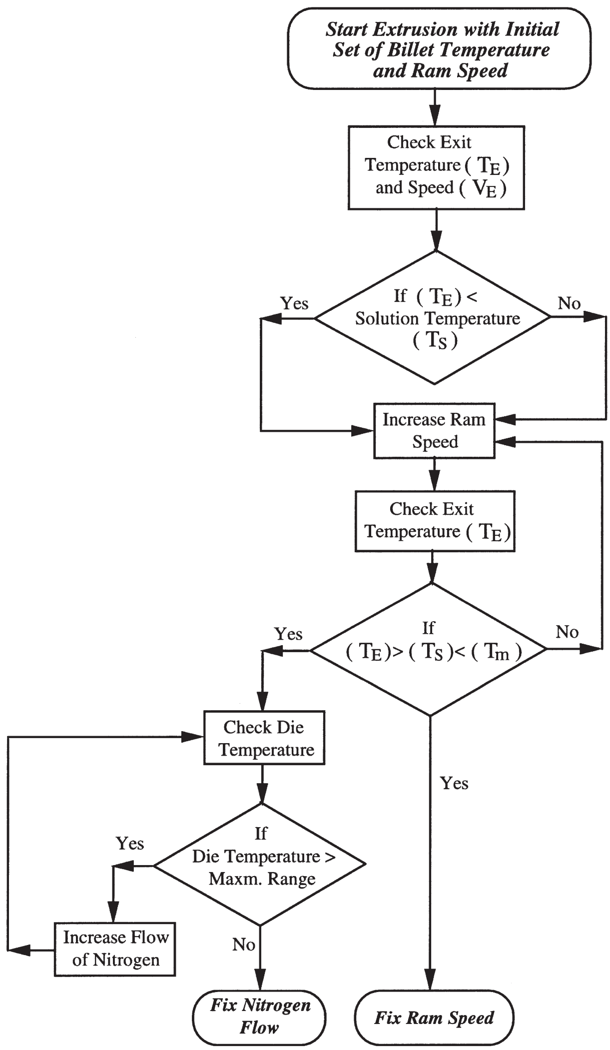


Fig. 21 Flow chart of temperature and speed control extrusion. T_m, incipient melting temperature

- Surface finish problems, such as hot tearing, occur when the exit temperature approaches the incipient melting temperature of the alloy.
- Die wear associated with the localized temperature rise to the die bearing can occur.
- Exit temperature must always be higher than the required solution treatment temperature for the alloy for inline air quench for thin sections or for air and water mist quench for heavier sections.

Auxiliary Operations

Stretching

After extrusion, the extruded length generally requires straightening. It is known that some geometrical changes occur during the cooling of profiles on the cooling table after extrusion. The sections are transferred from the runout and a cooling table to the stretcher bed to be straightened by stretching 1 to 3%. Separate shaped grips are used in both ends of the stretcher to stretch critical shapes without further distortion during stretching. Both heads are fitted on the same straight bed as shown in Fig. 22. The fixed head, also called the tailstock, can be moved and locked on the bed at various positions to adjust the starting position of the moving head to match the extrusion length. The clamping jaws are operated by either hydraulic or pneumatic means. The stretcher capacity has to be greater than the required stretching force, which is a function of the following factors:

- Cross section of the shape
- Yield stress of the extruded alloy

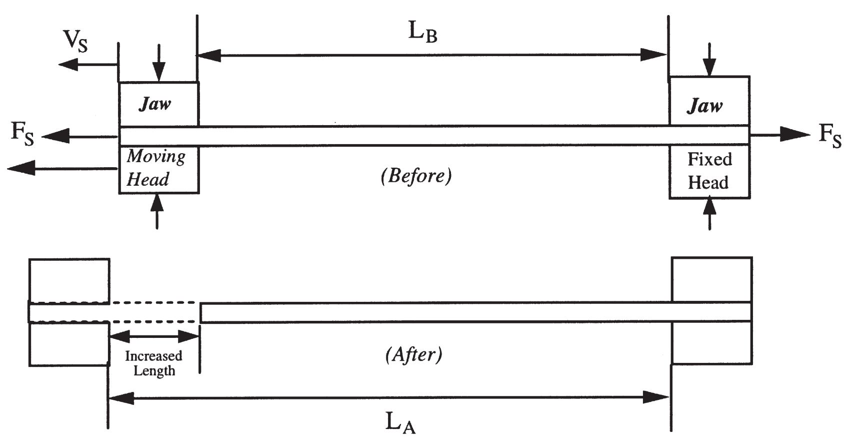


Fig. 22 Stretching principle

The stretching principle is shown in Fig. 22. The amount of stretching is determined by the permanent strain in the longitudinal direction:

$$\text{Stretching} = \frac{L_S - L_E}{L_E} \times 100\% \qquad \text{(Eq 9)}$$

where L_S is the length of extrusion after stretching, and L_E is the length before stretching. The amount of stretching may be adjusted to suit a particular product, depending on a number of factors, including product shape and size; critical dimensions, such as gap or tongue; close tolerance; and surface finish.

Factors Affecting Stretching. The following factors can affect stretching:

- Design of the jaws to accommodate different shapes
- Stretching force, F_S, for a particular alloy and shape
- Stretching speed, V_S

Sawing

Sawing is usually the next operation after stretching. The sawing principle is shown in Fig. 23. A high-speed circular saw is normally used to trim stretcher grip marks and front and back-end scrap allowances and to cut the finished lengths. The straight extruded lengths are cut to a single length or in multiple lengths according to the requirements of the customer. The saw is designed to both rotate and traverse. The sections are moved up against the gage stop, which is set to the required length, and saw chips are collected by using a high-pressure vacuum connected to the machine. Quality of the cut edge of a finished extrusion is a function of the following factors:

- Selection of blade geometry and tooth specification per alloy
- Lubrication system

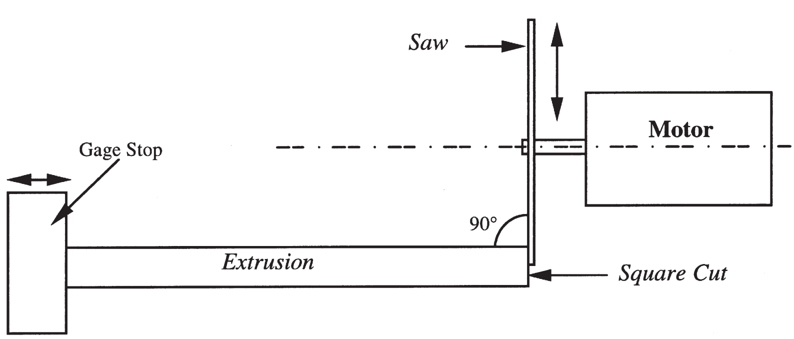


Fig. 23 Sawing principle

- Selection of the proper feed of the saw blade with respect to the rpm of the blade
- Volume of metal to cut in each stroke
- Positioning of the critical edge of the extrusion with respect to the direction of the cut
- Sharpness of the cutting edge of the blade
- Timely replacement of the used blade

Heat Treatment

Metallurgical and geometrical changes occur during the press quenching of an extrusion. Significant changes occur in larger sections, but they can also occur on small profiles. Depending on the alloy and extrusion shape/thickness, the quenching system may be air or water, or a combination of both.

Air cooling systems with increased cooling efficiency have been developed (Ref 12) using the rules of aerodynamics, where high-velocity air jets are employed close to the surface of the profile. With such a cooling unit on an industrial scale, cooling rates two to three times higher than conventional systems have been achieved, while still respecting rules of safety and noise emission.

For faster cooling and water quenching, independent and adjustable spray jets can be directed to different areas of the profile without subjecting the shape to undue distortion. A system has been developed using a new concept of water-air spray using Flexi-Jet spray modules (Ref 13) to perform profile cooling with minimum distortion within the metallurgical limitations. Water droplets with high kinetic energy accelerated by air-jet propulsion permits the cooling of profiles in a large range of different shapes while ensuring homogeneous mechanical properties. Minimum distortion and residual stress have been achieved using individual cooling conditions for every shape tested.

Correct heat treatment of soft- and medium-grade aluminum alloy extrusions is important to obtain the required mechanical properties, such as hardness and strength, to satisfy customer specifications. For all heat treatable aluminum alloys, heat treatment is a two-stage process, solution heat treatment and precipitation hardening (aging). The fundamental metallurgy behind solution heat treatment and aging is to allow the hardening constituents of different alloys, as shown in Table 6, into solid solution during solution treatment and subsequent precipitation during aging.

For 6000-series alloys, the extrusion may be cooled directly from the extrusion temperature. Normally, a forced-fan cooling system is sufficient, but water quenching is occasionally needed. Successful heat

Table 6 Principal hardening phases of different soft- and medium-grade alloys

Alloy	Principal hardening phases
1*xxx*	$FeAl_3$, Fe_2SiAl_5
3*xxx*	$MnAl_6$, $(FeMn)Al_6$
5*xxx*	Mg_2Al_3
6*xxx*	Mg_2Si

Source: Ref 14

transfer from the extrusion to air, which is important to achieve proper quenching, depends on the following factors:

- Air velocity
- Air temperature on the extrusion surface

Thus, a sufficient number of fans with adequate air velocity should ideally be provided to reach the cooling intensity needed for subsequent age hardening of thick-walled extruded sections. Uniform mechanical properties can be obtained over the full length of the extruded product if the air velocity along the axis of the press is equal to that at the first section of the cross-transfer conveyor.

In order to get a proper response to the final stage of heat treatment (aging), the extrusion must have previously undergone an adequate quench at the press, where the material has been cooled at a sufficient rate from the solid solution temperature. Successful quenching of softer- and medium-grade alloys is dependent on the following factors:

- Thickness/cross section of the extrusion
- Alloy and chemistry

For thin-walled light sections, an air quench in the press may be sufficient, provided the extrusion leaves the die above the solid solution temperature. For heavy sections of heat treatable alloys, especially 6061 structural extrusions, the material leaving the die may not reach the solid solution temperature range, so an air, or even water, quench at the press may not be sufficient to completely solution treat. A separate furnace solution treatment may, therefore, be necessary to effect full solutionizing. Furnace solution heat treatment usually incorporates a controlled-volume, full-immersion water (or glycol solution) quench. The separate heat treatment can be done in two different types of furnaces:

- Horizontal type with water-jet quench
- Vertical type with water-tank quench

Table 7 Typical heat treatment practices of some 6*xxx* alloys

	Solution heat treatment			Precipitation heat treatment			
	Temperature			Temperature			
Alloy	°F	°C	Temper	°F	°C	Time, h	Temper
6005	985	530	T1	350	175	8	T5
6061	985	530	T4	350	175	8	T6
6063	970	520	T4	350	175	8	T6
				360	182	6	T6
6066	990	530	T4	350	180	8	T6
6070	1015	545	T4	320	160	18	T6
6262	1000	540	T4	350	175	12	T6

Source: Ref 14

A polymer glycol solution may be used as an alternating quench medium to water to minimize distortion. After furnace solution heat treatment, the extrusions need to be stretched to both straighten and release internal quenching stresses. For stress relief, stretching between 1.5 and 3% is typically employed.

Aging, the final stage of the heat treatment process, is used to achieve the desired temper (e.g., hardness, strength, and/or ductility). Ramanan and Dery (Ref 15) conducted an experimental survey relating to the performance of aging ovens using a maximum of 32 thermocouples in a typical load measuring the temperature profile. They also suggested steps to improve productivity, throughput, quality, and product consistency and recommended that extruders perform a temperature survey on aging ovens at least once a year to ensure a proper aging operation. Typical heat treatment temperatures of some 6*xxx* alloys are shown in Table 7.

Mechanical and Physical Tests

Generally, with 6063 architectural and decorative shapes, hardness is the only qualifying test used by most extrusion manufacturers. For other industrial and structural applications, however, tensile tests are also required. Especially for the structural shapes, tests normally performed include tension, compression, and shear. The mechanical tests are usually performed on samples taken from the back end of an extrusion, although sometimes samples are collected from three different positions to establish any variation of properties along the length of the extrusion (i.e., front end, middle, and back, or butt end).

Macroetching of the extrusion samples from the back end, and possibly the above three mentioned positions, checks the grain structure in the recrystallized regions, which usually occurs around the profile periphery or at the tips of thin legs. The etching tests are also particularly necessary to check the back end for entrapped inclusions. Accordingly, the butt thickness may need to be adjusted or the proper difference between billet and container temperatures be maintained to stop ingress of inclusions from the oxide skins laminated on the container bore.

Extrusion Defects

Metal flow in the container, as well as through the die, can influence the occurrence of defects in the more common direct extrusion process. The common extrusion defects of 6*xxx*-series alloys are categorized in Fig. 24.

Detection of extrusion defects, analysis, and preventive measures are three important factors to be considered in every extrusion plant. To deal with these factors, it is necessary to have a complete understanding of the mechanics and extrusion variables and their effects on extrusion as discussed in Chapter 1. Any extrusion defect can be related to any of the following extrusion factors and variables or a combination of variables:

- Billet casting
- Metallurgical variables
- Initial billet and container temperature
- Extrusion ratio

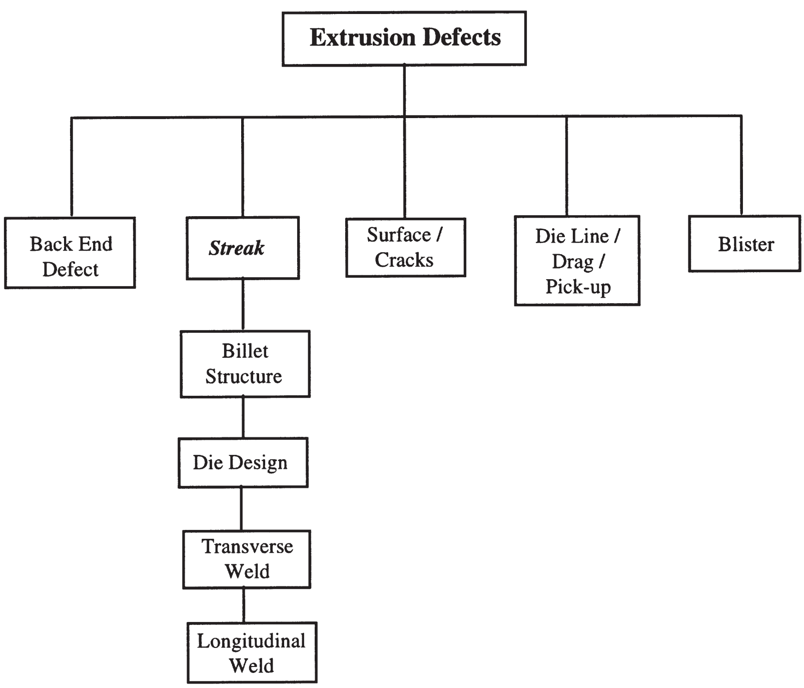


Fig. 24 Common extrusion defects of 6*xxx* series alloys

- Die design
- Extrusion speed
- Extrusion temperature
- Lubrication system

Extrusion recovery is related to the amount of scrap from both the front and the back end of any extrusion. Extrusion back-end quality is dependent on the butt thickness billet quality and billet/container temperatures. Some of the extrusion defects, such as transverse weld, longitudinal weld, and blistering, are directly related to both the front and the back end of recovery.

Parson et al. (Ref 16) reviewed the principal defects encountered during the extrusion of 6*xxx* alloys. Based on a metallurgical background, they discussed different problems that may arise during commercial extrusion of 6*xxx*-series aluminum alloys and also outlined an excellent study of causes, origins, and solutions to each extrusion defect or problem.

Ramanan (Ref 17) dealt with various day-to-day technical problems encountered by extruders and how these problems can be solved. He covered corrosion, anodizing, buffing, lack of mechanical properties, coring, and press-related extrusion defects.

The most common defects occur when the butt thickness is minimized to achieve maximum recovery. In direct nonlubricated aluminum extrusion, the oxidized billet skin is separated at the container layer due to friction at the billet-container interface. The mechanism of formation of this oxide layer at the container wall and its control are discussed in Chapter 7. These layers build up in front of the dummy pad as extrusion continues. After approximately 70% of the billet is extruded, the accumulated metal begins to flow inwardly across the face of the dummy pad.

In the extrusion of small architectural sections, many manufacturers use a butt thickness of 5% or less, especially those using powder or liquid paint to finish the extrusion. In such cases, the product homogeneity and surface quality are not seriously impaired. However, minimum butt thickness may also cause severe blistering at the back end of extrusion due to difficulties shearing the butt at the end of extrusion. Butt thickness control is necessary for extrusions with anodized finishes to avoid a streaking appearance.

The visual appearance of an extruded surface is an important feature of products for service in many applications, such as architecture, transportation, and window and door trim. Surface appearance in the mill-finish condition or after anodizing or painting is one of the most important characteristics of high-quality 6*xxx* extrusion. Die lines, scoring, pick up, and tearing all detract from the appearance of the as-extruded profile. A rough surface (i.e., one with heavy die lines or scores) is not always improved by painting, and these defects are sometimes exaggerated by a thin layer of gloss paint. Etching and anodizing can usually remove pick-up particles but cannot always remove all surface defects produced at the press, depending on how much metal is removed in the etch tank. Parson et al. (Ref 18) described the characteristics of these defects together with the effects of billet metallurgy, die surface condition, and extrusion process variables. Many authors (for example, Ref 19 and 20) have dealt with the surface quality of extrusions in terms of roughness, which is a convenient parameter to measure, and recommendations such as die bearing length, direction, and grade of die polishing have been made. Examples of some common extrusion defects are shown in Fig. 25 to 33.

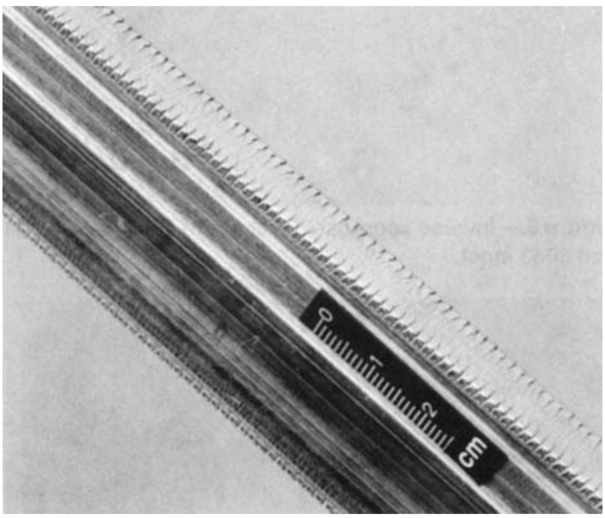


Fig. 25 Speed crack on a 6082 extrusion. Source: Ref 16

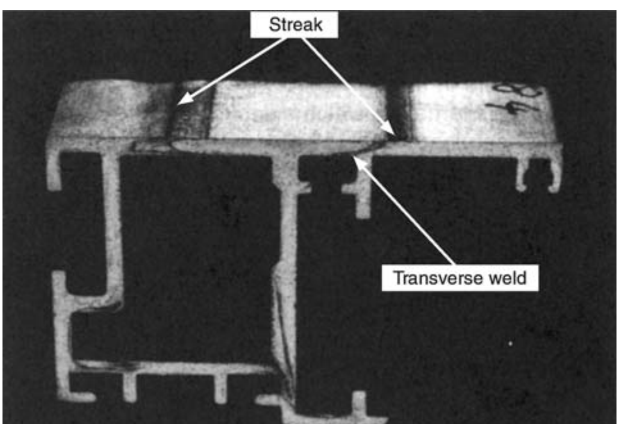


Fig. 26 Streaking after anodizing with back-end defect. Source: Ref 16

Figure 29 shows a macrograph of a 6063 billet cross section showing a large-grain-sized ring around the center of the billet. Figure 30(a) shows the macrograph of the etched section from the sheared end of the extrusion produced from a 6063 billet having a large-grain-sized ring. The same extrusion produced from another billet having the normal variation in grain size did not show any defect, as shown in Fig. 30(b).

The quality of weld joints within the welding chamber of a bridge or porthole die is an important factor. Figure 32 shows an example of improper bonding at the weld joint of a hollow die extrusion.

Extruded round stocks are used for subsequent drawing operations. Weld joints are critical in ensuring that the joint does not split in the

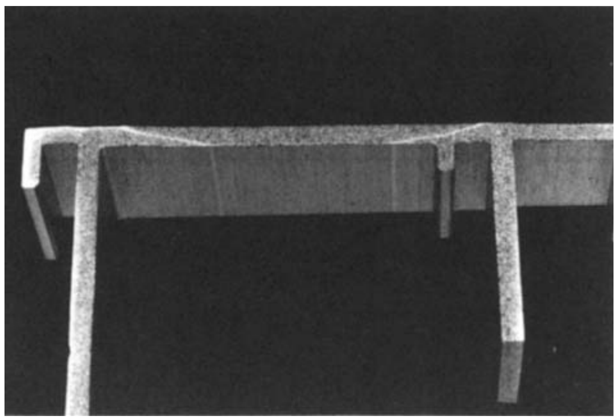


Fig. 27 Longitudinal weld streaking on anodized 6063 extrusion. Source: Ref 16

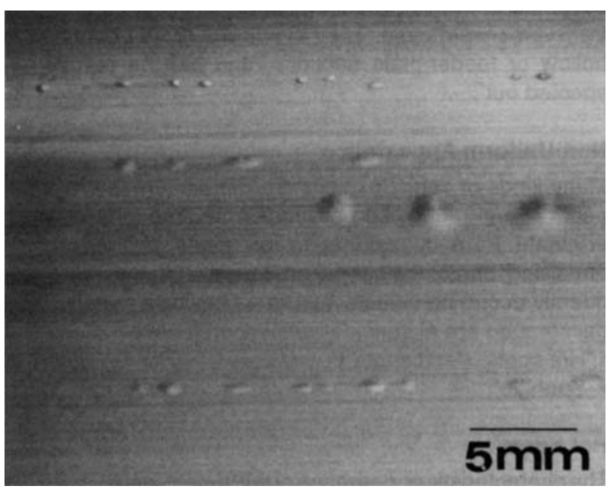


Fig. 28 Extrusion blister. Source: Ref 16

drawing process. Figure 33 shows the weld joint of a round tube extruded from a porthole die and from the first drawing pass.

The sticking of aluminum oxide on the die bearing is a common occurrence in aluminum extrusion due to a strong tendency for aluminum to adhere to the steel surface. The development of an oxide layer on the die bearing is dependent on many factors, such as the following:

- Alloy chemistry
- Temperature developed in the die bearing
- Speed of the extrusion, causing a temperature rise in the die bearing
- Shape and geometry of the die
- Die bearing length
- Surface roughness and hardness of the die bearing

When the temperature of the die bearing increases, the tendency for the oxide layer to stick increases and gradually develops more as the

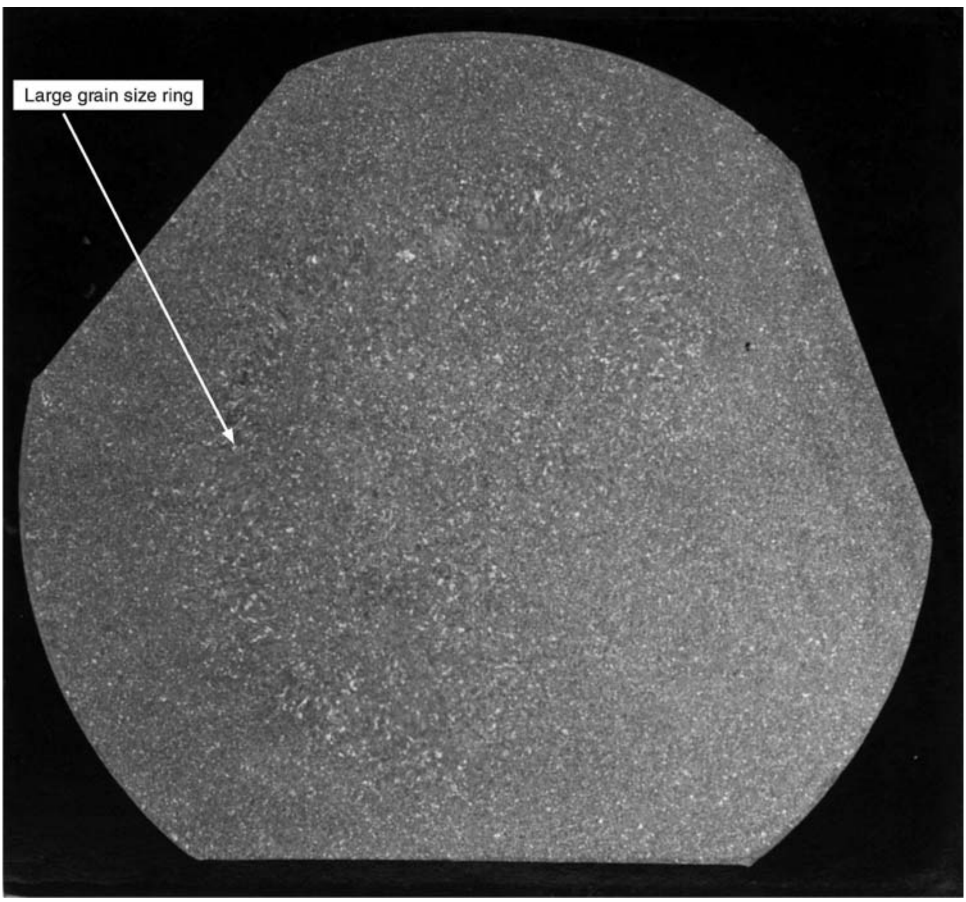
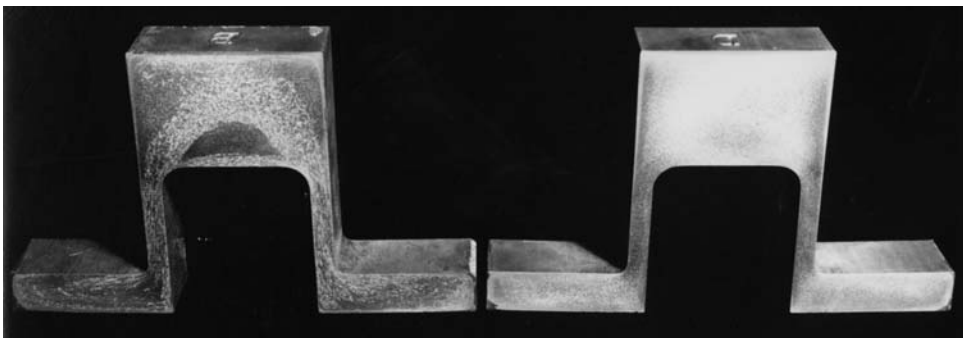


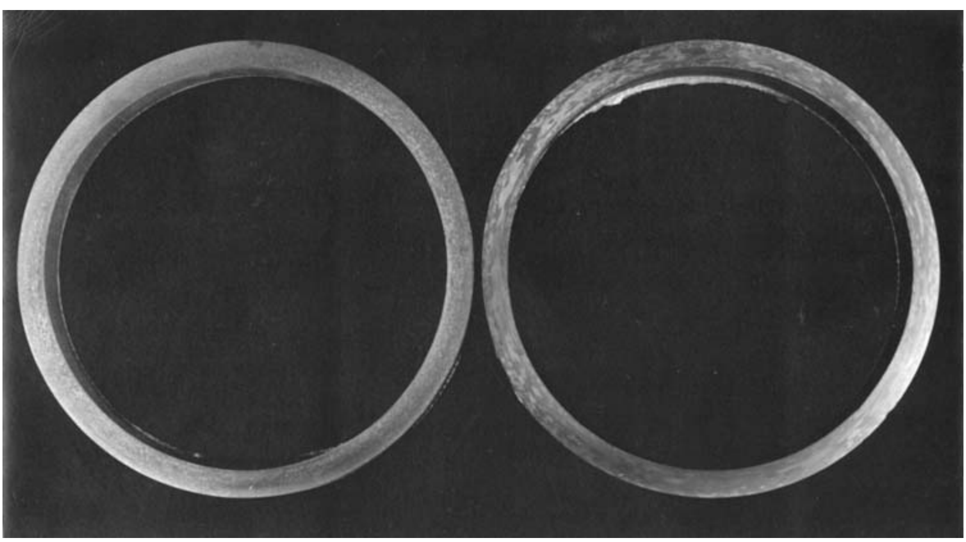
Fig. 29 Cross section of a 6063 billet showing large grain ring

press cycle increases. The oxide is a hard surface on the bearing with some roughness distribution (Fig. 34a); the same roughness pattern will be transferred to the soft, hot aluminum along the length of the extrusion. This tendency generates a very rough surface finish on the extrusion, normally called die drag. There is another defect, called the die line, which occurs when very hard oxide or any foreign hard particle hits the right angle edge of the entry of the die bearing, causing an uphill notch or a downhill groove on the die bearing as shown in Fig. 34(b). An uphill notch will generate a deep, continuous groove into the extrusion, and a downhill groove will make a continuous wedge mark on the extrusion. Die lines may also result from buildup at the back of the bearing.



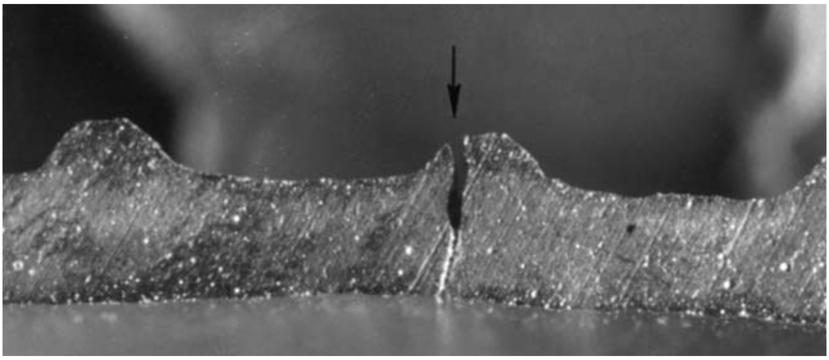
(a) (b)

Fig. 30 Comparison between large and normal grain size 6063 extrusion. (a) Large-grain-sized extrusion defect. (b) Normal grain size without any defect

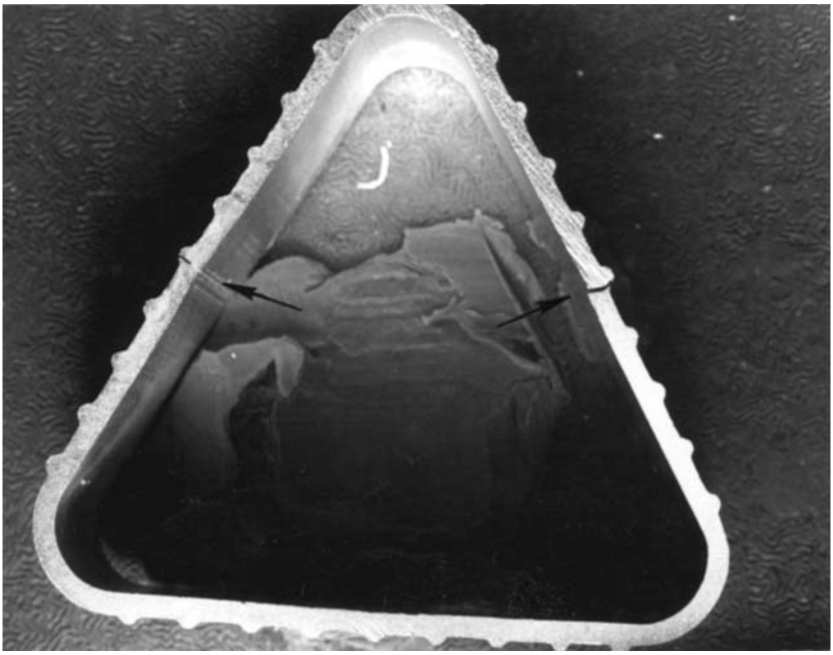


(a) (b)

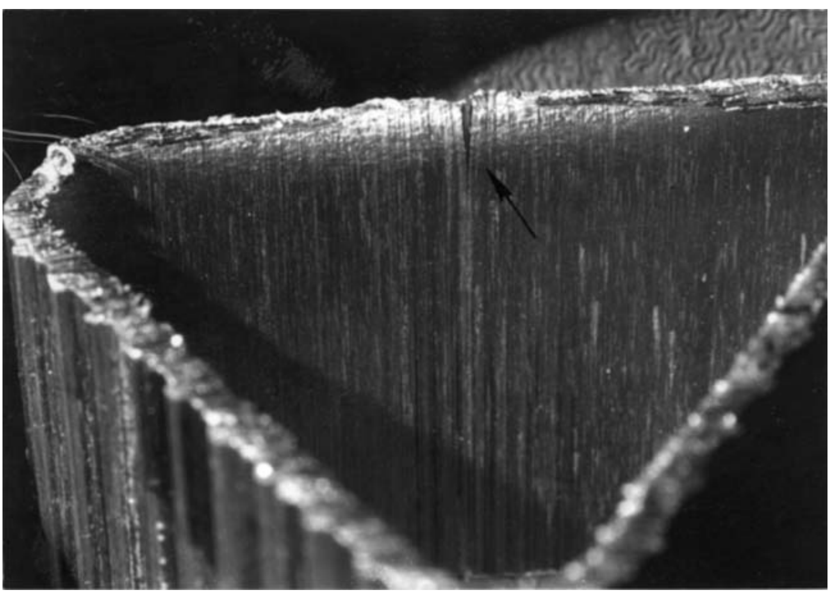
Fig. 31 Tube cross section from 6061 extruded at two different billet temperatures. (a) Normal billet temperature. (b) High billet temperature



(a)



(b)



(c)

Fig. 32 Typical example of an improper weld joint in hollow shape extrusion. (a) Split at the fracture (magnification, 2×). (b) Full cross section showing two poor-quality welds (magnification, 3×). (c) Partially bonded joint (magnification, 12×)

The main objective of the extrusion manufacturer is to make a product as defect free as possible. To achieve this objective, it is important to institute quality check measures in the processes. The general outline of the steps involved and possible check measures in both billet casting and the extrusion process are shown in Fig. 35.

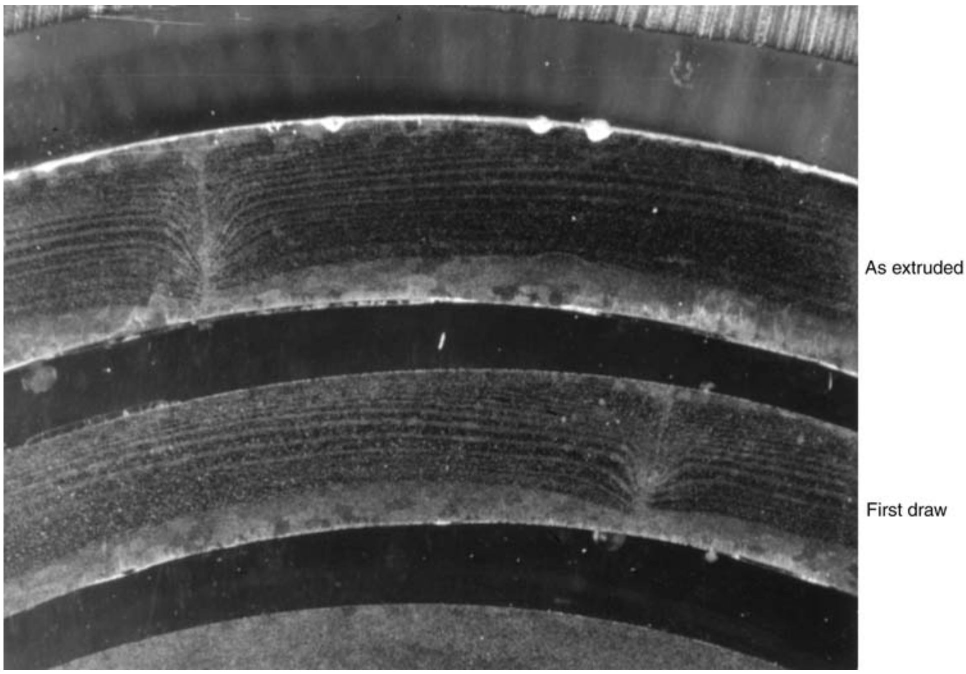


Fig. 33 Weld joint in round-tube extrusion

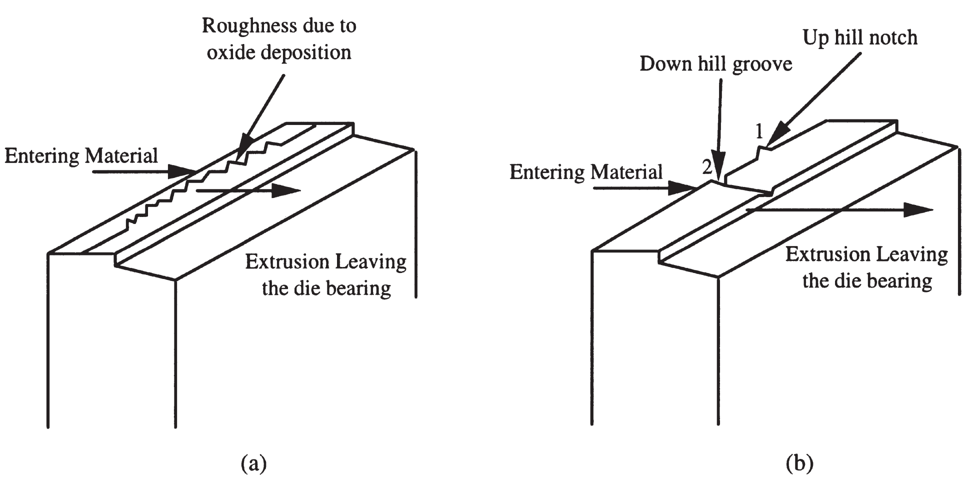


Fig. 34 Effects of oxides on the bearing surface. (a) Die drag. (b) Die line

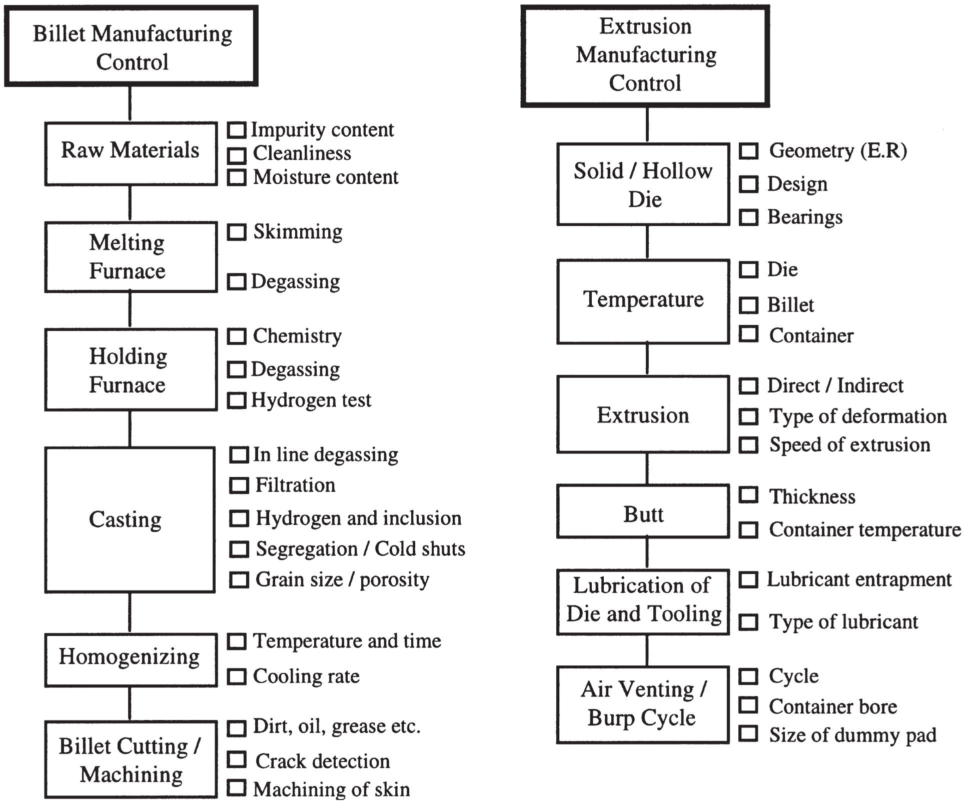


Fig. 35 Billet casting and extrusion manufacturing control in relation to extrusion defects

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CHAPTER 7

Extrusion of Hard Alloys

In Chapter 6, the extrusion process of soft- and medium-strength alloys is discussed. The fundamentals are the same for extrusion of the harder alloys, the only difference being alloy chemistry and its effect on process parameters, such as billet temperature, extrusion speed, exit temperature, and quench procedure. With harder alloys, based on specification requirements, auxiliary steps, such as stretching, sawing, and heat treatment, often differ from those for softer-grade alloy extrusions. The 2000-series, AlCuMg systems were discovered by Wilm (Ref 1) in 1911, while more recently, Sheppard (Ref 2) has researched these and other harder alloys, with particular reference to extrusion. After the discovery of the first heat treatable alloy, now designated as 2017, research continued to establish that the principles of age hardening in 2017 also applied to other alloy systems. A few alloys developed in the 1920s and 1930s are still in use today, but the results of more recent developments are reflected in 2014 and 2024, which are some of the most widely used hard alloys, especially in the aerospace industry.

In the development of the 2014 alloy, an improvement over the 2017 alloy, silicon additions were used to facilitate the aging response to provide a higher level of strength that cannot be obtained by natural aging. Alloy 2024 was introduced in the 1930s as a high-strength, naturally aged alloy to replace 2017. The response of 2024 to artificial aging is accelerated by strain hardening of the heat treated material, and the alloy is available in a number of naturally and artificially aged tempers that reflect several degrees of strain hardening (Ref 3). Tempers of 2014 are usually limited to the naturally and artificially aged conditions.

While these two alloys continue to have wide applications in the aircraft industry, improved versions have recently been introduced. Purer derivatives, such as 2214 and 2124, offer better fracture and toughness properties (Ref 4). The toughness of alloy 2048 also has improved. Alloy selection depends on the service requirements, which can be very diverse. Thus, many different considerations must be taken into account for successful extrusion parameters and subsequent heat treatment.

The Aluminum Association's 5000-series medium- and harder-strength alloys represent the most important commercial non-heat-treatable alloys. Their hot working range is very limited because they have a high deformation resistance throughout the working range. High extrusion temperatures are necessary, and incipient melting is a likely occurrence. The 5000-series alloys are mainly used in applications where corrosion resistance as good as the pure aluminum is needed, but higher strength is imperative. The alloys are also used in aerospace, shipbuilding, and transport components. Typically, 5 to 6% magnesium (Mg) is the maximum alloying addition because alloys with higher Mg are difficult to extrude and are more susceptible to intergranular and stress-corrosion cracking (SCC) or exfoliation (Ref 5).

The 7000-series, AlZnMgCu alloy systems contain zinc (Zn), magnesium, and copper (Cu), as well as additives, such as chromium (Cr), manganese (Mn), or zirconium (Zr), and the ever-present impurities, iron (Fe) and silicon (Si). These alloys have a very short hot-working temperature range due to a high deformation resistance and a tendency for incipient melting at relatively low hot-working temperatures (Ref 6, 7). The most commonly used alloy for small- and large-shaped extruded sections in the aircraft industry is 7075, which offers a high strength-to-weight ratio.

Alloys and Extrudability

Extrudability has already been defined in the section "Alloys and Extrudability" in Chapter 6. Different extrudability ratings of hard alloys are given in Table 1. Zasadzinski and Misiolek (Ref 9) presented the results of investigations of the extrusion of certain alloys that are difficult to deform, applying controllable container temperatures. The extrudability as a limiting deformation under the given process conditions is defined, and the maximum extrusion speed without cracks is suggested as its measure. In a recent study (Ref 10), extrudability of some 7*xxx* alloys was measured as the maximum extrusion speed before hot tearing or speed cracks occurred in the extruded section. Their results show that the extrudability of these alloys is strongly dependent on some of the alloying constituents, such as Mg, while only slightly de-

Table 1 Extrudability ratings of various hard alloys

Alloy designation	Type	Major alloying elements	Relative extrudability (a)
2014	Heat treatable	Cu, Si, Mn, Mg	20
2024	Heat treatable	Cu, Mg, Mn	15
5083	Non-heat-treatable	Mg, Mn, Cr	20
5086	Non-heat-treatable	Mg, Mn, Cr	25
5456	Non-heat-treatable	Mg, Mn, Cr	20
7001	Heat treatable	Zn, Mg, Cu, Cr	7
7075	Heat treatable	Zn, Mg, Cu, Cr	10
7079	Heat treatable	Zn, Mg, Cu, Mn, Cr	10

(a) ≤25, difficult to extrude. Source: Ref 8

Table 2 Relationship between minimum wall thickness, circumscribing circle diameter (CCD), and press size for various harder-grade alloys

		Minimum wall thickness, mm, at CCD:										
Alloy	Section type(a)	<25	<50	<75	<100	<150	<200	<250	<300	<350	< 400	<450
AlMg3	A	1	1	1.2	1.5	2	2.5	3	4	4	5	6
AlMg5	A	1	1	1.2	1.5	2	2.5	3	4	4	5	6
AlCuMg1	A	1.2	1.2	1.2	1.5	2	3	5	5	6	7	8
AlCuMg2	A	1.2	1.2	1.2	1.5	2	3	5	5	6	7	8
AlCuMg2(b)	B	2	2	3	4	5	5	6	8	10	10	12
AlZn5MgCu	A	2	2	2.5	3	3	5	6	8	12	12	14
Press size, MN	…	10	10	10	10	10–25	25–35	35–50	50	50–80	80	80

(a) A, solid and semihollow sections; B, hollow sections with uniform wall thicknesses (including tube); C, hollow sections with varying wall thickness (one or more cavities in the section). (b) Extruded over the mandrel. Source: Ref 11

pendent on Zn content. The addition of certain percentages of Cu and Zr also reduces the extrusion speed.

Product Shapes and Sizes

The fundamental points describing product shapes and sizes are discussed in the section "Product Shapes and Sizes" in Chapter 6 and are essentially the same for the extrusion of soft and hard aluminum alloys. Based on the difficulty of extrusion, Laue and Stenger (Ref 11) drew a good relationship between minimum wall thickness, circumscribing circle diameter (CCD), and press size of hard alloys, as shown in Table 2.

Extrusion Practices

Extrusion Parameters

Extrusion parameters (e.g., billet temperature and extrusion speed) are fully dependent on the chemistry of each alloy. The container temperature is controlled based on the initial billet temperature. The typical values of extrusion parameters of some harder alloys are given in Table 3

Table 3 Typical values of billet temperature and extrusion speed of some harder alloys

Alloy	Type	Billet temperature °F	Billet temperature °C	Exit speed ft/min	Exit speed m/min
2014–2024	Heat treatable	788–842	420–450	5–11	1.5–3.5
5083, 5086, 5456	Non-heat-treatable	824–842	440–450	7–20	2–6
7001	Heat treatable	700–780	370–415	2–5	0.5–1.5
7075, 7079	Heat treatable	572–860	300–460	3–7	0.8–2
7049, 7150, 7178	Heat treatable	572–824	300–440	2.5–6	0.8–1.8

Note: Temperatures and extrusion speeds are dependent on the final shape and the extrusion ratio, and it may be necessary to start with lower billet temperatures than mentioned in the table. Source: Ref 11

for guidance only. Actual billet temperatures and extrusion speeds vary with product complexity.

Temperatures and extrusion speeds are dependent on the final shape and the extrusion ratio, and it may be necessary to start with lower billet temperatures than mentioned in Table 3.

Press Control

Harder alloy extrusions used in actual applications, such as the aerospace industry, present challenges to an extruder that they be defect free. Many press parameters, such as billet temperature, container temperature, extrusion speed, and butt thickness, need to be controlled carefully to prevent any inclusions from being entrapped into the extruded shapes, and to avoid other defects, such as cracking and blistering. Entrapping oxide or any nonmetallic inclusions can cause failure of the material due to a different, yet related, feature, such as surface or subsurface blisters and other undesirable surface defects. It is important to recognize that accumulation of the billet surface layer into an extrusion butt of adequate size is actually desirable compared with the detachment of oxide skin from the container surface and emanating as a defect on the extrusion surface or subsurface.

Aluminum's property of adhering to steel leads to the separation of the oxide skin of the billet onto the liner interior surface due to the following:

- Difference in temperature between billet and container (container temperature is typically 50, either °C or °F, lower than the billet temperature)
- Increased billet-container interface friction

Friction prevents the outer surface of the billet from sliding, and the undesirable skin of the billet is left in the container as the dummy pad shears metal during its forward stroke. The oxide layer separation and cleaning mechanism are shown schematically in Fig. 1 to 3. Figure 1 shows that the container has a residual built-up oxide layer prior to the

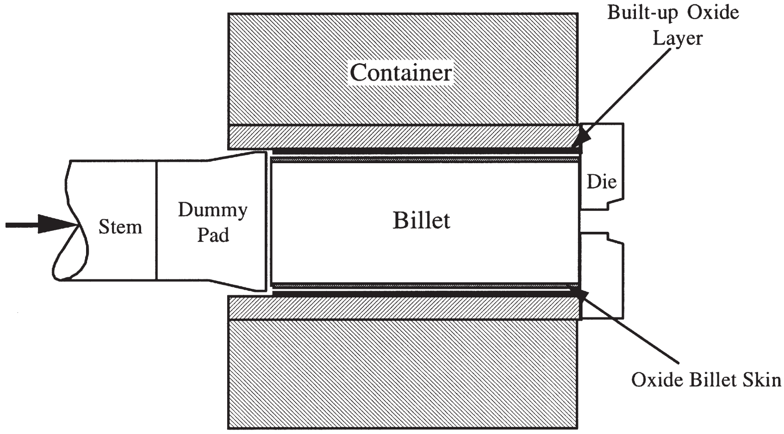

Fig. 1 Billets with initial oxide layer sitting inside the container having a left-over oxide layer

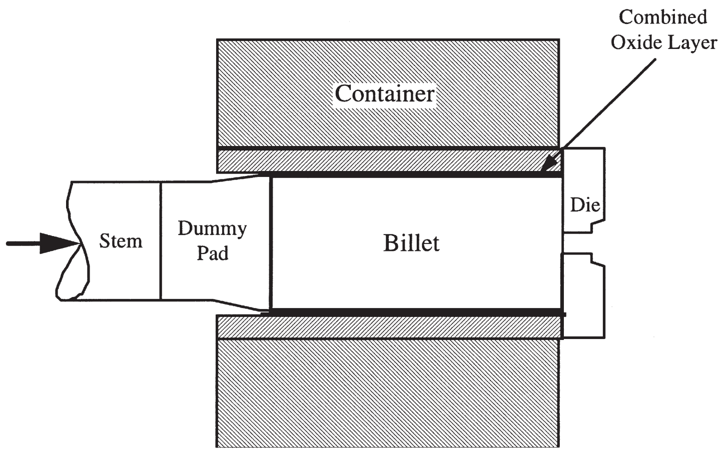

Fig. 2 Oxides combined under pressure

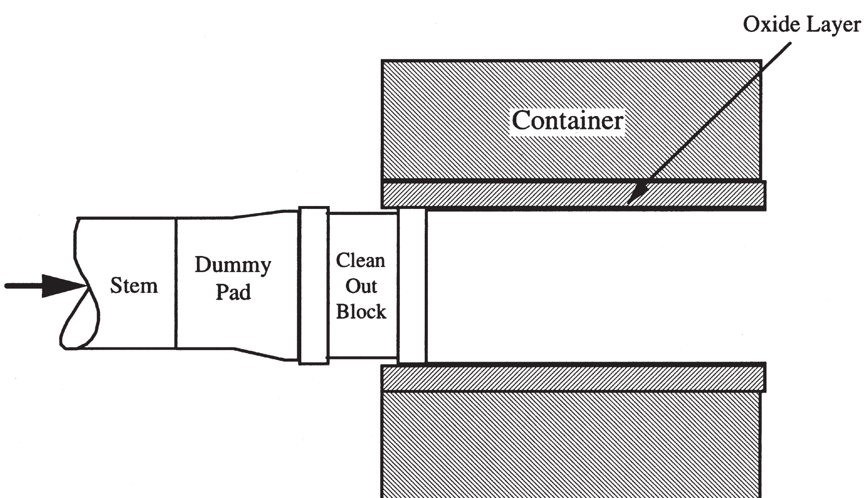

Fig. 3 Cleaning of oxide layer using a clean-out block

next billet being loaded. Figure 2 shows that after billet upset, the oxide layer of the new billet mixes with the previous oxide layer left in the container. Figure 3 explains the cleaning procedure of the container using the clean-out block recommended after every 15 to 20 billets and at every alloy change. During upsetting, normally the temperature of the container inside the layer skin is less than the temperature of the current billet. When the temperature difference is small, skin is not readily separated. Built-up skin oxide in the container layer is removed by using a clean-out block, as shown in Fig. 3. Correct clearance between the clean-out block and the container bore is an important factor in the removal of the maximum quantity of the oxide skin from the container. After using the clean-out block, the oxide skin is removed according to the clearance between the clean-out block and the container bore, making some room to fill up the gap with the oxide layer by running a few more billets. For harder alloy extrusions, where the amount of oxide layer inclusion is an important factor in maintaining the highest quality extrusion, especially for aircraft applications, it is recommended to maintain certain practices:

- Using a clean-out block of proper size for every 15 to 20 billets run
- Using a scalped billet
- Maintaining a proper temperature differential between billet and container
- Using a clean-out block at every alloy change

For the same diameter of the dummy pad, oxide will continue to combine with the existing oxide layer in each billet. After a certain number of billets, the deposition will be the maximum allowable.

For a given container temperature, if the billet temperature is changed, the difference between the billet and the container temperature also changes. The greater the difference in temperature is, the greater the risk of arresting oxide on the container skin will be. With less temperature differential between the billet and the container, plus the additional temperature rise during extrusion, separation of the oxide skin is reduced, allowing oxide to flow into the container and into the extrusion.

In the extrusion industry, there is a standard size of dummy pad and clean-out block with respect to the size of the container bore. An important aspect to keep in mind when making a new dummy pad and respective clean-out block is that it is important to measure the current bore of the container. Normally, a container may be used for a long period of time if it is not required to be replaced due to some maintenance problem or to change the size of the container due to a change in the billet diameter. Due to wear and tear of the container, especially with hard alloy extrusions, the effective diameter of the container will change, or the container will locally deform. It is better to make the dummy and the clean-out block a little larger diameter (outside) to allow some room to correct the size according to the current size of the container. The dummy block hot clearance should be 0.010 to 0.012 in. (0.254 to 0.305 mm) on each side or 0.020 to 0.024 in. (0.508 to 0.609 mm) on diameter. The clean-out block should have ½ the clearance of the dummy pad.

Process Variables and Control

Harder alloy extrusions are a rather complex process compared with that of soft- and medium-strength alloys. Because the hot-working temperature range is very short, there is relatively more interaction between process variables and material properties at the working temperature. The main process variables are extrusion ratio (ER), ram speed, V_R, extrusion temperature, T_E, and extrusion speed, V_E. However, the extrusion ratio is generally fixed by the shape required by the customer for a particular die configuration and the size of the container so the temperature and the speed are the only controllable factors.

Other than process variables, the die variables are also critical for harder alloy extrusions. The die bearing length controls metal flow and friction, which causes hot spots due to localized heat generation, especially on the outer skin of the extrusion before it leaves the die. The higher the die bearing length, the higher the amount of shear deformation and the higher the temperature rise for a fixed ram speed. It is always recommended to optimize the die bearing length for a fixed extrusion ratio to improve the extrusion quality as well as the productivity. There are other possibilities of having some problems associated with a longer die bearing length, mainly, the following:

- Surface cracks
- Variation in grain structure (peripheral coarse grain)
- Die drag due to adhesion of aluminum on the die bearing

Heat Treatment

Heat treatment procedures for harder alloys differ from those for 6000-series alloys. Most of the extruded shapes of 6000-series alloy systems are normally quenched at the press. For harder alloys, aging is normally performed after solution heat treatment stretching and sawing operations. Solution heat treatment of 7075 and 2024 alloys is done separately in a temperature- and time-controlled vertical- or horizontal-type furnace with moisture control, followed by a controlled water or polymer glycol quench. The heat treatment sequence is summarized as follows:

1. Heating to the appropriate solution heat treatment temperature
2. Soaking at that temperature for a required time based on thickness

3. Quenching in water or glycol solution to a relatively low temperature
4. Aging to cause precipitation hardening at room temperature (natural aging) or at a specified temperature for the necessary time (artificial aging)

Steps 1 to 3 cover the solution heat treatment process. During solution heat treatment of aluminum alloys, the hardening constituents of the alloy, as shown in Table 4, dissolve into a solid solution. The process consists of soaking the alloy at a specific temperature for a controlled time to achieve a nearly homogeneous solid solution. Cooling from the solution temperature must exceed a certain critical rate for each alloy to obtain maximum tensile properties and resistance to intergranular corrosion after aging. Especially for aircraft alloys, such as 7075 and 2024, the cooling rate should not be less than 800 °F (445 °C)/s in the temperature range of 750 to 550 °F (400 to 285 °C). In the as-quenched condition, precipitation-hardenable alloys are unstable. On aging, submicroscopic particles form pin dislocations or irregularities in the atomic structure and grain boundaries and thus strengthen the alloy. The size and distribution of precipitates determine the optimal mechanical properties. Typical heat treatment practices of some harder alloys are shown in Table 5. Solution soak time is thickness dependent. Solution and aging temperatures and aging times vary with specifications and supplier practices. Detailed information about heat treatment processes of aluminum alloys is discussed in Ref 12.

Dixon (Ref 13) prepared a review paper on the extrusion of 2*xxx* and 7*xxx* alloys. The paper outlined the fundamental information about al-

Table 4 Principal hardening phases of different harder grade alloys

Alloy	Principal hardening phases
2*xxx*	$CuAl_2$, $CuMgAl_2$
5*xxx*	Mg_2Al_3
7*xxx*	$MgZn_2$, $CuAl_2$, $CuMgAl_2$

Source: Ref 12

Table 5 Typical heat treatment practices of various harder alloys

	Solution heat treatment			Precipitation heat treatment			
	Temperature			Temperature			
Alloy	°F	°C	Temper	°F	°C	Time, h	Temper
2014	935	500	T4	320	160	18	T6
2024	920	495	T3	375	190	12	T81
7001	870	465	W	250	120	24	T6
7075	870	465	W	250	120	24	T6

Source: Ref 12

loys and their metallurgy, extrusion process parameters, and heat treatment conditions.

Auxiliary Processes

Slight, but at times significant, dimensional changes can occur during heat treatment. These changes can be mechanical (thermal expansion and contraction) or metallurgical (structural). Mechanically, the changes can be due to thermally induced stresses or relaxation of residual stresses. Metallurgically, the changes can be due to recrystallization, solution heat treatment, and precipitation hardening. Other than the dimensional change, shape distortion may occur during heating and warpage during quenching. The extent of distortion varies with changes in section thickness. In very thick sections, the outside distortion is decreased but creates more residual stress that may be a problem in some auxiliary operations (e.g., machining). To minimize residual stress and distortion and to supply extruded shapes cut to specified lengths, the following auxiliary steps are normally used:

1. Stretching or straight forming (2 to 3%)
2. Stretching and detwisting
3. Stretch forming to give any special contour (special requirement)
4. Roll forming
5. Hand forming (if needed)
6. Sawing

Extrusion Defects

Extrusion defects related to soft- and medium-strength aluminum alloys are discussed in the section "Extrusion Defects" in Chapter 6. The fundamental cause of most extrusion defects is a lack of attention to the correct extrusion parameters. Some defects relating to the harder aluminum alloys result from the alloy chemistry and the characteristics of that particular alloy. Because the safe hot-working temperature range of any hard alloy is comparatively quite small, it is important to handle the variables such that the final temperature of the extrusion does not exceed the incipient melting temperature of that particular alloy. Some of the typical extrusion defects, mentioned by Dieter (Ref 14), related to the harder alloys are discussed in this section.

In homogeneous deformation during direct extrusion, the center of the billet moves faster than the periphery. As a result, the dead-metal zone extends down along the outer surface of the billet. After about two-thirds of the billet is extruded, the outer surface of the billet moves toward the center. Because the surface of the billet often contains oxides (Al_2O_3 or $MgAl_2O$), this type of flow may result in internal oxide stringers. This extrusion defect is generally considered to be an "internal pipe." On a transverse section through the extrusion, the defect will appear as an annular ring of oxide. The extrusion defect increases as the container wall friction increases. If a heated billet is placed in a container with a temperature significantly lower than that of the billet, the temperature of the outer layer of the billet decreases, and the material flow stress in that region will increase. Thus, the center part of the billet extrudes faster, and an extrusion defect will result. To avoid this defect, the extrusion should be stopped as surface oxides begin to enter through the die into the rear part of the extrusion, as shown in Fig. 4(a).

Back-end defects are common and could be adverse in many applications. A few examples of back-end type defects are illustrated in this section. The defect may also appear when the butt thickness is small compared with the diameter of the billet. Rapid radial metal flow (Fig. 4b) into the die results in the creation of axial holes, or funnels, in the back of the extrusion, especially in the case of heavy extrusion (low extrusion ratio), where this type of radial flow could be more prevalent.

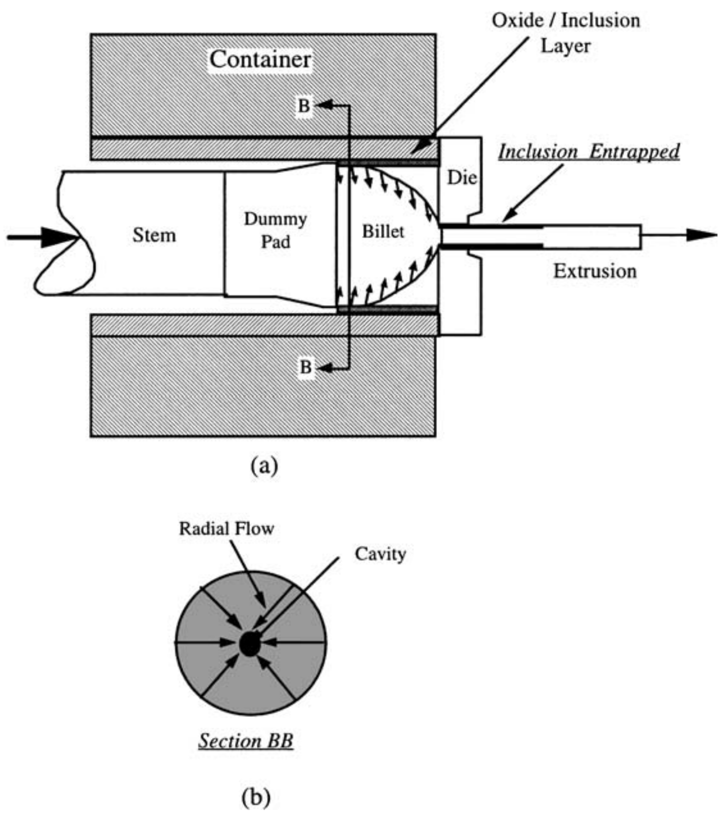

Fig. 4 (a) Model of back-end extrusion defect. (b) Schematic of billet-dummy interface, showing the radial flow

The hole, known as piping, may be extended for a certain distance from the back of the extrusion (Fig. 5). Macroetching of the end part of the extrusion helps identify any presence of piping.

Figure 6 shows the transverse cross sections of a 7016 alloy bumper extrusion showing internal voids. Samples were taken well away from a blister that appeared in the extrusion. It appears to be "feed-in" from the butt. The voids are related to the incoming depleted zone adjacent to the surface (liquation) of the billet into the extrusion. This is more evident from the cross sections of two different butts collected from the same 7016 bumper extrusion as shown in Fig. 7.

Figure 8 shows the cross section taken from the butt end of the extrusion from a 14 in. (356 mm) diameter 7075 billet. In this instance,

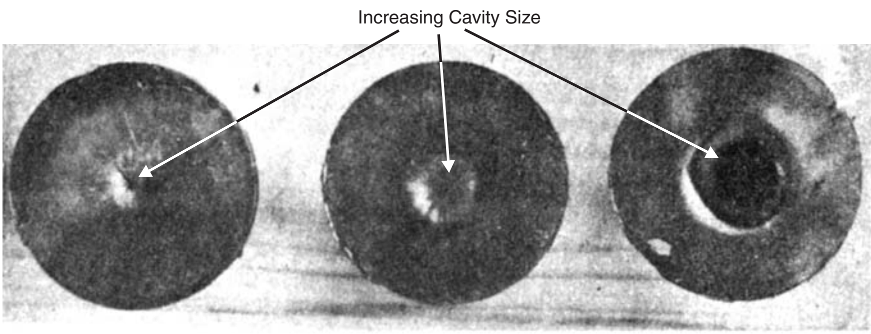

Fig. 5 Progressing piping defects. Source: Ref 15

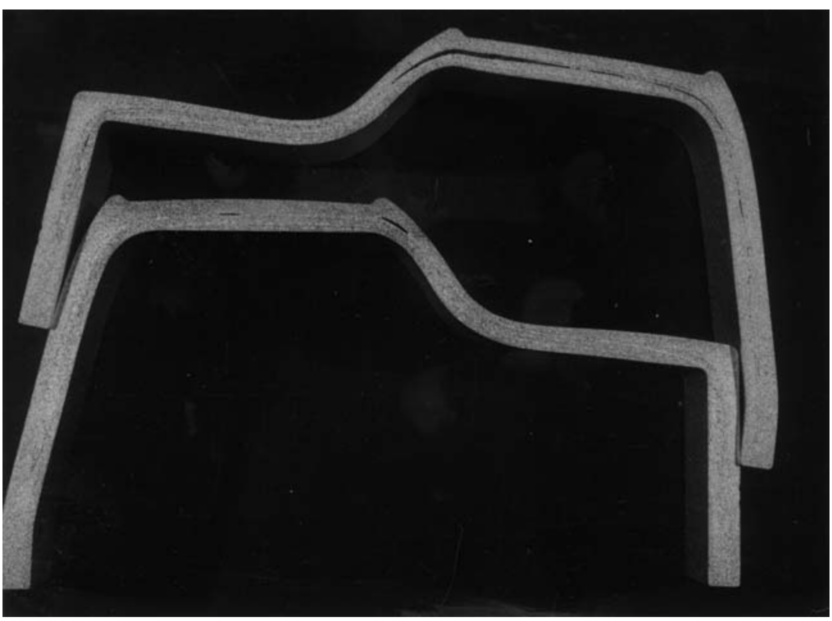

Fig. 6 Internal voids in 7016 bumper extrusion

a duplex structure occurred even though a standard extrusion practice was used.

Surface cracking, especially for harder alloy extrusions, is an important issue in extrusion defects. When the extrusion is performed at a higher speed or at a higher temperature or both, a severe form of surface serration, called *speed cracking,* can appear. This condition results

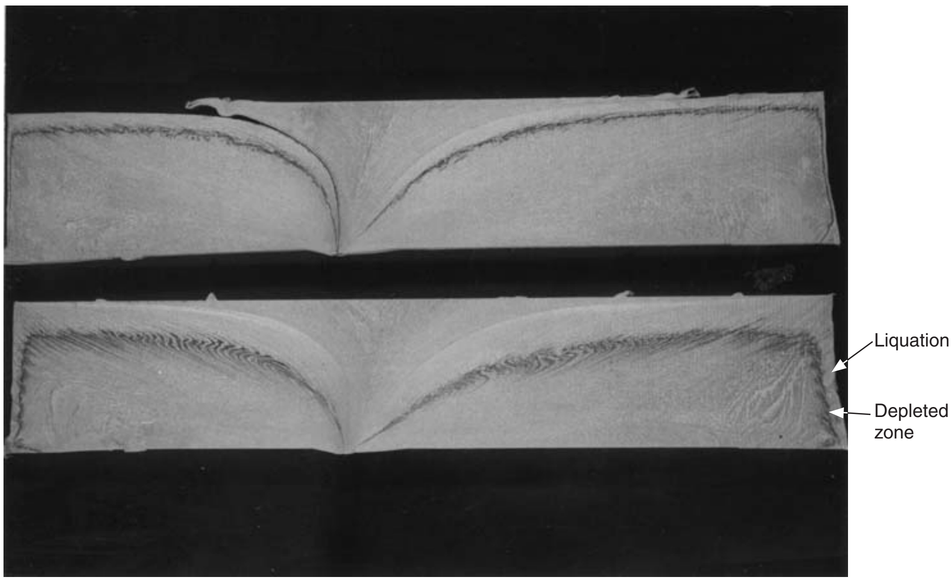

Fig. 7 Mechanism of internal voids

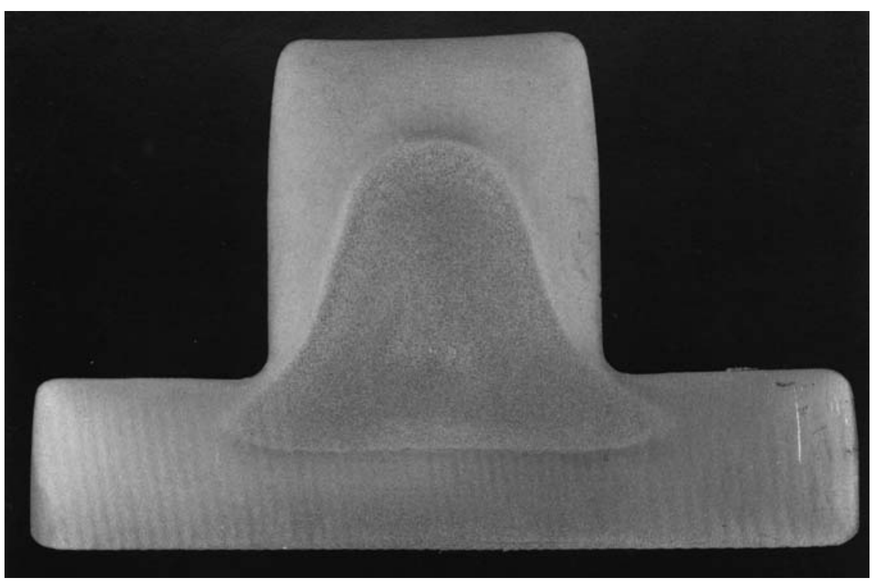

Fig. 8 Duplex structure in 7075 extrusion

from the momentary sticking of the extrusion on the die bearing due to the localized temperature rise in the extrusion. As the extrusion continues, material at the die-bearing interface loses strength due to a rise in the temperature, and surface cracks occur due to the velocity gradient of the flowing material at the die bearing-material interface. When this becomes more severe, the surface cracks appear as a "fir-tree defect."

Because of nonhomogenous deformation in the extrusion process, there is considerable variation in both structure and properties from the front to back end of an extrusion. On commencement, the material leaving the die is subjected to less deformation until steady-state conditions are reached. This condition is illustrated by viewing the variation of strength with extrusion ratio as shown in Fig. 9 by Sachs and Van Horn (Ref 16).

The surface layer of an extrusion undergoes more severe shear deformation than regions in the center of the extrusion. Friction at the die-bearing surface and the increased localized deformation both contribute to higher temperature rises on the surface compared with the center of the extrusion. The difference in temperature is more prominent in a thicker extrusion. This temperature rise and increased deformation (or strain rate) can cause the formation of larger grains in the surface layer due to localized recrystallization during subsequent solution heat treatment (Fig. 10).

In high-strength aluminum alloys such as 7075, blisters seem to be one of the major extrusion defects, especially in thin-gage extrusions. Blisters appear on the extrusion surface either during extrusion or during post-heat treatment processes. What is a blister? A blister is a bubble-shaped void on the extrusion surface that results from the thermal expansion of entrapped gas inside the grain boundary. The sources of entrapped gas in the extrusion can be from either the extrusion manufacturer or the user's handling, cleaning, and heat treatment processes. Which gas is responsible for the blister? Hydrogen (H) is the only gas

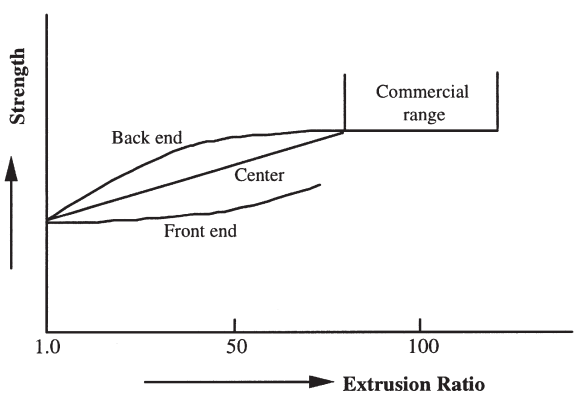

Fig. 9 Schematic representation of extrusion ratio on strength. Source: Ref 16

known to be appreciably soluble in either solid or molten aluminum (Ref 17). It is well known that hydrogen can easily be introduced into aluminum during melting, casting, heat treatment, cleaning, and pickling processes. In fact, any process that involves atomic hydrogen to the aluminum surface, whether by thermally activated dissociation of the hydrogen gas molecules, or by the electrochemical or chemical reaction, is capable of introducing sufficient hydrogen to cause blistering problems.

Blisters are formed as a result of the reaction or diffusion of hydrogen (from internal and/or external sources) on the aluminum surface. Hydrogen from different external sources diffuses into the lattice in the ionic/atomic form and forms molecular hydrogen in preferred locations, such as around an inclusion, as shown in Fig. 11(a). In addition, hydrogen already entrapped in the extrusion will migrate to areas of inclusion/high stress, as shown in Fig. 11(b).

The hydrogen ions/atoms continue to migrate at these sites until the lattice strain energy is minimized. The precipitated hydrogen atoms then recombine at the trapped sites to form molecular hydrogen, which cannot migrate through the lattice.

During heat treatment at elevated temperatures, the hydrogen gas (in the molecular state) expands, enlarging the cavity to form a blister on the surface (Fig. 12). The size of the blister is dependent on the surface area of the inclusion. The greater the surface area of the inclusion is, the greater the size of the blister will be.

Diffusion of hydrogen on the extruded surface at inclusion sites is dependent on the following factors:

- *Time of heat treatment:* Time is an important factor because hydrogen deposition is an accumulative process that increases with time. Thus, with a short-cycle time at an elevated temperature, only a

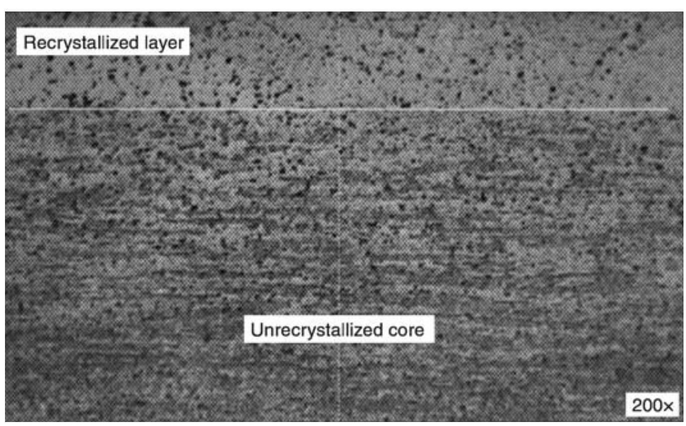

Fig. 10 Recrystallized layer in 7075 thin-gage extrusion

small amount of hydrogen will deposit, and accordingly, the size of the void will be very small.

- *Temperature of heat treatment:* At higher temperatures, atomic mobility is greater, and hydrogen can diffuse more readily. Furnace temperature control becomes a very critical issue: If the temperature exceeds the normal solution heat treatment temperature and reaches the incipient melting range of the material, blisters readily form.
- *Area of grain boundary:* The amount of hydrogen deposition at any point will be a function of the area of the grain boundary. Coarse

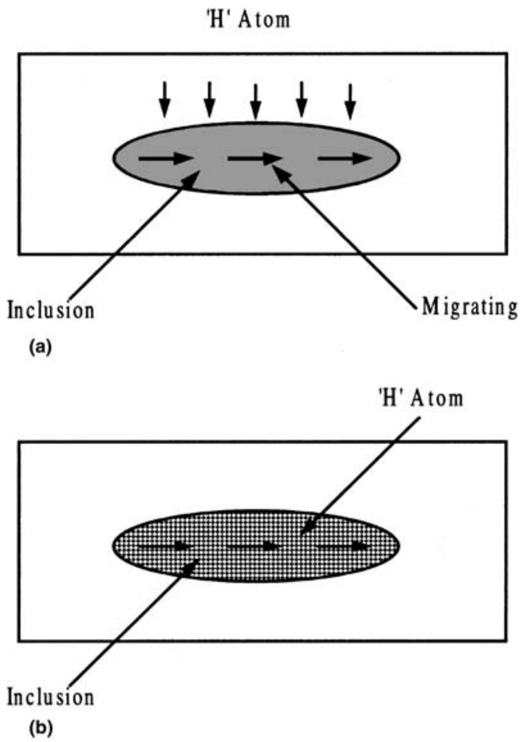

Fig. 11 Reaction/diffusion of hydrogen (H) with aluminum at inclusion sites. (a) External. (b) Internal (already trapped)

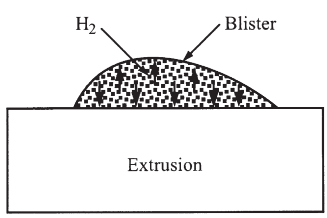

Fig. 12 Expansion of hydrogen gas (in molecular state) at an elevated temperature

grain structure has very little grain boundary, but fine grain structure has large grain boundary. Thus, with a coarse grain structure, deposition of a given amount of hydrogen can produce many large voids, whereas with fine grain structure, the deposition of hydrogen will be spread out, and the effects will be less pronounced.

- *Chemistry of alloy:* Alloys with high alloying constituents, particularly those containing appreciable amounts of magnesium, such as the 7*xxx* series, are generally more susceptible to picking up hydrogen. This tendency is because the natural protective oxide film is less continuous or more porous, permitting easier access of moisture to the metal.

The undesirable effects of furnace atmospheres with high moisture content generally can be alleviated by introducing volatile fluoride-containing compounds inside the furnace during heat treatment.

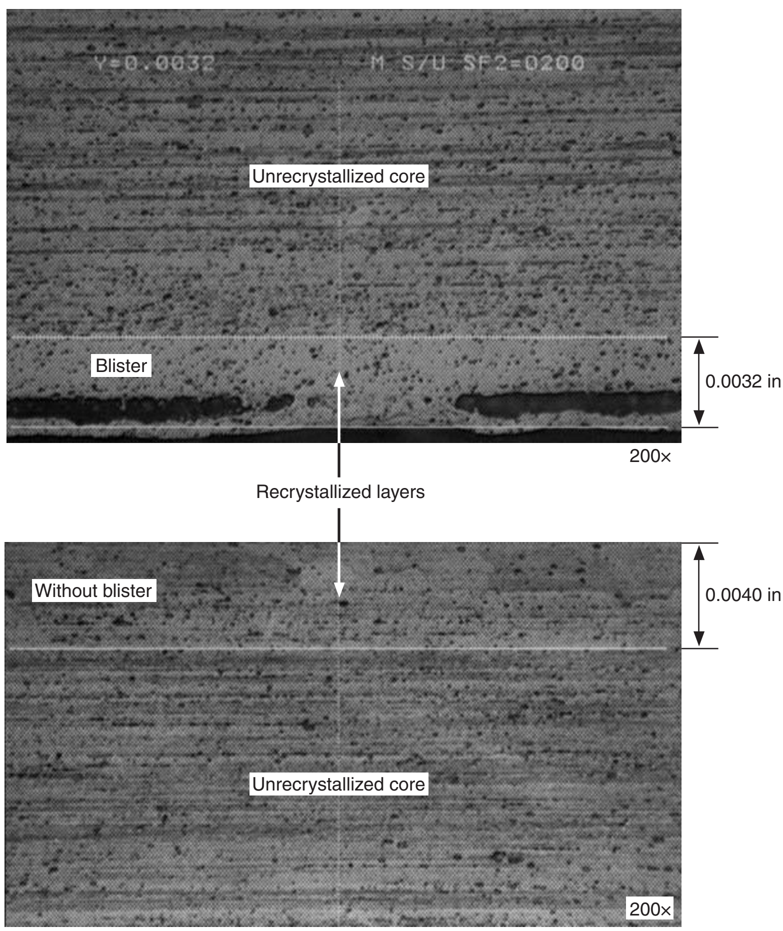

Fig. 13 Microscopic photographs showing the recrystallized layer in both blistered and unblistered areas

Ammonium, sodium and potassium fluoborate, and boron trifluoride (Ref 18) are among the compounds used for such control.

A recent study was done by Saha (Ref 19) to find the sources of blisters that were appearing on the surface of thin-gage 7075 'O' temper extruded shapes during solution heat treatment. A series of tests were conducted in three different phases with extrusions from three different manufacturers, with different heat lots, and with differing cleaning and heat treatment process variables. Variables used in the solution heat treatment process included the use of, and the exclusion of, sodium fluoborate (a drying agent). The microstructures of the unblistered and blistered sections of the extruded parts in the T6 condition (solution heat treated and then artificially aged) were studied. Both blistered and unblistered areas exhibited a recrystallized surface layer with an unrecrystallized core (Fig. 13). The depth of the recrystallized zone varied from part to part. Blisters were found mainly in the recrystallized zones or at the junction of recrystallized and unrecrystallized zones, as shown in Fig. 14. These observations are in agreement with those of Hunter, Montgomery, and Wilcox (Ref 20). A protective corrosion inhibitor, applied by the extrusion mill, minimized blisters or prevented blisters from forming during solution heat treatment. Additional analysis revealed that blistering was not affected by the type of furnace used for heat treating. The presence of sodium fluoborate decreased the likelihood of blistering in both furnaces. This study also explored the formation of blisters on extruded material delivered in two different O and

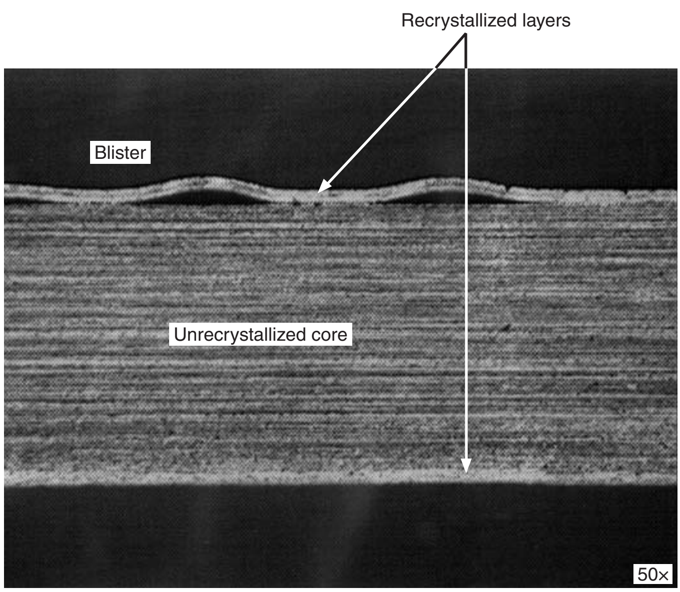

Fig. 14 Micrograph showing a blister at the junction of the recrystallized and unrecrystallized zones

F tempers from the same extrusion. The F-tempered material had a greater tendency to form blisters than did the O tempered material.

A recent review was done by Bryant and others (Ref 21) on the metallurgical defects found in medium- and high-strength aluminum extrusions. Possible causes and prevention were also discussed.

Quality Assurance

Quality assurance standards generally require heat treated extruded shapes to meet certain conditions, such as tensile, compression, and shear properties. The major market for harder alloy extruded shapes is aerospace, which imposes stringent demands to ensure satisfactory extrusion quality for many critical extrusions, such as airframe structural members. Before going for mechanical and physical testing, extrusions need to be inspected using sophisticated computer-controlled inspection machines to compare the actual image with the original design to meet demanding dimensional tolerances.

Test Methods

In the previous chapter, in the section "Mechanical and Physical Tests," general mechanical and physical test methods are mentioned. In harder alloy extrusions, quality assurance standards may specify that the following tests be conducted:

- Tensile/compression/shear
- Hardness (for process control)
- Intergranular-corrosion (especially for 2014 and 2024 alloys)
- Electrical conductivity
- Fracture toughness (for aerospace alloys)
- Nondestructive (ultrasound)

Extrusion of Aluminum Matrix Composites

Aluminum metal matrix composites are conventional aluminum alloys with additions of ceramic, typically, alumina (Al_2O_3) or silicon carbide (SiC), in short-fiber or particulate form. Extrusion of aluminum alloy-based metal-matrix composites (MMCs) is becoming recognized in the aluminum industry. MMCs have favorable properties, such as lighter weight, increased stiffness, improved wear resistance, and higher strength compared with conventional aluminum alloys. Initially expensive in the early days of development, MMCs are becoming less costly as volume increases. Alumina particles reinforced with MMCs are more cost effective and easier to extrude than other types of composites containing short or long ceramic fibers. Dixon (Ref 22, 23) outlined applications and developments in the extrusion of aluminum-base MMCs.

Today, the most cost-effective MMCs are produced by ingot metallurgy, where the ceramic particles are vigorously mixed into molten aluminum alloy to ensure complete wetting and incorporation. The composite is then cast in the extrusion billet using standard direct chilled (DC) casting technology. The ingot metallurgy process is limited to producing MMCs containing up to 25% by volume of alumina. Other MMCs available for extrusion can be produced by more costly processes, such as powder metallurgy and can contain higher reinforcement levels, either as ceramic in particulate form or as short whiskers. MMCs produced by the P/M process can have enhanced material characteristics, but they also present increased difficulties during deformation in extrusion. In the last few years, MMCs have been successful in penetrating recreational and automotive markets. Due to the presence of Al_2O_3 particles in the matrix, the more abrasive material can cause excessive wear of extrusion dies, and tooling costs tend to be higher. Extrusion pressure is also higher due to an increase in the material flow stress. In this section, the recent developments in ingot metallurgy, extrusion die materials and design, extrusion practices, and specific areas of post processing, which influences the properties of the extruded MMCs, are discussed.

Billet Metallurgy and Flow Stress

Aluminum-base MMC billets for extrusion can be produced by ingot metallurgy using Al_2O_3 particles for reinforcement. The Al_2O_3 particles are essentially blocky or platelet in nature. The aspect ratios of the particles are kept around 3 to 1 to facilitate the deformation process during extrusion with less chance of fracture, a common problem with high-aspect ratio reinforcement (e.g., whiskers). The particle size is nominally 10 to 20 μm. Aluminum-base MMC billets are currently available for extrusion, as shown in Table 6.

Table 6 Al_2O_3 percent by volume for different composites

Composite	Al_2O_3 content, vol%
6061/ Al_2O_3 /xp	10
	15
	20
2014/ Al_2O_3 /xp	10
	15
	20
1060/ Al_2O_3 /xp	10
7005/ Al_2O_3 /xp	10
7075/ Al_2O_3 /xp	10

Source: Ref 23

In DC casting, segregation at the surface of the billet causes a region of particle-free material around the periphery of the billet. The depth of the particle-free zone depends on mold design and casting variables and can be controlled to a very minimum value.

Billet quality control practices are similar to those employed for standard aluminum alloys, with additional checks for Al_2O_3 vol% consistency, particle distribution, particle/matrix reaction, and clustering of unwetted particles. Currently, higher-standard billet quality is maintained by proper statistical process control (SPC). MMC billets are homogenized prior to extrusion, as are regular alloy billets, to reduce macrosegregation and achieve a fine distribution of matrix secondary phases.

Brusethaug et al. (Ref 24) investigated the use of SiC reinforced in AlSi7Mg alloys for automotive applications. They found that an AlSi7Mg alloy can be extruded with good results. Maximum extrusion speed can be obtained by bringing the Mg-containing phases into solid solution. Adding 15% vol SiC particles reduces the maximum extrusion speed by 30 to 40% by causing a more rapid increase of the surface temperature of the extruded profile. The extrusion pressure is increased by 10 to 15%.

Die Materials and Die Design

Hot die steel, typically AISI H13, is used as a standard die material for the extrusion of aluminum alloys throughout the aluminum industry worldwide. However, when extruding MMCs, dies made from tool steel are not used due to the abrasive action of the hard ceramic particles. The development of suitable die materials and die design has been the greatest challenge in extrusion of aluminum-based metal matrix. Dixon, Jeffery, and Holcomb (Ref 23, 25) studied both die wear and die design using a variety of die materials. Recently, Zhou et al. (Ref 26) attempted to find the replacement of tool steel with hard metals, such as tungsten carbide (WC) containing three different levels of cobalt (Co). They experimented with 6061 with 15% Al_2O_3 composite through a channel-shaped die. They found that these hard metals can be used as candidate die materials to extrude aluminum-base MMCs under various extrusion conditions.

Dixon indicated that the die life is still limited to usually not more than 5000 feet (1524 m) of extrusion, even using wear-resistant carbides and ceramic dies (Ref 22). However, the die wear is a complex phenomenon, and it is related to many variables such as the following:

- MMC matrix alloys
- Type and amount of particulate reinforcement
- Extrusion parameters, such as temperature and speed

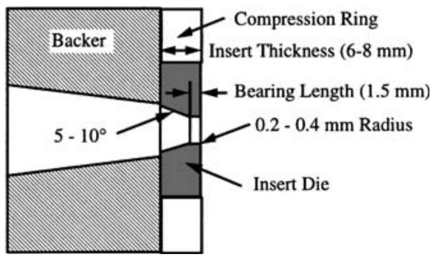

Fig. 15 Typical insert die with backer and recommended insert details. Source: Ref 22

- Extrusion ratio
- Shape of the profile

Flat-faced dies and conventional porthole and bridge-die technology is still applicable for MMC extrusion. To improve the surface quality of the extruded shapes and to extend the die life, the following design steps are recommended:

- A short bearing length with tapered relief (Fig. 15) should be used for all insert materials.
- A lead radius of approximately 0.01 to 0.02 in. (0.2 to 0.4 mm) should be provided in the bearing.
- A bearing surface finish of 1 μm or less should be used, and the direction of polishing should be in the same direction as the extrusion.
- Mating surfaces in the H13 tooling and carbide inserts must be as square and as parallel as possible, and the surfaces must be fine machined or ground.
- Clearance between the exit of the insert die and the die holder should be at a minimum to ensure maximum strength

Extrusion Process and Defects

Like regular aluminum alloys, direct or indirect extrusion processes are used to extrude aluminum-base MMCs. Because the flow stress of aluminum-base MMCs is higher than that of aluminum matrix alloy, extrusion of MMCs employs higher pressures. The relationship between flow stress of the billet MMC and the extrusion variables, such as temperature, strain, and strain rate, is important in determining the extrudability of the MMC for a required shape.

Due to the presence of ceramic particulate reinforcement, MMCs have lower ductility than aluminum matrix alloys at an elevated extrusion temperature. Surface tearing is a common extrusion defect in MMCs; such tearing includes hot shortness at high temperatures as well as ductility-related tearing at lower temperatures and speeds.

Forming of Extrusion

Lloyd (Ref 27) studied the occurrence of particle fractures and void formations when a composite is subjected to tensile strain at an ambient temperature. One of the prime benefits of particle addition is that it increases the stiffness, or elastic modulus, of the material. Therefore, it is important to understand the effect cold work, such as tube drawing, may have in reducing material stiffness or density. The effect of cold-draw reduction on the elastic modulus of extruded aluminum composite of 6061 aluminum alloy reinforced with 20% vol Al_2O_3 particulate was examined by Klimowicz et al. (Ref 28). Metallographic examination showed modulus loss was caused by the fracture of some of the Al_2O_3 particles. The results indicated that the amount of cold drawing must be minimized in order to maximize modulus. Lesser amounts of cold work in regular stretching operations after extrusion where the total reduction lies within 2 to 3% have an insignificant effect on modulus reduction.

Powder Metallurgy Alloy Extrusions

In this section, a short review based on work by Davis and Cook (Ref 12, 29) outlines the P/M process for making billets for extrusion. The P/M process begins with mixing and blending prealloyed metallic powder and SiC whiskers, followed by heating, degassing, and pressure consolidation into intermediate or final product forms. The flow diagram of the P/M process to produce SiC whisker-reinforced MMCs in a dense, gas-free condition is shown in Fig. 16.

Cylindrical billets of SiC whisker-reinforced aluminum alloys have been hot extruded into a wide variety of solid and hollow shapes, including rod, bar, and tube. The sequence of operations in direct extru-

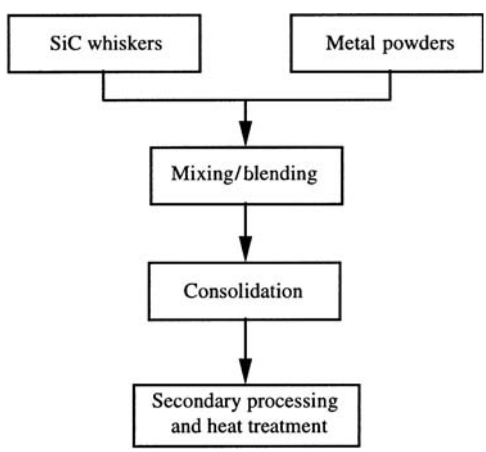

Fig. 16 Flow diagram of SiC whisker-reinforced MMCs

sion is the same as for regular aluminum alloys but with subtle differences relating to the deformation characteristics of the material. Because P/M composites have a higher flow stress compared with that of regular aluminum alloys, higher extrusion pressures are needed. Load-versus-ram displacement curves indicate that more work is required to upset and overcome friction and shearing for P/M composites than for the unreinforced regular alloys. The initial P/M billet temperature must be carefully controlled to prevent incipient melting of the metal matrix due to heat generation, plastic deformation, and friction in the container and die in the direct extrusion process. Powder metallurgy composite materials are, at times, extruded in lubricated conditions to prevent surface defects by reducing friction at the die bearing. Most shapes are produced using shear face or conical dies. Streamlined dies are required for more complex shapes. Extrusion ratios as high as 70 to 1 have been successfully achieved with whisker-reinforced composites. Because whiskers align in the extrusion direction, tensile properties tend to be strongly directional.

Dashwood and Sheppard (Ref 30) described the consolidation and extrusion of two AlMg alloys, strengthened by the addition of the transition elements, Zr and Cr, and prepared from rapidly solidified powders. Extrusion of rods and shapes was performed using a cold-compacted, nondegassed billet induction heated prior to extrusion. Limit diagrams prepared for the alloys investigated showed them to be considerably more extrudable than their cast counterparts.

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CHAPTER **8**

Process Control in the Aluminum Extrusion Plant

Quality is the basic marketing factor in the aluminum extrusion industry. Quality is a key factor leading to business success, growth, and an enhanced competitive position. There is a substantial return on investment from an effective quality-improvement program that provides increased profitability to the company that effectively employs quality as a business strategy. Consumers believe that the products of certain companies are substantially better than those of other companies, and they make purchasing decisions accordingly. Effective quality-improvement programs can result in increased market penetration, higher productivity, and lower overall costs of manufacturing and service. Consequently, companies with such programs can enjoy significant competitive advantages.

The quality of extrusion is totally dependent on the functions of the process control of each head of the functional block diagram of the quality control system shown in Fig. 1. The better the process control is, the better the quality of extrusion will be. It is important to pay attention to the total process control system, from billet casting to the heat treatment of extrusion. In this chapter, process control of each section is discussed, with detailed process control charts and flow diagrams of each process to provide a better understanding of each process stage. The main components of extrusion plants are the billet, the die, the extrusion

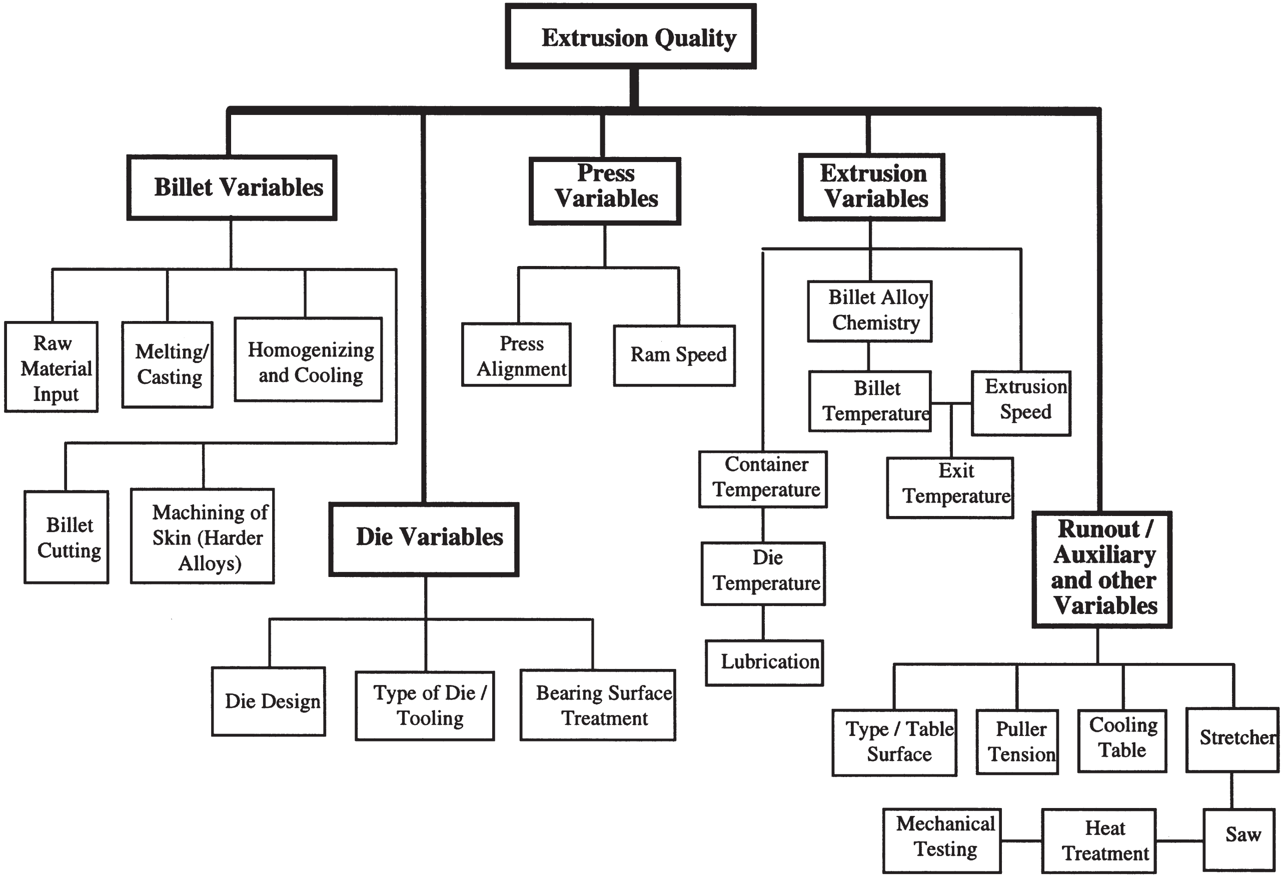

Fig. 1 Typical flow diagram of an extrusion quality control system

press, the extrusion process, stretching, cutting, heat treatment, and surface treatments.

This chapter presents a complete process and quality control system to enable effective control of extrusion process variables, billet, die, and press properties to achieve quality objectives at minimum costs. A test program was designed to determine the effect of variables from the extrusion process, billet properties, die shop performance, heat treatment process, and hydraulic press capabilities. The result forms a powerful framework for troubleshooting an aluminum extrusion operation to effect process stability and improve productivity and quality.

Extrusion Plant and Processes

Method of Operation. In general, aluminum extrusions are categorized into two different areas based on the properties and application of the alloys in commercial and industrial use:

- *I, Soft- and medium-grade alloys:* Architectural, commercial, and industrial applications (non-heat-treatable and heat treatable alloys)
- *II, Harder alloys:* Structural, industrial, and especially, aircraft applications (heat treatable alloys)

Figure 2 shows the functional block diagram of a softer alloy extrusion plant. Similarly, Fig. 3 and 4 show the functional block diagrams of harder alloy extrusion plants with different heat treatment processes to satisfy customer requirements.

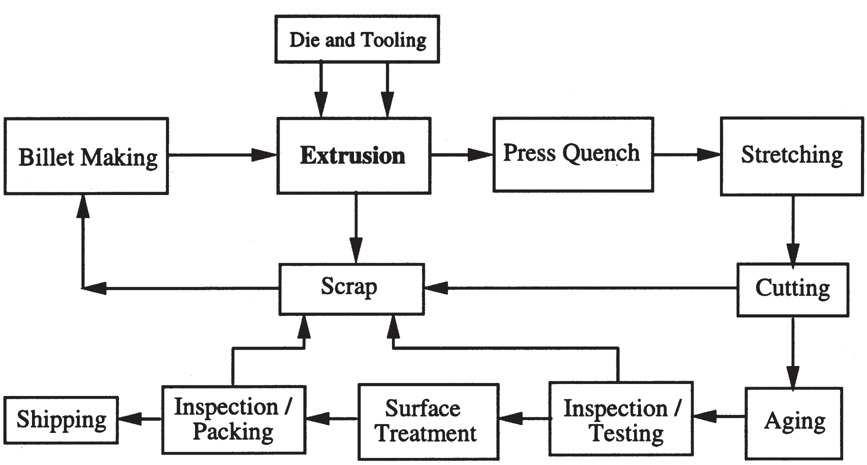

Fig. 2 Functional block diagram showing the principal process steps involved in a soft aluminum alloy extrusion plant

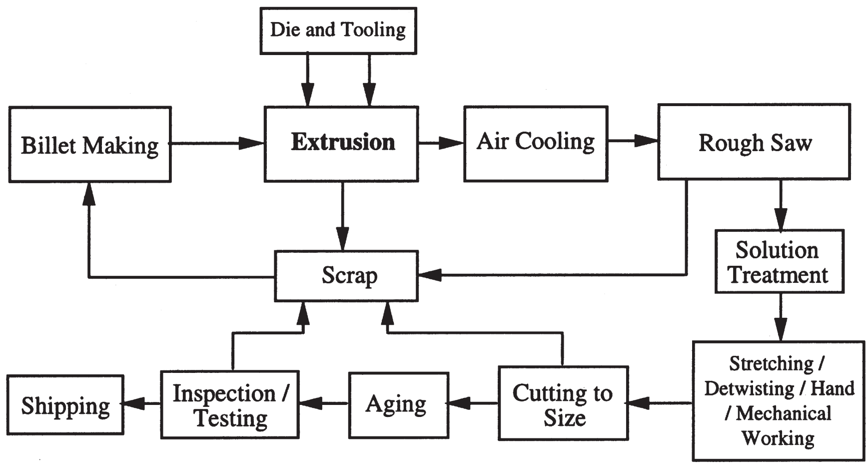

Fig. 3 Functional block diagram showing the principal process steps involved in a harder aluminum alloy extrusion plant

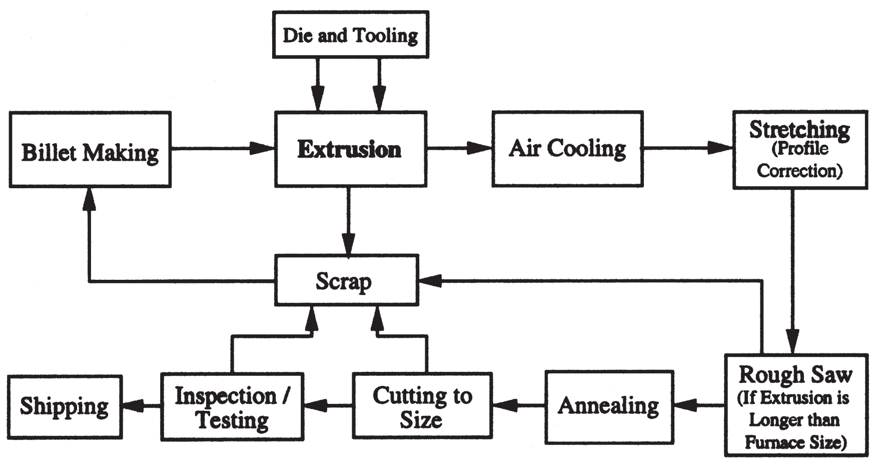

Fig. 4 Functional block diagram showing the principal process steps involved in a harder aluminum alloy extrusion plant with an annealing process

Billet-Making Variables

Process Control Chart. A typical quality control checklist for billet-casting facilities has been designed (Table 1) for proper documentation of potential parameters to form a powerful framework for troubleshooting an aluminum extrusion operation.

The flow diagram and the quality check points are shown in Fig. 5. The parameters collected from Table 1 (Ref 1) are checked through the flow chart for statistical analysis.

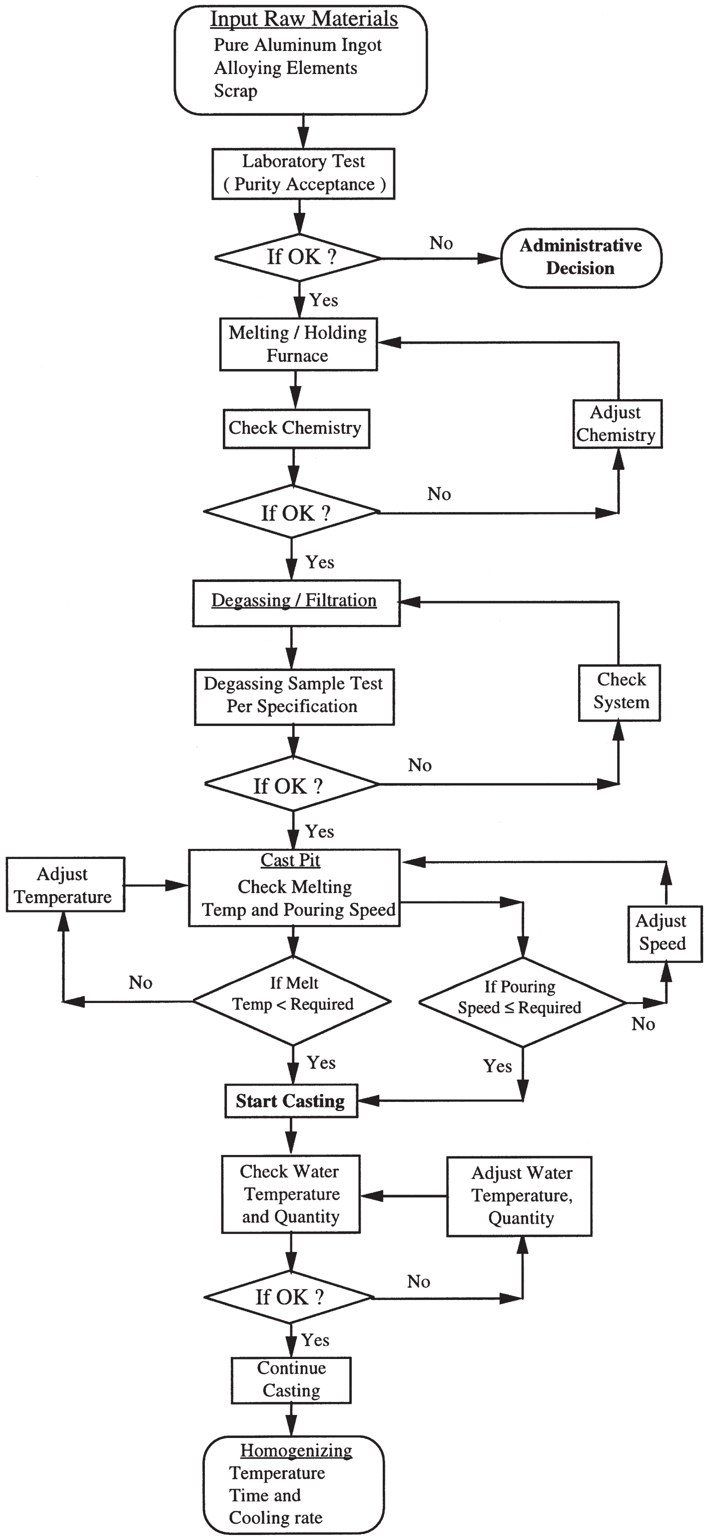

Fig. 5 Typical flow diagram of billet casting variables

Table 1 Billet casting checklist

Furnace operator: **Alloy:** **Date:**

Saw operator: **Shift:**

	Cast/drop No.	
Parameters	**1**	**2**
Charge material		
Pure aluminum		
Alloying elements		
Scrap, %		
Type of scrap		
Charge weight		
Melting furnace		
Firing rates		
Melting rates		
Temperature		
Dross generation		
Melt chemistry		
Holding furnace		
Fluxing practice (solid or gaseous)		
Temperature		
Grain refiner		
Chemistry adjustments		
Filter systems		
Filter quality		
In-line degassing		
Hydrogen content		
Melt cleanliness		
Temperature		
Cast Pit		
Head control		
Cooling water flow		
Casting speed		
Water temperature		
Water quality		
Pouring temperature		
Time of casting		
Homogenization		
Temperature		
Time		
Cooling Rate		
Sawing and Packaging		
Stamp cast No.		
Billet length		
Surface quality		
End scrap		
Recovery, %		
Gross weight of logs		
Melting loss, %		

Source: Ref 1

Extrusion Die Variables

Dies for Solid and Hollow Shapes. Die construction is one of the most important determinants in the successful extrusion of even the simplest shapes. Many factors affect the running of a die at the press, including close correlation between die correction and initial design, press operation, tooling design, and maintenance. Close cooperation between the press operator and the die corrector, as well as the die designer, is necessary in order to reach the best solution in each instance. Extrusion dies can be divided into simple ones used for solid and open shapes and those with welding chambers (porthole, spider, and bridge dies) for semihollow and hollow shapes. A die for an aluminum section must have the following characteristics:

- Accurate dimensions and product shape to avoid the need for any corrective work
- Maximum possible working life
- Maximum length of the extruded section
- A high-quality surface finish maintained over many extrusions
- High extrusion speeds
- Low manufacturing costs

These requirements are usually fulfilled for rods and other simple shapes. However, as the complexity of the die increases, it becomes more difficult to comply with all the above-mentioned requirements. Many factors have to be considered in the design and construction of a die, including the flow pattern, maximum specific pressure, geometrical shape of the section, the extrusion ratio, wall thickness and tongue sizes, bearing length, and, finally, the tolerances of the section.

Incorrect metal flow can give rise to areas of critical deformation, which form visible streaks on the surface of the finished product. Skill and experience are required to obtain uniform metal flow through all parts of the die, especially with unsymmetrical shapes and different wall thicknesses. The resistance to flow is greatest in the narrow parts of the die, and the bearing lengths in that region have to be reduced. If insufficient attention is paid to these preventive measures, the extruded product will be twisted and warped. Some basic rules should be followed during the initial laying out of a die for solid shapes, and these determine the position of the die aperture.

Because many factors are involved in pushing aluminum through a die at the press, it is necessary to keep a close relationship between the die correction and the initial design based upon press operation, tooling design, and maintenance. A system has been designed by Saha (Ref 2) for both solid and hollow dies as shown in Tables 2 and 3, respectively, to collect potential die parameters for proper documentation and necessary analysis on die performance and die life. Besides the die performance, a series of experiments can be performed using an extrusion process checklist to determine the best possible process parameters for a particular die with a particular alloy. The same analysis can also determine the best die design for better productivity and quality of extrusion.

Table 2 Die shop parameters for solid dies

Press size: **Item:** **Type:** **Die size:**
Container size: **Die No.:** **Die vendor:** **Bolster size/No.:**

Design parameters																	
	Die bearing (as received)				Correction			Trial/production run						Hardness, HRC		Die deflection	Comments
Wall	Bearing length	Squareness	Surface condition	Pocket/ feeder plate	Wall	Bearing length (b1, b2, etc.)	Pocket/ feeder plate	Date	Shift	Billet size	Runout	Wt/unit length	No. of billets	New	Old		

Table 3 Die shop parameters for hollow dies

Press size: **Profile No.:** **Type of die:** **Die size:**

Container size: **Die No.:** **Die vendor:** **Bolster size/No.:**

Design parameters, mandrel/die cap					Correction, mandrel/die cap				Trial/production run						Hardness, HRC (new/old)		Mandrel deflection/crack	Comments
Bearing			Wall	Port/ weld chamber/ pocket														
Squareness	Flatness	Surface			Port	Weld chamber	Wall	Bearing length (b1, b2, etc.)	Date	Shift	Billet size	Runout	Wt/unit length	No. of billets	Mandrel	Cap		

The flow diagram of die variables is shown in Fig. 6. The parameters collected from Tables 2 and 3 should be checked through the flow chart for an analysis of the performance and the life of the die.

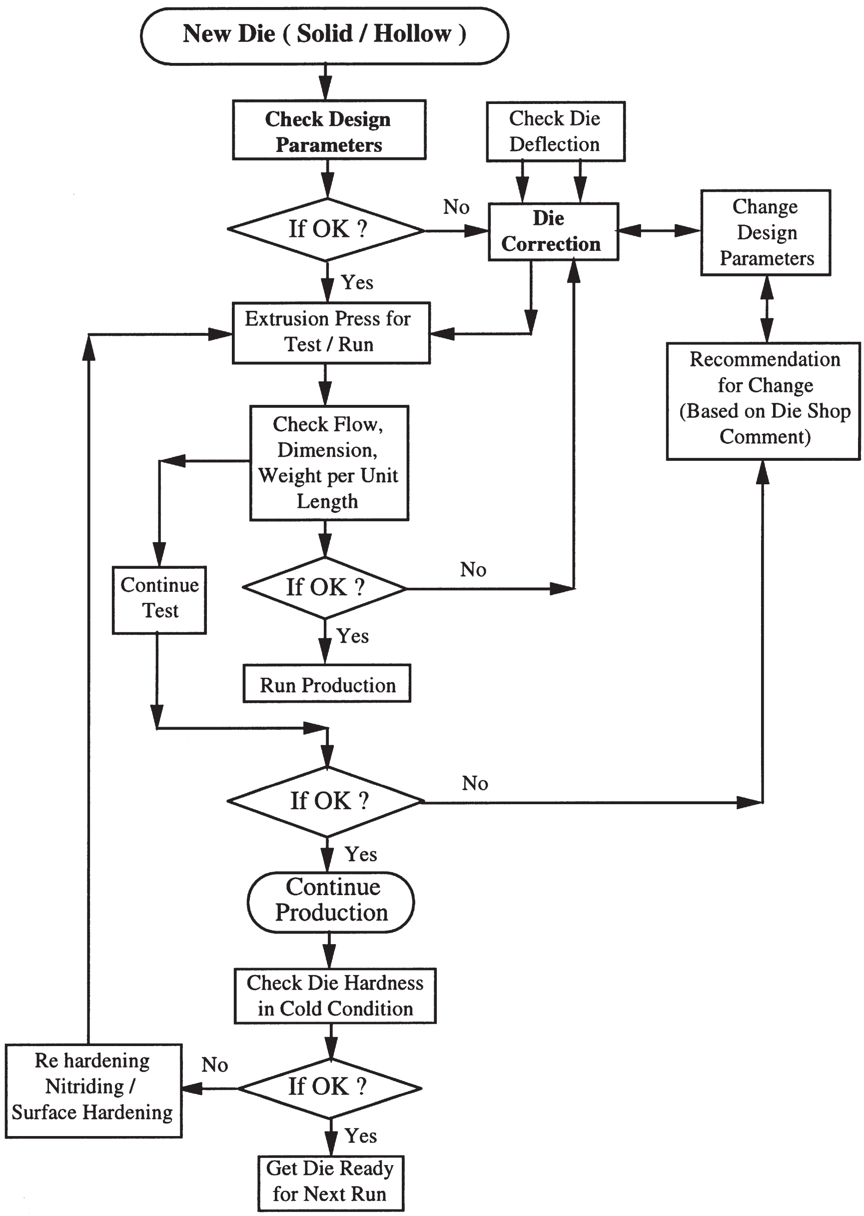

Fig. 6 Flow diagram of die variables

Extrusion Press and Auxiliary Equipment

The total quality of extrusion is completely dependent on the performance of the extrusion press and its auxiliary equipment. In addition to performing preventive maintenance, completing a routine checklist of the function of each unit of the press and its auxiliary systems is an important day-to-day task. For proper documentation of the performance of the extrusion press and the auxiliary equipment, a system has been designed to collect the important variables of the press as well as the auxiliary equipment (Table 4).

Extrusion Process Variables

In this section, brief attention is focused on extrusion variables and the factors that influence successful extrusion. A quality checklist has been designed to document the extrusion process variables against each die (Table 5) and to monitor changes in critical variables to ensure product quality. Checklists for stretching and sawing as shown in Table 6 finally determine the dimensional accuracy and percentage recovery against each die.

Extrusion Process Control Chart. For the statistical process and quality control of the extrusion process, it is important to collect the process variables. The extrusion variables included in the flow diagram with quality checkpoints for the statistical analysis are shown in Fig. 7.

Auxiliary Process Variables

Stretching and Sawing Variables. An example of the process control chart for stretching and sawing 6063 alloy extrusions is shown in Table 6. The stretching and sawing variables with quality checks are explained in the flow diagram shown in Fig. 8.

Heat Treatment and Mechanical Testing

Heat Treatment Variables for Soft Alloys. Heat treatment variables for soft alloy extrusions are shown in the flow chart (Fig. 9). Laue and Stenger (Ref 3) mentioned two different extrusion procedures, depending on the alloys and the product:

- *Non-heat-treatable alloys:* The exit temperature and the cooling of the extrusion are not critical for the mechanical properties.

Table 4 Typical extrusion plant maintenance checklist

Press size: **Date:**

Parameters	Checked	Comments
Function of each unit of press		
Main ram movement		
Stem with cross head		
Container movement		
Die slide movement		
Vertical shear		
Billet loader		
Function of pumps		
Pump No. 1		
Pump No. 2		
Pump No. 3		
Auxiliary pump		
Sealing pump		
Pressure gages		
Main pressure		
Sealing pressure		
Pilot pressure		
Press alignment		
Container and stem		
Die slide and container		
Press oil temperature		
Start of the shift		
End of the shift		
Heat exchanger		
Water temperature of cooling tower		
Container temperature		
Set temperature		
Actual temperature		
Die temperature		
Set temperature		
Actual temperature		
Billet heater (induction/gas)		
Set temperature		
Actual temperature		
Auxiliary equipment		
Platen shear		
Runout table surface		
Puller system		
Cooling table		
Cooling fans with air flow		
Stretcher table		
Storage table		
Saw changing table		
Saw gage table		
Inspection table		
Automatic stacker (palletizer)		

Table 5 Typical extrusion process checklist

Press capacity: **Clean-out block:** **Yes:** **No:** **Date:**
Press operator: **Nitrogen cooling:** **On:** **Off:** **Shift:**

Parameters	Die descriptions (No. and type of die)			
	1	2	3	4
Press and auxiliary				
Container temperature (set/actual)				
Die temperature				
Runout table speed				
Air quench/water mist				
Puller speed				
Puller tension				
Extrusion				
No. of holes/extrusion ratio				
Billet cast No.				
Billet length				
No. of billets extruded				
Billet temperature (start/steady)				
Break-through pressure (start/steady)				
Cut-off pressure				
Ram speed				
Butt thickness				
Runout (calculated/actual)				
Billet push time				
Extrusion speed				
Exit temperature				
Front				
Middle				
Back				
Comments:				

Table 6 Stretching and sawing checklist

Stretching operator: **Date:**
Saw operator: **Shift:**

Parameters	Die description (No. and type of die)			
	1	2	3	4
Critical dimensions				
Squareness				
Angularity				
Flatness				
Surface finish				
Cut size				
Rack No./stack No.				
No. of pieces/billet				
Length of scrap/billet				
Front				
Middle (weld joint)				
Back				
Total scrap/billet				
Wt/unit length				
Recovery, %				
Comments:				

- *Heat treatable alloys:* If there is a separate solution heat treatment before aging, the exit temperature and extrusion cooling are usually not critical; quenching immediately from the extrusion temperature (solution temperature) without any subsequent solution heat treatment necessitates control of the quenching temperature and the rate of cooling.

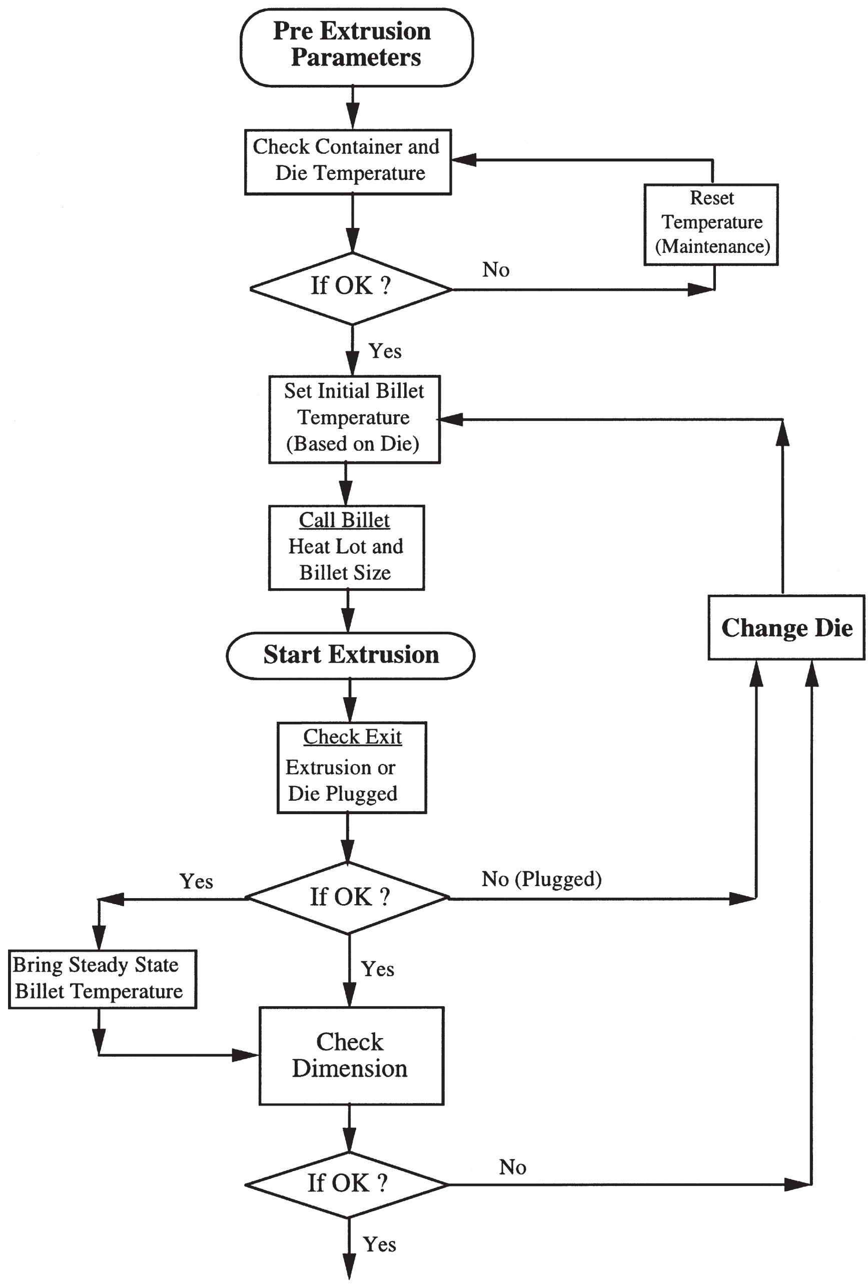

Fig. 7 Flow diagram of extrusion variables

Heat Treatment Variables for Hard Alloys. Harder alloy extrusion normally does not respond well in the press quench due to the following factors:

- Working temperature range is lower than that of softer alloys.
- Exit temperature generally remains below the solution temperature range due to slow speed extrusion.

Harder alloy extrusions need separate solution heat treatment. Because there is a wide application of harder alloys, especially in the aircraft

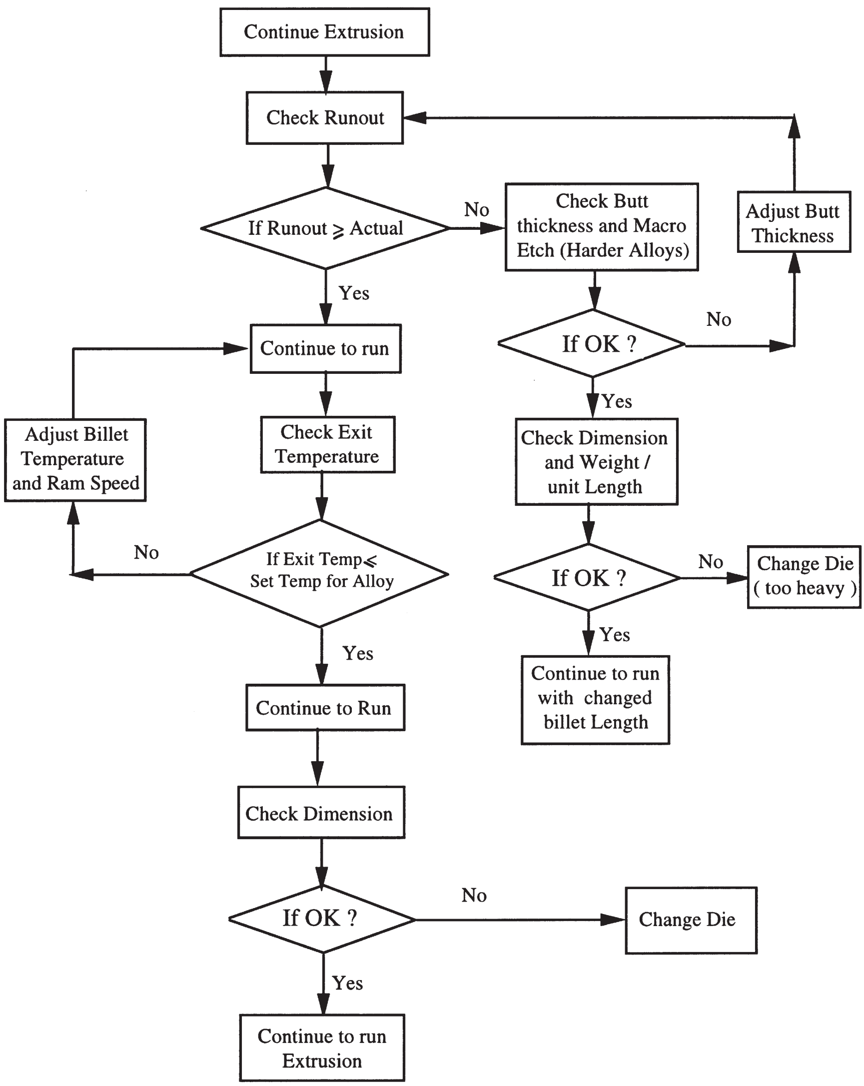

Fig. 7 (continued)

industry, material is required to be produced in different hardening tempers. A flow diagram of the heat treatment variables is shown in Fig. 10. A flow diagram of the annealing process variables of harder alloys is shown in Fig. 11.

Mechanical Test Variables. For proper documentation of the aging process and subsequent physical test parameters, a chart was designed as shown in Table 7.

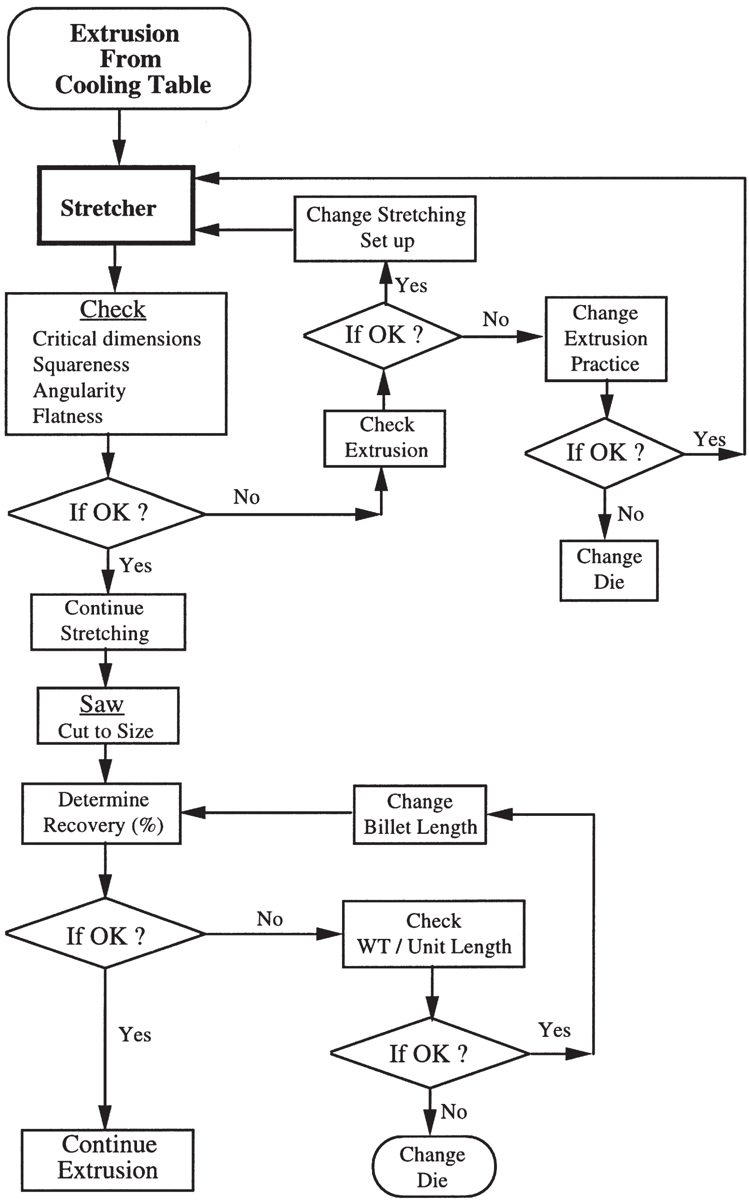

Fig. 8 Flow diagram of stretching and sawing variables

Surface Treatment of Extruded Shapes

After extrusion is completed, it is usually necessary to treat the surface to improve corrosion and oxidation resistance. The surface treatment is generally done by mechanical, anodizing, electrolytic coloring, and painting (both powder and liquid) processes. According to the company facility and the requirements of the customer, every company has its own surface treatment process. Surface treatment parameters control

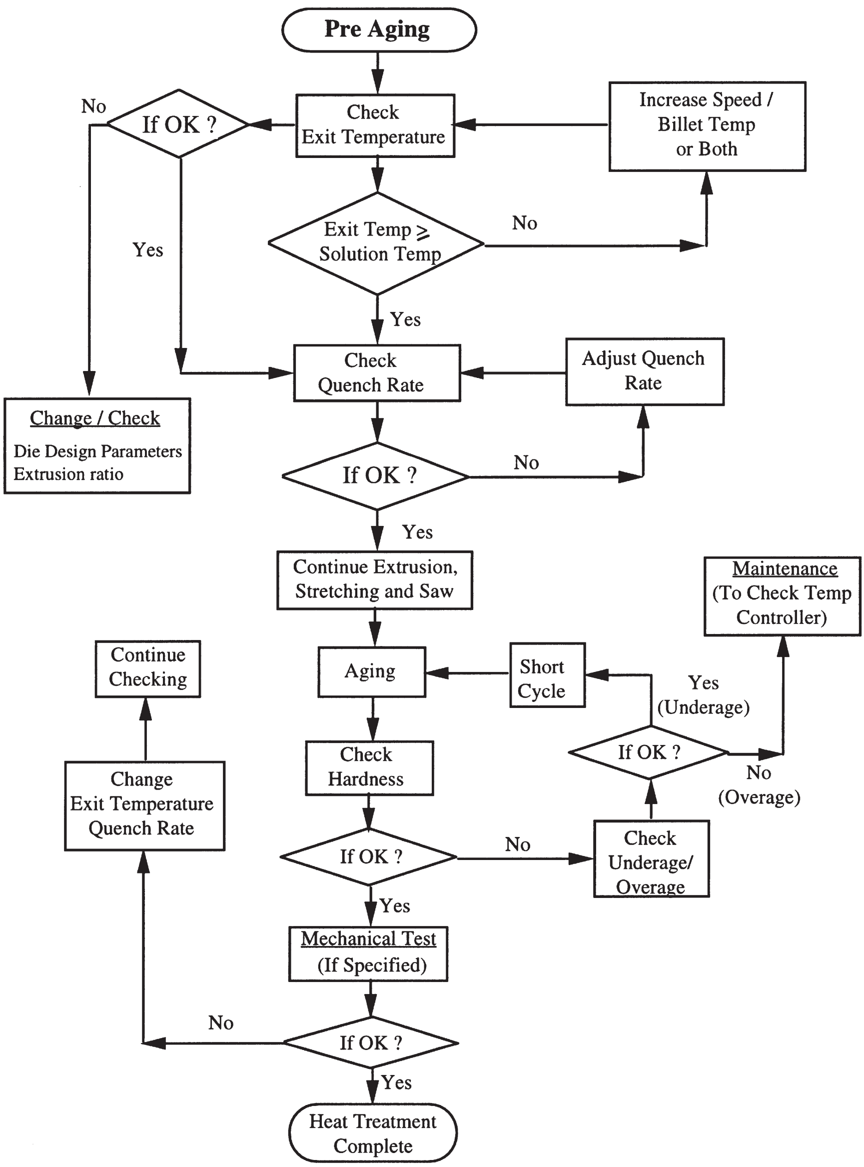

Fig. 9 Flow diagram of heat treatment variables of soft alloy extrusions

charts could be designed according to the existing process. Because each process is different, a generalized process chart could not be provided for the surface treatment.

Quality Control Framework

Figure 12 shows the complete quality control frame structure of an aluminum extrusion plant, from primary material to the finished extrusion.

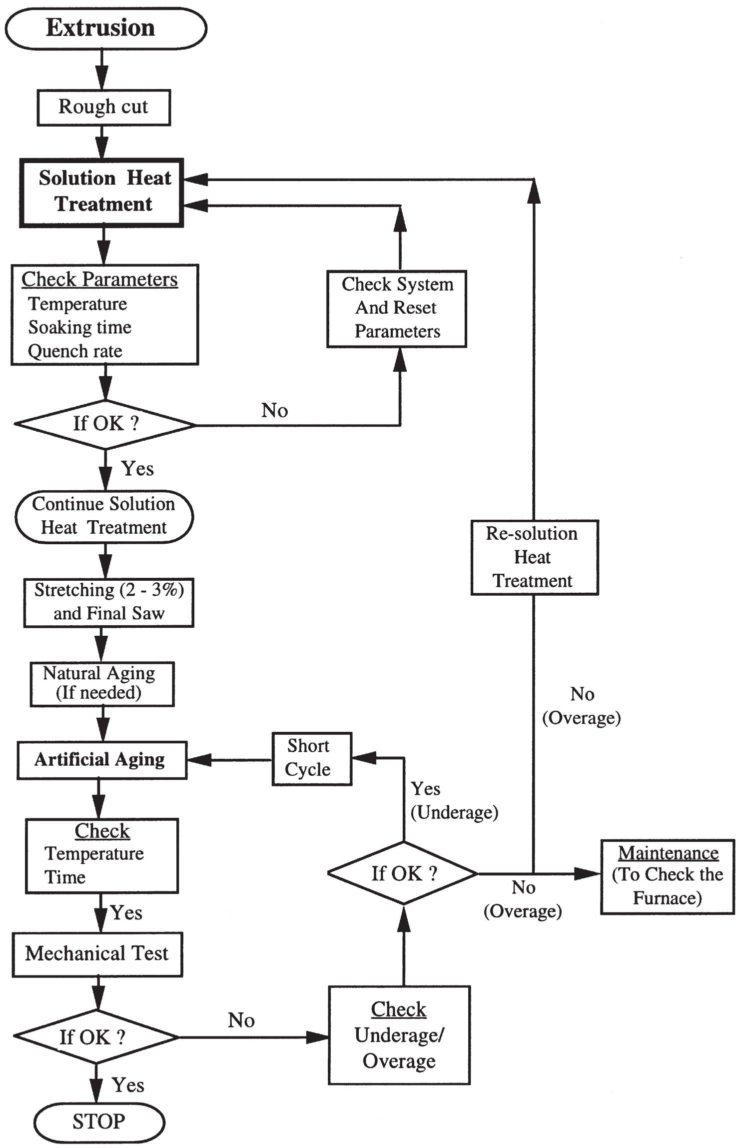

Fig. 10 Flow diagram of heat treatment variables of harder alloys

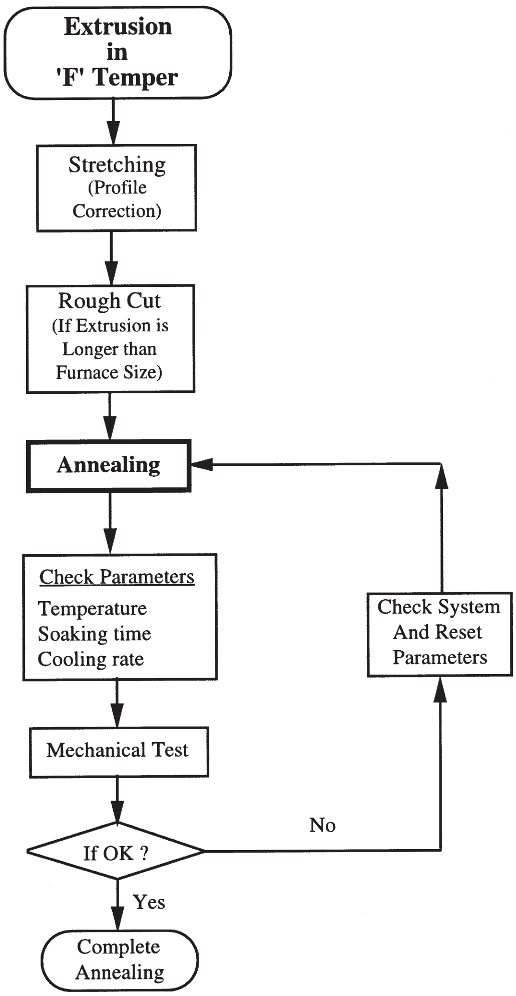

Fig. 11 Flow diagram of annealing process variables of harder alloys

Table 7 Aging oven and mechanical testing parameters

Oven No.: **Date:**
Operator: **Shift:**

Rack/lot No.	Item No.	Alloy/ temper	Age cycle			Webster hardness (softer alloys)	Mechanical tests (harder alloys)			
			Temperature	Cycle time	Soak time		Yield strength	Ultimate strength	Elongation, %	Etch test

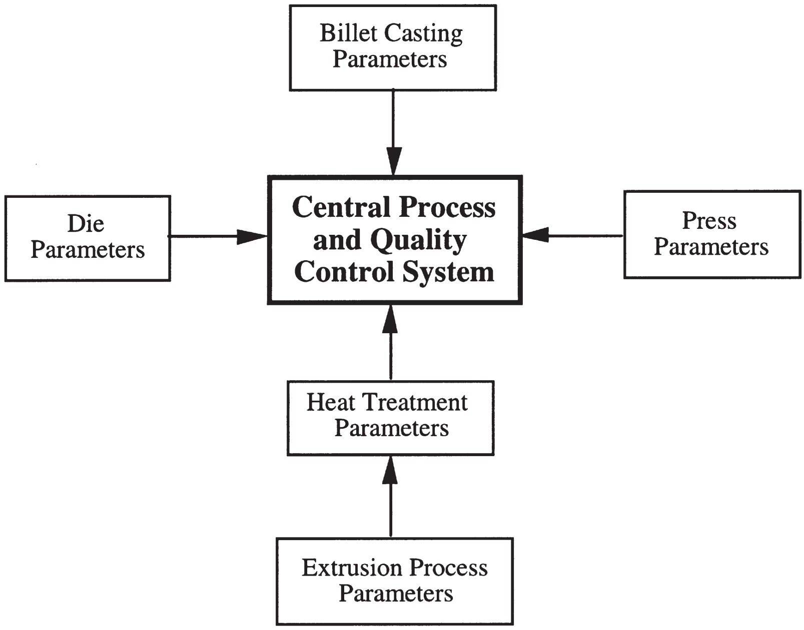

Fig. 12 Complete process and quality control frame structure of an aluminum extrusion plant

Documentation and close control of each parameter or variable of the individual units is an important practice from the quality point of view. Central process and quality control systems may analyze each unit separately and statistically to determine any fault in any unit of the system and to take a necessary preventive measure.

Each unit has its own quality checklist to determine the quality/performance of the individual unit. This system will not only assess the quality but also will do experiments of each unit or combined units to develop new products or to determine new process parameters of a particular product shape of a particular alloy.

Using this system, an experiment can be done with different die designs to discover the best design to achieve high productivity and quality of extrusion.

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CHAPTER 9

Statistical Process and Quality Control

Statistical process control and experimental design can potentially have a major impact on manufacturing, product design activities, and process development. The systematic introduction of these methods usually marks the start of substantial quality, cost, and productivity improvements in the organization. At the highest levels of maturity, companies use design of experiments and statistical process control methods extensively and make relatively modest use of acceptance sampling. The introduction of statistical process controls helps stabilize the process and reduce the variability. However, it is not satisfactory just to meet requirements; further reduction of variability usually leads to a lower cost of quality and an enhanced competitive position. The design of experiments can be employed in conjunction with statistical process controls to minimize process variability, resulting in virtually defect-free manufacturing.

Bird (Ref 1) provided an understanding for the extrusion expert of the basic process of experimental design and to document, for both the statistician and the process expert, some concepts particular to processes in an extrusion operation that should be considered in the initial design stages. Some considerations for the process of selecting variables were discussed and clarified with specific examples. He also provided an explanation of the basic methods and terminology of statistical experimentation and analysis for those who are not familiar with these techniques. Wolf (Ref 2) reviewed the application of five of the seven tools, including Pareto charts, flow process charts, histograms, run charts, and control charts of statistical process control (SPC) to the aluminum extrusion and drawn-tube processes.

Boatman (Ref 3) discussed the application of SPC and continuous improvement philosophy in an extrusion plant. He mentioned that SPC, which emphasizes prevention of defects rather than detection, structured problem solving, design of experiments, and continuous improvement with employee involvement are important tools that can and must be used in an effort to increase productivity, improve quality, and reduce costs. Rogers (Ref 4) discussed the practical application of SPC in all areas of aluminum billet casting. He discussed one potential application of SPC that would have a major effect on the aluminum industry, the quantifying of molten metal cleanliness using ceramic foam filters as the sensing device. Schwarz (Ref 5) discussed the quality management system to be applied in casting facilities. Schwarz (Ref 6) designed and implemented a system to improve procedures and documentation, training and education, standards, and increased accountability and awareness to meet the quality of billet-casting facilities. Holder (Ref 7) described experience with total quality management (TQM) in the extrusion industry. Steadman (Ref 8) focused on how a management-controlled system applies to the heart of any plant, the extrusion process itself. This assessment included details concerning a typical management system's capabilities, including diagrammatic representation of the extrusion process, production/press diary, current job status, file maintenance, die and fault histories, reports, analysis, fault diagnostics, and press control.

There are various well-known definitions of quality. Juran (Ref 9, 10) defines quality as "fitness for use." Japanese companies find that the old definition of quality, "the degree of conformance to a standard," is too narrow and, consequently, have started to use a new definition of quality in terms of "user satisfaction." It is interesting to note that satisfying customers' needs and expectations is the main factor in all these definitions. Therefore, it is important for a manufacturer to identify such needs early in the product development cycle. The ability to define accurately these needs, including design, performance, price, safety, delivery, and so on, will place a manufacturer ahead of competitors in the market.

Quality control is used to obtain control of quality in a production process and to monitor the output of a respective production process. It is recognized that the product will occasionally not meet specifications and that any measured characteristics of a product will show some variation from one item to the next, even though all the items are supposedly made by the same process. The likelihood of failure in the process under test, or the variation of measured characteristics of a product, may be examined under conditions believed to be normal or "in control" in order to establish a basis of comparison for judging future items. In some cases, the basis of comparison may be prescribed by specifications. The quality control procedure is then put into operation in order to detect any significant change in the likelihood of failure or the variation of measured characteristics of the product, with the purpose of having an early warning when some feature of the production process has changed. When a significant change in the output is found, the production is said to be "out of control." Quality is determined either by quantitative measurements or by classification into a category such as "accept" or "reject," the latter being known as inspection by attributes.

Application of proper statistical methods in the process control activity of an aluminum extrusion plant can significantly increase the quality of the product, increase productivity, and lower overall service and manufacturing costs. Application of statistical methods can lead to a continuous improvement of the process and also increase the knowledge base of the overall system. Collection of proper data and maintenance of those data are important factors for quality management in any industry. A well-planned calibration process is necessary for the measurement instruments. A systematic introduction of statistical methods is necessary to control the process. Many aluminum extrusion plants that follow TQM or International Organization for Standardization (ISO) 9000 standards maintain statistical quality plans and quality manuals.

The quality process starts with a plan for sampling. The collection of proper data is dependent on the sampling process. A group of items considered as a lot may have to be judged to determine whether the lot contains more than the given proportion of defects. An evaluation also might be necessary when the variation of some quantity is too high within the lot, or when the average of some measurement is not within an acceptable limit. It is often impractical or expensive to inspect the whole lot, so inspection is confined to one or more samples. A judgment, accept/reject, concerning the whole lot is then made on the basis of the samples with a calculated risk of error. The collected data and the error trend for different subsequent samples are stored and analyzed, and if any correlation can be obtained, feedback is given to the process control system.

The following are sampling processes used in statistical analysis (Ref 11):

- Single-sampling plan
- Double-sampling plan
- Sequential-sampling plan
- Grouped sequential-sampling plan
- MIL-STD-105D

The following are statistical methods used in the manufacturing process (Ref 12, 13):

- Test of significance
- Statistical co-relations and regression
- Analysis of variance and so on

Basis of the Statistical Control Chart

How the Control Chart Works. A typical control chart is shown in Fig. 1, which is a graphical display of a quality characteristic that has been measured or computed from a sample versus the sample number. The chart contains a "centerline" that represents the average value of the quality characteristic corresponding to the in-control state. Two other horizontal lines, called the upper control limit (UCL) and the lower control limit (LCL), are shown in the chart. These control limits are chosen so that if the process is in control, nearly all of the sample points will fall between them. As long as the points plot within the control limits, the process is assumed to be in control, and no action is necessary. However, a point that plots outside of the control limits is interpreted as evidence that the process is out of control, and investigation and corrective action are required to find and eliminate the assigned cause or causes responsible for this behavior. It is customary to connect the sample points on the control chart with straight-line segments so that it is easier to visualize how the sequence of points has evolved over a period of time. Even if all the points plot inside the control limits, if they behave in a systematic or nonrandom manner, this is an indication that the process is out of control.

The estimates of central line and control limits are made in different ways, depending on whether the population means, X, and standard deviation, σ, are known. It is generally preferable from the standpoint of

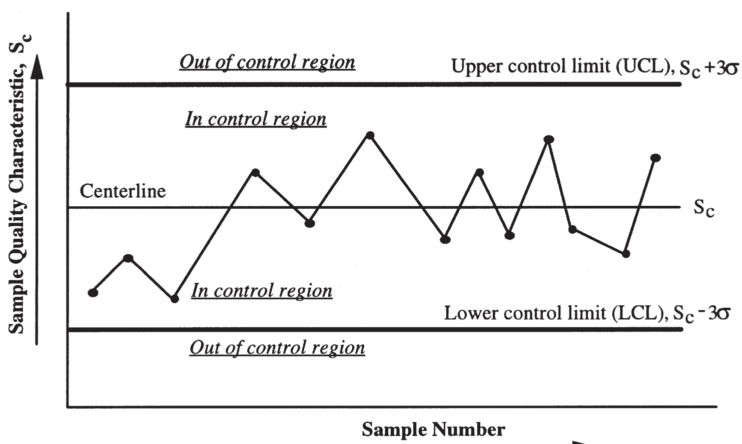

Fig. 1 Typical control chart for any extrusion variable

most effective control with a given sample size to use the standard deviation, σ, rather than *R*, as a measure of scatter in the samples. The range should not be used if $n > 10$ (Ref 11). For smaller values of *n*, the range is sometimes used because it is so simple to compute in a practical sampling procedure.

Implementation of SPC. The methods of SPC can provide significant payback to the extrusion plant that can successfully implement them. Management involvement and commitment to the quality-improvement process is the most vital component for potential success of SPC. Management is a role model, and others in the organization will look to management for guidance and for example. A team approach is also important because it is usually difficult for one person alone to introduce process improvements.

The objective of an SPC-based quality-improvement program is to realize continuous improvement on a weekly, quarterly, and annual basis. SPC is not a one-time program to be applied only when the business is in trouble, only to be abandoned later. Quality improvement must become a part of the culture of the organization. The control chart is an important tool for process improvement. Processes do not naturally operate in an in-control state, and the use of control charts is an important step that must be taken early in an SPC program to eliminate assignable causes, reduce process variability, and stabilize process performance. In order to improve quality and productivity, an SPC program must be managed with the use of facts and data, rather than by judgment alone. Control charts are an important part of this change in the managerial approach.

In implementing a company-wide SPC program, the following elements are usually present in all successful efforts:

- Managerial leadership
- A team approach
- Education of employees at all levels
- Emphasis on continuous improvement
- A mechanism for recognizing success

Quality Control in Billet Making

A sampling plan should be introduced to acquire the statistical variables needed for testing. Data may be entered in the billet casting checklist shown in Table 1 in Chapter 8. The checklist should be completed during each shift and by lot number. There are different statistical checkpoints in the billet casting process, as shown in Fig. 5 in Chapter 8.

For all checkpoints, the collected data should be analyzed by a suitable statistical method, such as the "student t-test." Calculations for numerical coefficients of estimating central limits should be performed, as illustrated in the "laboratory test" (purity acceptance) example shown in Fig. 2.

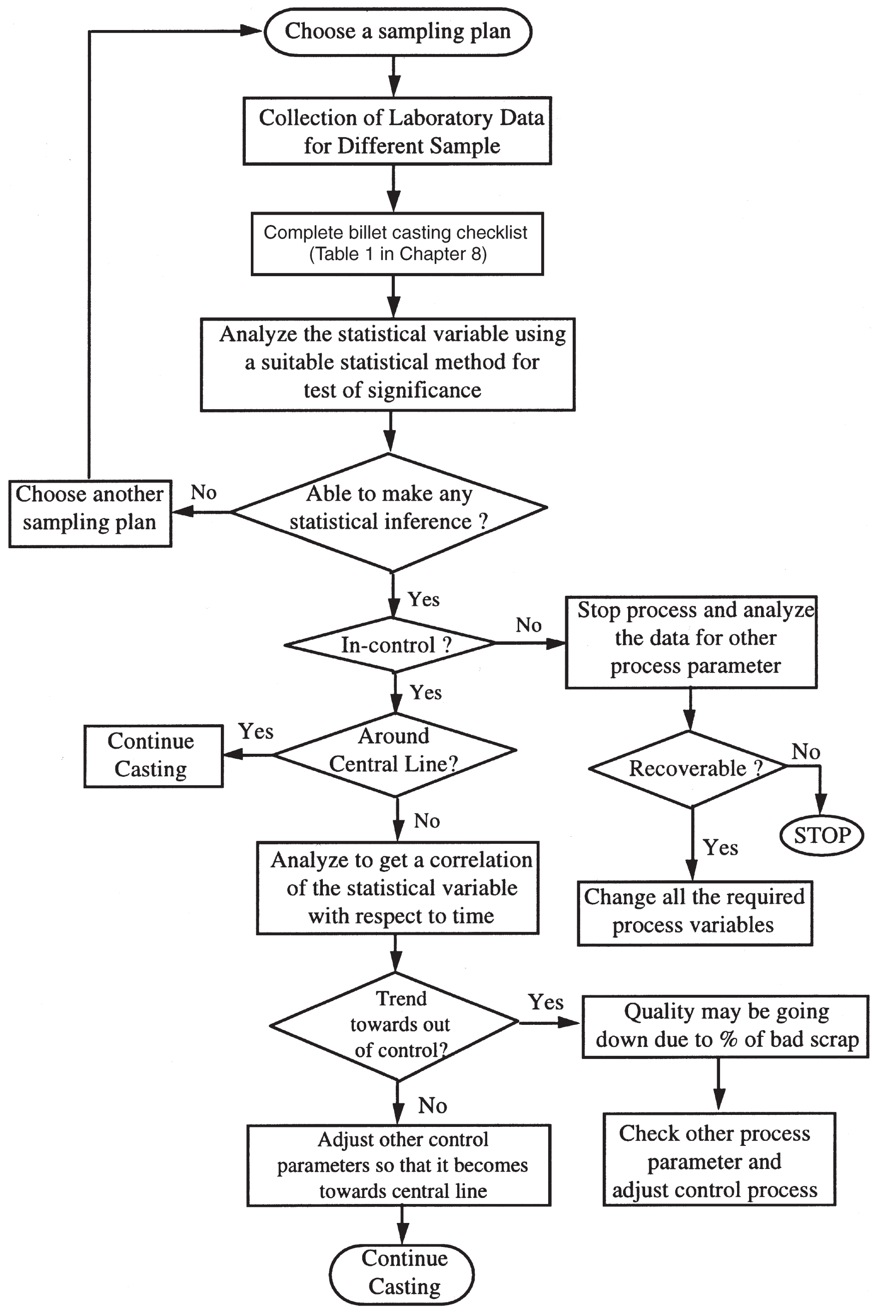

Fig. 2 Flow diagram for statistical quality test for purity acceptance

Quality Control of Dies

A sample plan should be introduced to acquire the statistical variables needed for testing. Data may be entered in the tabular form as shown in Tables 2 and 3 in Chapter 8. There are different statistical checkpoints in the die variable flow diagram shown in Fig. 6 in Chapter 8.

For all checkpoints, the collected data should be analyzed with a suitable statistical method. The case of "extrusion process parameters and die variables" shown in Fig. 3 is an example.

Quality Control of Extrusion

The quality of extrusion depends on a number of variables, including preextrusion, extrusion, cooling table, stretching and sawing, and heat treatment, as shown in the previous chapter. Proper monitoring and analysis of those variables is necessary to control the extrusion quality. If any automated process feedback for quality control is implemented in the process, proper maintenance and calibration is necessary; otherwise, it can lead to poor quality. For other parameters, statistical analysis is needed. A sampling plan should be introduced to acquire the statistical variables needed for the test. Data may be entered in the tabular form shown in Tables 4 to 7 in Chapter 8. There are different statistical checkpoints in the flow diagram, as shown in Fig. 7 to 11 in Chapter 8.

For all checkpoints, the collected data should be similarly analyzed to determine whether the process is in control or out of control (Fig. 4).

Total Quality Management

There are many definitions of TQM. Tobin (Ref 14) defines TQM as the totally integrated effort for gaining a competitive advantage by continuously improving every facet of organizational culture. Witcher (Ref 15) defines TQM as follows:

- *Total:* Every person in the firm is involved (and where possible, its customers and suppliers).
- *Quality:* Customer requirements are met exactly.
- *Management:* Senior executives are fully committed.

TQM is a system for managing work to achieve the highest possible quality at the lowest possible cost, with the greatest degree of customer satisfaction. As a new century begins, the creation of the global market, international orientation of management that sweeps national boundaries, introduction of new technologies, and a shift toward customer-

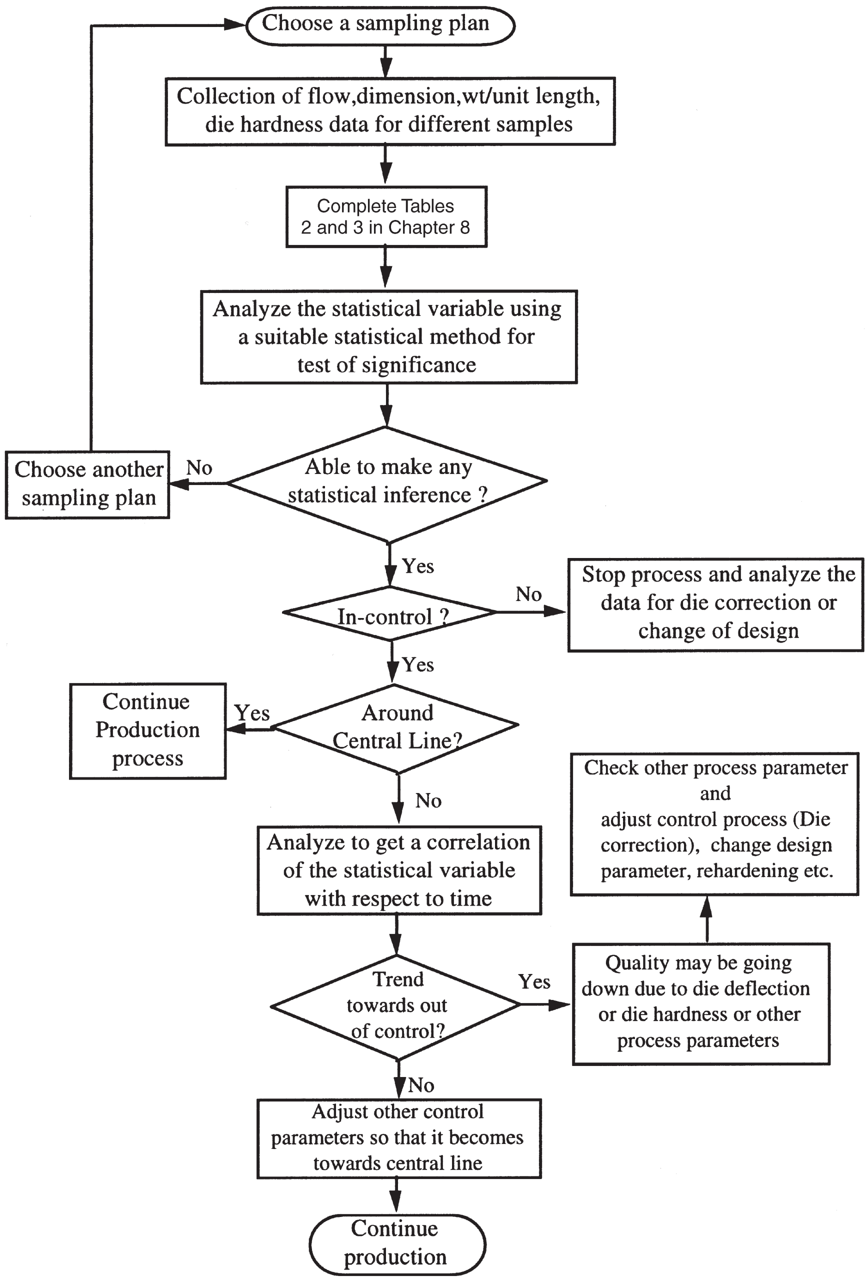

Fig. 3 Flow diagram of statistical quality control for extrusion die variables

focused strategies make the competition stronger than ever. The criteria for success in this global, internationally oriented aluminum extrusion market have been changing rapidly. In order to expand business, enter new markets, and set realistic, competitive long-term objectives, excellence is imperative. Management's effort has been directed toward discovering what makes a company excellent.

To achieve excellence, companies must develop a corporate culture of treating people as their most important asset and must provide a

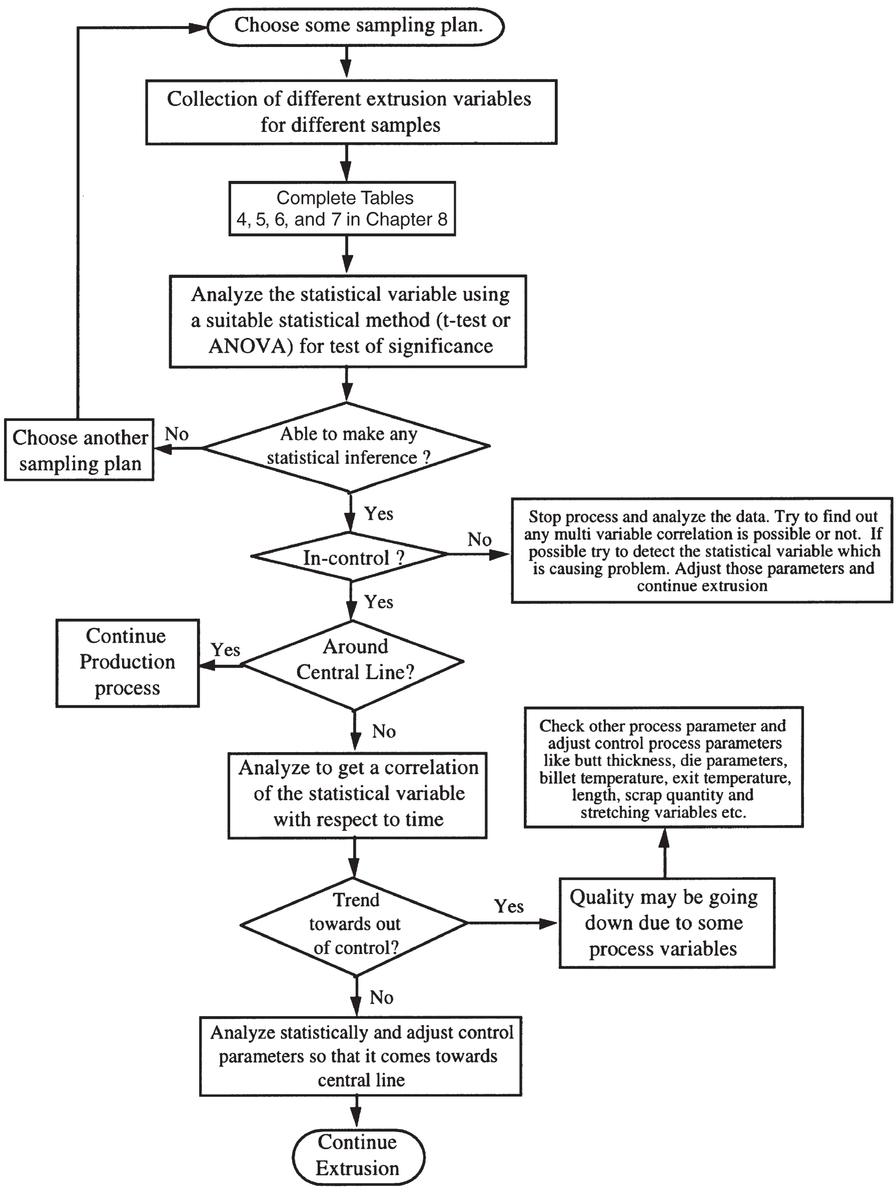

Fig. 4 Flow diagram of statistical quality test for extrusion variables

consistent level of high-quality products and services in every market in which they operate. Such an environment has supported the wide acceptance of TQM, which emerged recently as a new, challenging, marketable philosophy. TQM involves three spheres of changes in an organization, namely, people, technology, and structure.

TQM philosophy provides the overall concept that fosters continuous improvement in an organization. This philosophy stresses a systematic, integrated, consistent, organization-wide perspective involving everyone and everything. It focuses primarily on total satisfaction for both internal and external customers within a management environment that seeks continuous improvement of all systems and processes. The TQM philosophy emphasizes the use of all people, usually in multifunctional teams, to bring about improvements from within the organization. It stresses optimal life-cycle costs and uses measurements within a disciplined methodology to target improvements. The key elements of the philosophy are the prevention of defects and an emphasis on quality in design.

Important aims include the elimination of losses and the reduction of variability. Further, it advocates the development of relationships between employee, supplier, and customer. Finally, the philosophy is based on an intense desire to achieve victory.

TQM principles are the main factors that guarantee the successful implementation of the system. Broadly speaking, these principles can be classified under ten major headings:

- Leadership
- Commitment
- Total customer satisfaction
- Continuous improvement
- Total involvement
- Training and education
- Ownership
- Reward and recognition
- Error prevention
- Cooperation and teamwork

TQM Guidelines. In order to have a systematic approach to TQM, it is necessary to develop a conceptual model. Generally, a model is a sequence of steps arranged logically to serve as a guideline for the implementation of a process in order to achieve the ultimate goal. The model should be simple, logical, and yet comprehensive enough for TQM implementation. It also has to sustain the changes in the business environment of the new era. The idea was to develop universally applicable, step-by-step guidelines by including recognized practices in TQM:

- Japanese 5-S practice (5-S)
- Business process reengineering (BPR)
- Quality control circles (QCCs)
- ISO 9001/2 quality management system (ISO)
- Total productive maintenance (TPM)

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CHAPTER **10**

Research and Development

Aluminum extrusion technology is developing rapidly to meet the costs of production in the recently competitive market. Extrusion plants are facing customer demands for excellent quality and higher productivity with a reduction in wall thickness and much more integrated shapes. Every four years the Aluminum Extruders Council and the Aluminum Association present many research and technical papers from all over the world in areas such as extrusion process and equipment, billet process and equipment, die design and technology, applications, and product innovations. The major trend of research is in the advancement of productivity and quality. To satisfy these two areas, technology is advancing toward the development of more controls in press equipment to finally control the exit temperature and speed to optimize production. Technology is also advancing tremendously in the area of die technology to increase productivity with low production costs. Improvements are still continuing in degassing, filtration, mold, and cooling systems in billet-casting technology as well as homogenizing processes to manufacture billets of improved extrudabilty.

Extrusion Presses and Auxiliary Equipment

There are quite a few extrusion press manufacturers in the world. Extrusion presses must meet the stringent demands of their customers for minimum dead-cycle time, increased productivity, isothermal extrusion capability, and enhanced product quality. These demands provide continuous advancements in press design and manufacturing technology.

In the last few years, a tremendous amount of advancement has been made in the automatic handling system, including runout tables with puller systems, cooling tables, walking conveyers, automatic stretcher heads, saw gage tables and palletizing devices. In order to run any extrusion plant successfully without wasting valuable press time, billet and die tooling temperatures are important concerns.

Tremendous improvements have already taken place in billet heating, including log heating and hot log shear with taper-spray quench. Improvements have also been made in developing multichamber die ovens to maintain each die at a precise temperature in a controlled atmosphere to improve expensive die life and to finally improve the surface finish of extrusion. Further improvements continue.

Tooling and Die Technology

With the application of computers in both the design and manufacturing of extrusion dies, it has been possible to use very small bearing lengths. The scope is still there to optimize bearing lengths for each shape with respect to the alloy to be extruded and the life of the die.

Friction and wear in the aluminum extrusion process has a direct influence on the accuracy of the shape and the surface finish of extrusion. The friction between the die/material interface may vary in a complicated manner when metal is flowing through the die opening. The wear process in the die bearing is dependent on the thermodynamics of the extrusion process, which is influenced greatly by the effects of extrusion variables. Further experimental research is still necessary to gain a better understanding of the wear mechanism and its effect on the extrusion performance as follows:

- Study of the relationship between surface roughness of the die bearing and extrusion to understand the friction model at the bearing-material interface
- Study of the different methods and compounds for the thin, hard coating on the bearing surface and their effect on extrusion surface quality, the die wear, and finally, the die life

Design and correction of hollow dies are rather difficult compared with solid dies. The future trend in design will be to develop systematic methods for calculating port size, bridge height, and depth of the welding chamber and the welding chamber (pocket) provided in the die cap. The size and shape of the bridge need to satisfy the design strength of the die material to balance the bending stress. To reduce the breakthrough pressure, the die designer needs to pay attention to how to reduce frictional resistance right from the billet material entering into the port to the exit die bearing. Another important step is to balance the volume of metal from the port entry to the exit through the bearing to achieve the maximum possible speed. Science is continuously heading toward manufacturing repeatable dies to eliminate die trials to increase productivity and die life.

Alloy Making and Billet Casting

Through research, new alloys or derivatives of existing alloys with improved extrudability and higher mechanical properties continue to be developed. Research also continues to be responsible for improved mold designs and cooling systems that avoid many billet skin-related problems in extrusion. The future task in billet making is to make more purity billets through continuously developing degassing, grain refining and filtration systems. There is a continuous scope of improving the homogenizing cycle (heating, holding, and cooling) to improve the productivity as well as the final mechanical properties of extrusion.

Extrusion Process Technology

Extrusion process technology research is continuously improving in many areas including increasing extrusion speed, extrusion with constant mechanical properties, improving productivity and quality, and the extrusion of new alloys with improved strength-to-weight ratio, especially in the aircraft industry. Quenching of extrusion on the runout table is an important issue to those in the aluminum extrusion industry. Research continues to improve high-pressure and high-velocity water and water/air spray systems.

Thermodynamics and tribology in aluminum extrusion are big concerns in the productivity and the quality of extrusion. Theoretical work is also necessary to develop a more realistic thermodynamics model by combining more realistic friction models at billet-container, dead-metal-zone-flowing material, and die-material interfaces. Finally, the results could be visualized on real time during the extrusion cycle.

Process and Quality Control

Designing proper process control procedures and analyzing the parameters are important considerations in maintaining the highest quality of extrusion. Quality of extrusion is related to mechanics, tribology, and thermodynamics. The deformation process within the container in aluminum extrusion is normally inhomogeneous, causing some variation of structure along the length and cross section of the extrusion. It is very important to have a better understanding of the mechanics, tribology, and thermodynamics of extrusion to obtain uniform temperature distribution throughout the cross section of the extrusion profile. The higher the bearing length is, the greater the effect of frictional heat generation due to the increase in frictional surface area will be. There will be a greater chance of having a localized temperature rise on the surface to a certain depth within the cross section of extrusion. There is definitely enough scope of research in the future associated with the variation of properties from the surface to the core that ultimately affect quality, especially for aircraft alloys.

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