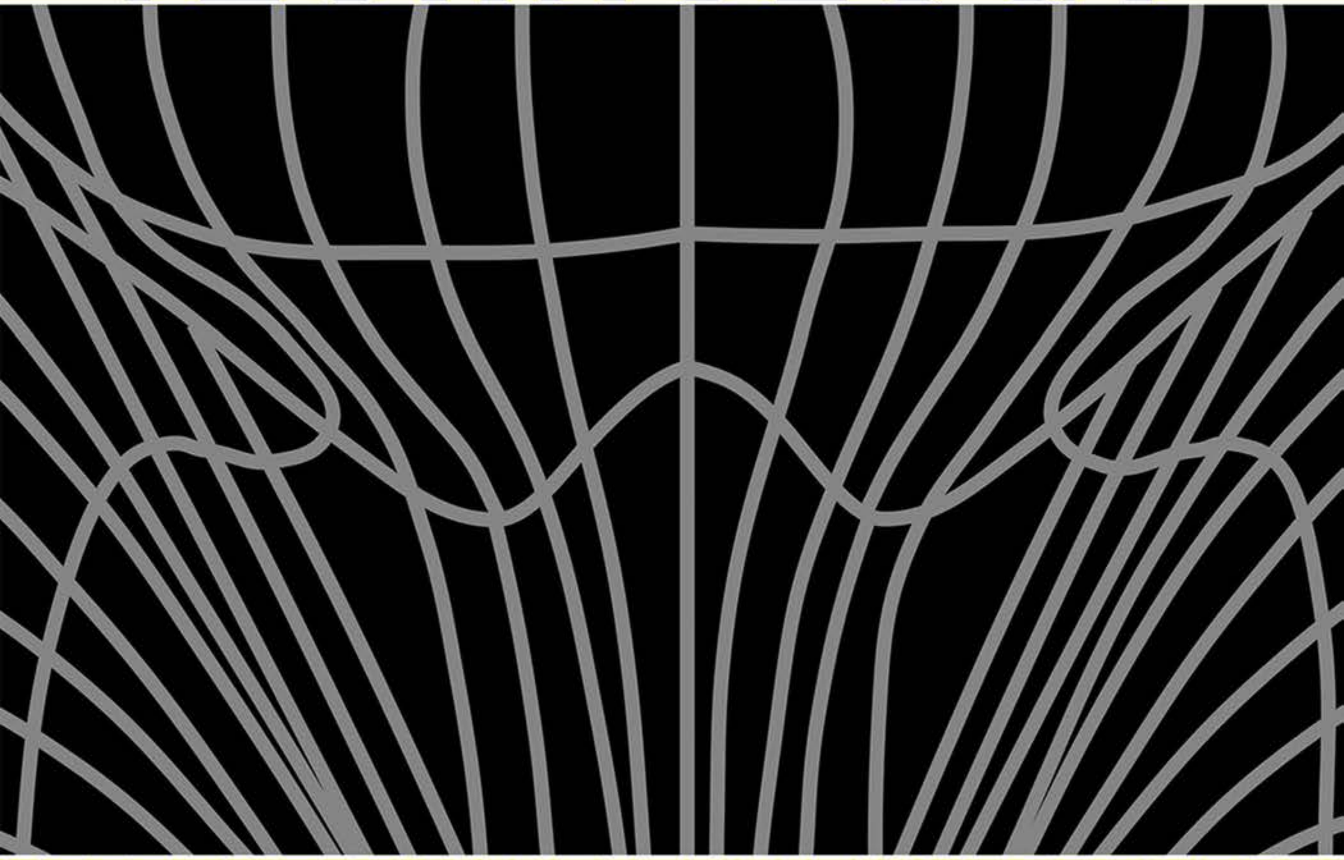
ALUMINUM EXTRUSION TECHNOLOGY



Pradip K. Saha

ASM INTERNATIONAL

Aluminum Extrusion Technology, 06826G
Pradip K. Saha

Aluminum Extrusion Technology

Pradip K. Saha

The Materials Information Society

ASM International®
Materials Park, Ohio 44073-0002

Preview for: *Aluminum Extrusion Technology,* by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

Copyright © 2000
by
ASM International®
All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, March 2000

Great care is taken in the compilation and production of this book, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

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

Downloaded from http://dl.asminternational.org/technical-books/monograph/148/bookpreview-pdf/675729
by guest
on 24 March 2025

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

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

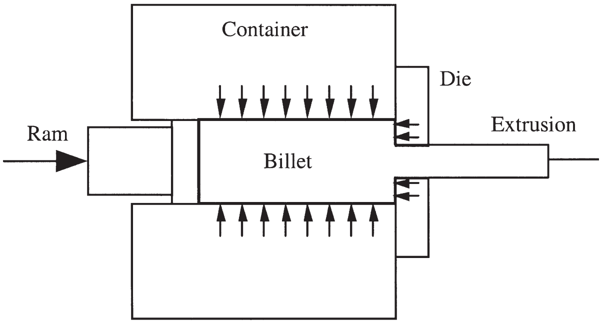


Fig. 1 Definition and principle of extrusion

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)

Preview for: *Aluminum Extrusion Technology*, by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

- 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

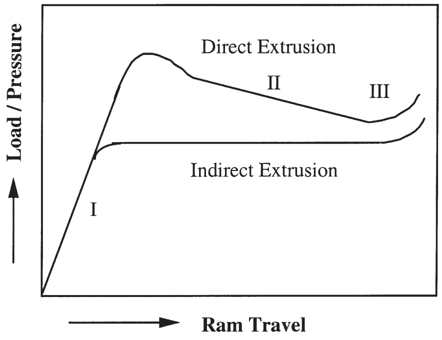


Fig. 2 Variation of load or pressure with ram travel for both direct and indirect extrusion process

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).

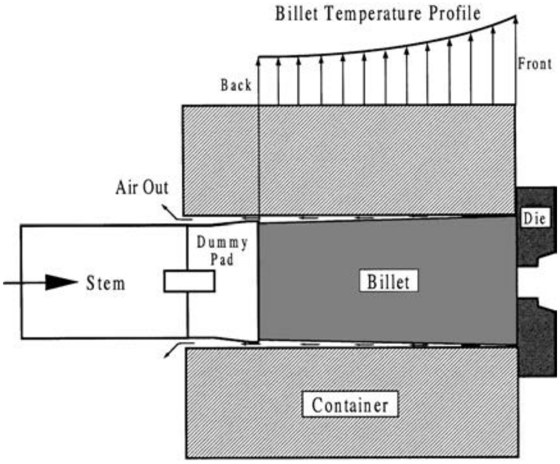


Fig. 3 Bleeding out air during upsetting

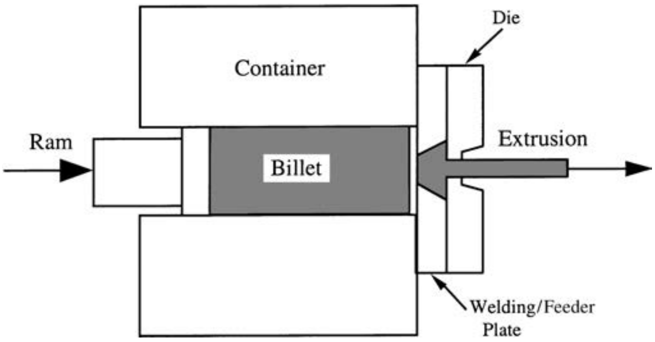


Fig. 4 Continuous-type extrusion using welding plate in front of the die (method 1)

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.

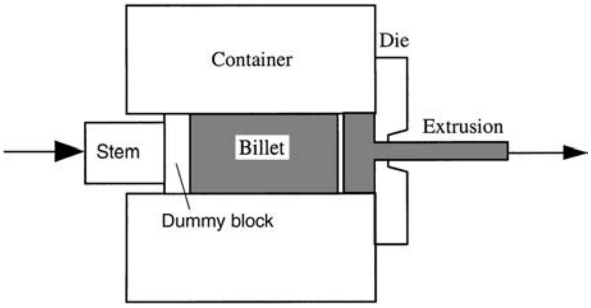


Fig. 5 Billet-on-billet extrusion (method 2)

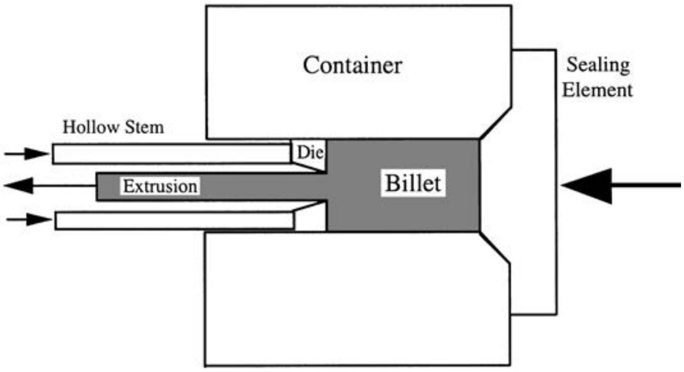


Fig. 6 Indirect extrusion process

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.

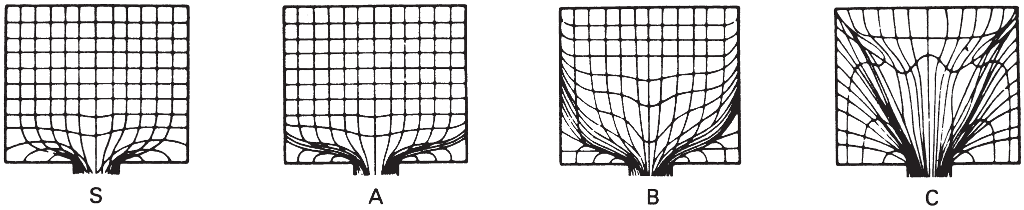


Fig. 7 Schematic of the four different types of flow in extrusion. Source: Ref 3

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)

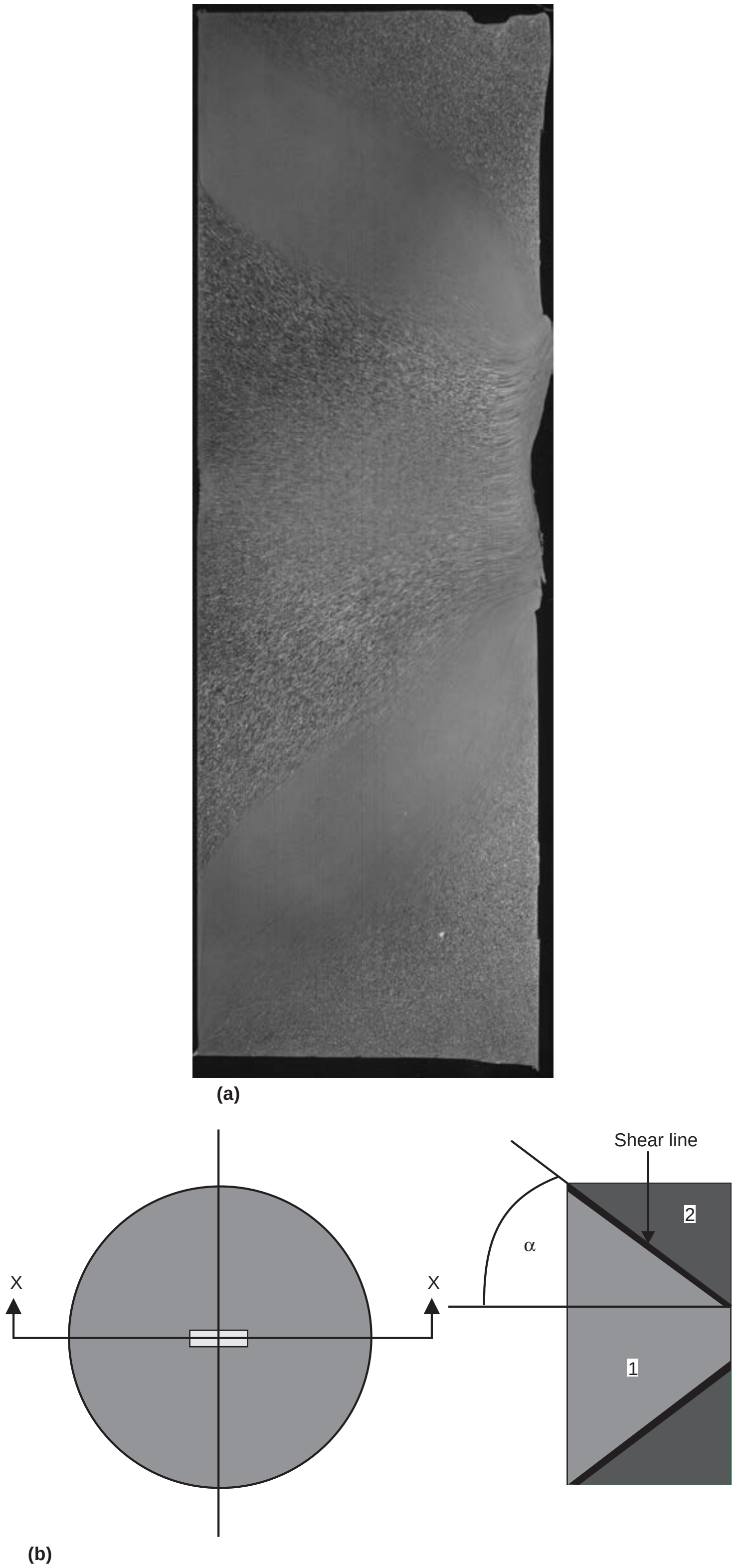


Fig. 8 Longitudinal cross section of butt after extrusion. (a) Typical etched cross section of a 7075 butt. (b) Schematic diagram of butt cross section showing dead zone

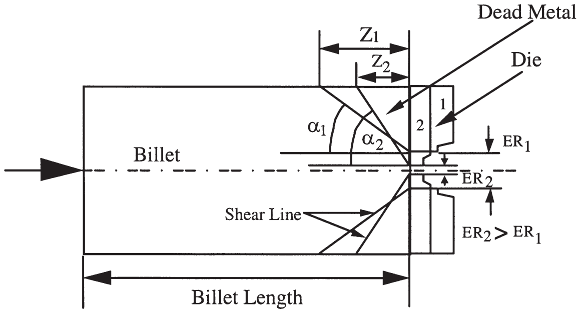


Fig. 9 Relationship between extrusion ratio and semidead-metal zone angle

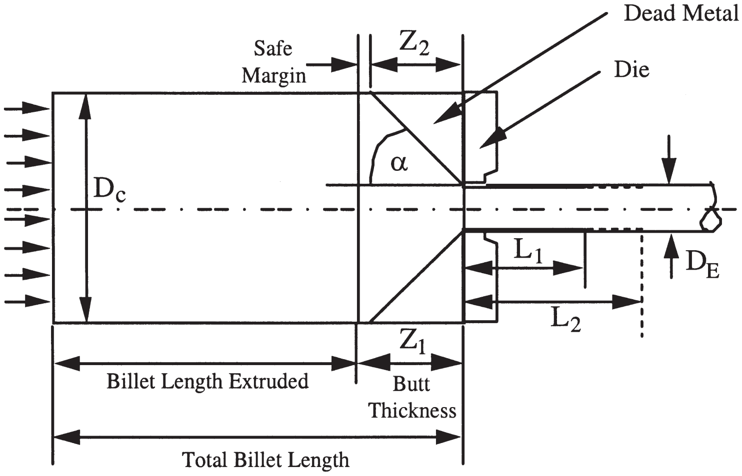


Fig. 10 Relationship between dead zone and butt thickness

- 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:

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

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:

$$Al = A_0 l_0 \tag{Eq 3}$$

Now, the natural strain is given by:

$$\bar{\varepsilon} = \ln\frac{l}{l_0} = \ln\frac{A_0}{A} \tag{Eq 4}$$

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:

$$\bar{\varepsilon} = 2\ln\frac{D_C}{D_E} = 2\ln\sqrt{\mathrm{ER}} \tag{Eq 5}$$

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:

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

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:

$$\mathrm{ER} = \frac{A_C}{A_E} \tag{Eq 7}$$

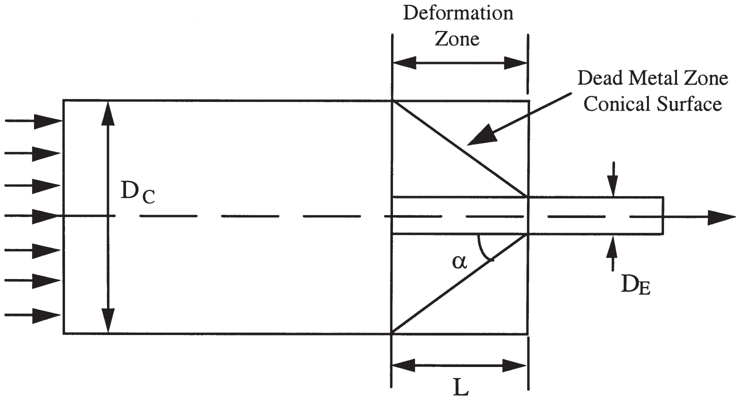


Fig. 11 Billet geometry inside the container

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:

$$D_E = \frac{D_C}{\sqrt{ER}} \tag{Eq 8}$$

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

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

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:

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

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

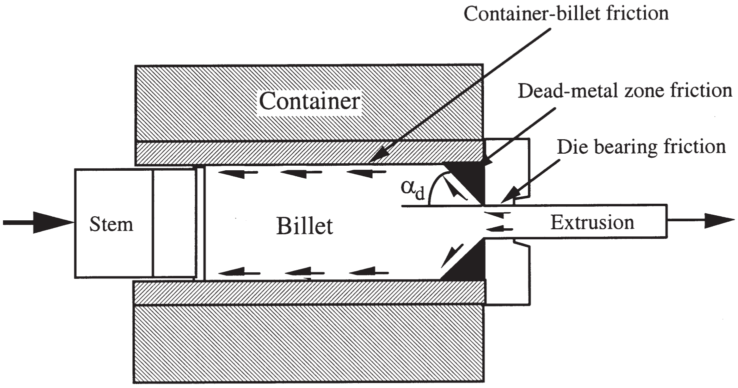


Fig. 12 Friction components in direct extrusion

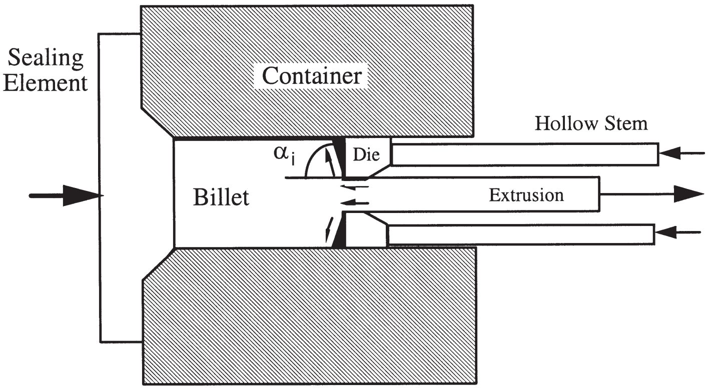


Fig. 13 Friction components in indirect extrusion

(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.

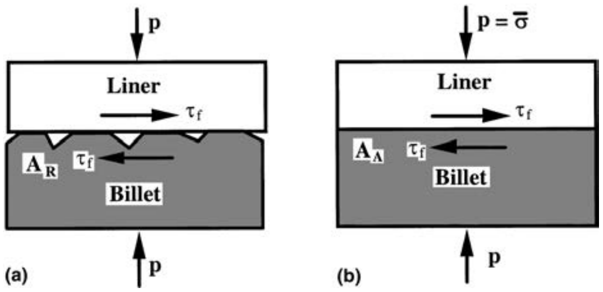


Fig. 14 Friction model in direct extrusion process. (a) $A_R < A_A$. (b) $A_R = A_A$, $p = \bar{\sigma}$

Preview for: *Aluminum Extrusion Technology,* by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

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:

$$F_\mathrm{f} = m_1 k A_{\mathrm{R}_1} + m_2 k A_{\mathrm{R}_2} \qquad \text{(Eq 13)}$$

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:

$$\tau_\mathrm{f} = k \frac{A_{\mathrm{R}_1}}{A_\mathrm{A}} + m_2 k \frac{A_{\mathrm{R}_2}}{A_\mathrm{A}} \qquad \text{(Eq 14)}$$

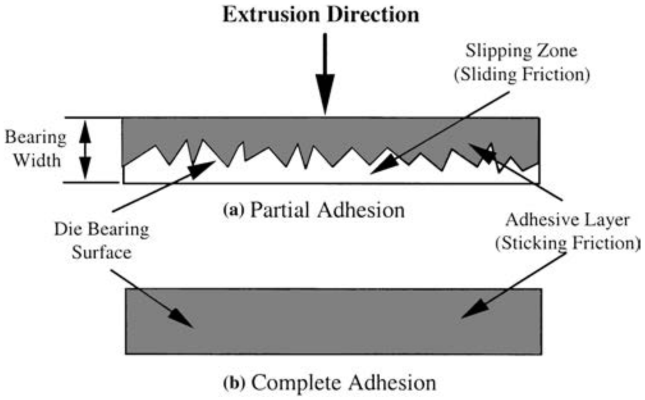


Fig. 15 Schematic of the morphology of the die bearing surface

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.

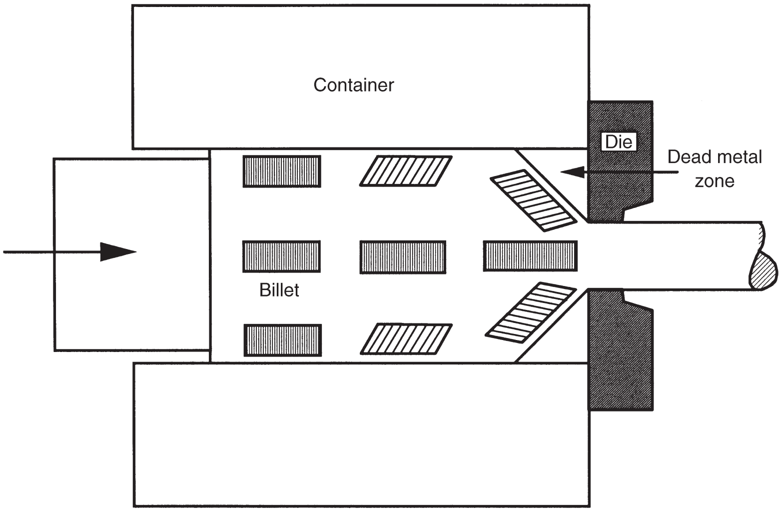


Fig. 16 Redundant work

- 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:

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

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:

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

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

From the yield criterion,

$$p_r = p_z + \overline{\sigma} \qquad \text{(Eq 26)}$$

where p_r is the radial pressure, p_z is the pressure in the Z direction and $\overline{\sigma}$ 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:

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

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

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

where *C* is the integration constant.

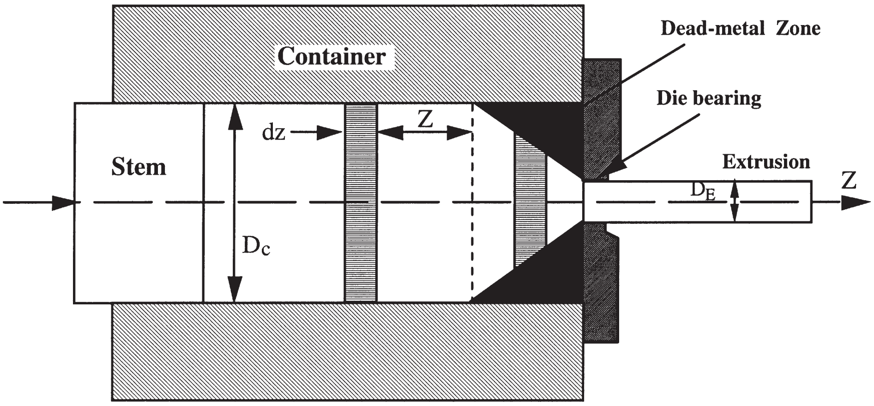


Fig. 17 Extrusion through a square die with dead-metal zone and equivalent rod diameter

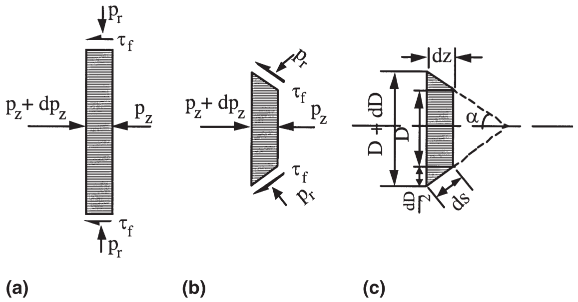


Fig. 18 State of stress for the extrusion shown in Fig. 17. (a) Freebody diagram of element inside the container wall. (b) Freebody diagram of element under the dead-metal zone. (c) Geometric relationship among *dz, dD,* and *ds*

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

$$C = \frac{1}{D_E^2} \tag{Eq 29}$$

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:

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

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:

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

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:

$$\frac{dp_z}{\tau_f} = \frac{4}{D_C}\,dz \tag{Eq 32}$$

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

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

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

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

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:

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

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:

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

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:

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

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.

Preview for: *Aluminum Extrusion Technology*, by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

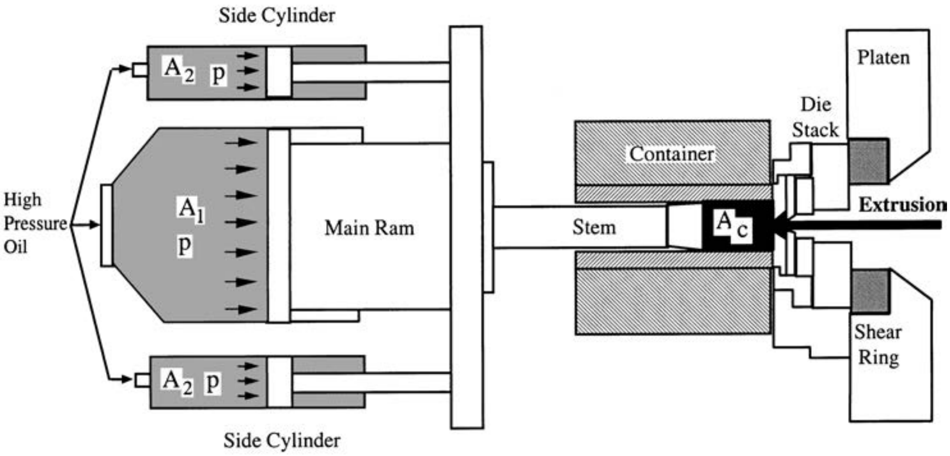


Fig. 19 Schematic of direct extrusion press

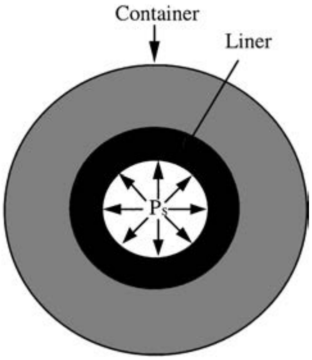


Fig. 20 Specific applied pressure

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:

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

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

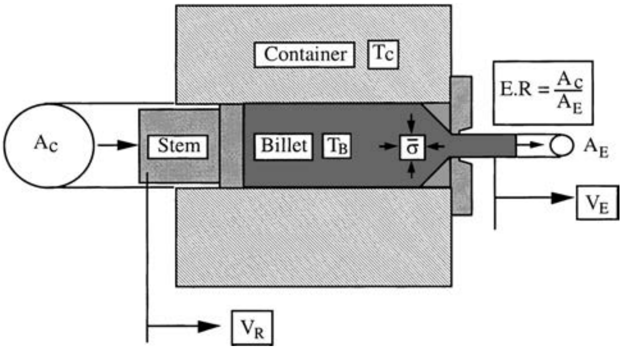


Fig. 21 Principal extrusion variables

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:

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

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):

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

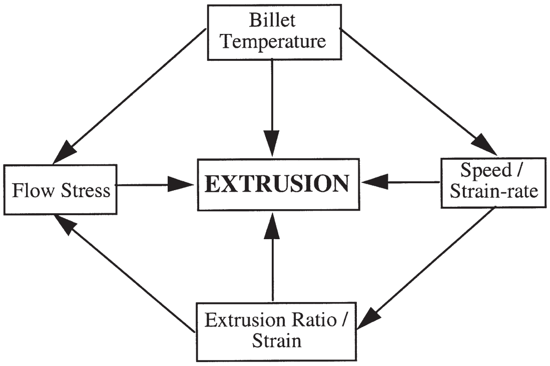


Fig. 22 Effect of principal variables on extrusion

where, $\overline{\sigma}_0$ is the known flow stress at a known strain-rate $\dot{\varepsilon}_0$, and similarly, $\overline{\sigma}$ is the flow stress at the strain rate $\dot{\varepsilon}$. 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.

Chapter 1: Fundamentals of Extrusion

References

1. S. Kalpakjian, *Manufacturing Engineering and Technology*, 2nd ed., Addison-Wesley Publishing Company, 1992

2. G.E. Dieter, *Mechanical Metallurgy*, McGraw-Hill, Inc., 1961

3. K. Laue, and H. Stenger, *Extrusion*, American Society for Metals, 1981

4. W.A. Backofen, *Deformation Processing*, Addison-Wesley Publishing Company, 1972

5. G.W. Rowe, *Principle of Industrial Metalworking Processes*, Edward Arnold Publisher, London, 1977

6. W. Johnson and P.B. Mellor, *Engineering Plasticity*, Van Nostrand Reinhold Company, London, 1975

7. E.G. Thomsen, C.T. Yang, and S. Kobayashi, *Mechanics of Plastic Deformation in Metal Processing*, The Macmillan Company, 1965

8. E.C. Pearson and R.N. Parkins, *The Extrusion of Metals*, 2nd ed., Chapman and Hall Ltd., London, 1960

9. H. Valberg, A Modified Classification System for Metal Flow Adapted to Unlubricated Hot Extrusion of Aluminum and Aluminum Alloys, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Aluminum Extruders Council and The Aluminum Association, Inc., May 1996

10. A.F. Castle and T. Sheppard, Hot Working Theory Applied to Extrusion of Some Aluminum Alloys, *Met Technol.*, Vol 3(No. 10), 1976 doi: 10.1179/030716976803391485

11. A.F. Castle, Temperature Control in Aluminum Extrusion, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Aluminum Extruders Council and the Aluminum Associations, Inc., 1992

12. G. Amontons, *Hist. Acad. R. Soc.*, Paris, 1699

13. F.P. Bowden and D. Tabor, “The Friction and Lubrication of Solids, Part II,” Oxford University Press, 1964

14. J.A. Schey, *Tribology in Metalworking*, American Society for Metals, 1983

15. S. Abtahi, Interface Mechanisms on the Bearing Surface in Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, May 1996

16. P.K. Saha, Thermodynamics and Tribology in Aluminum Extrusion, *Wear*, Vol 218, 1998 doi: 10.1016/S0043-1648(98)00210-5

17. T. Altan, Oh Soo-lk., and L. Harold Gegel, *Metal Forming: Fundamentals and Applications*, American Society for Metals, 1983

18. B. Avitzur, *Metal Forming: Process and Analysis*, McGraw-Hill Book Company, 1968

19. T. Altan and S. Kobayashi, A Numerical Method for Estimating the Temperature Distribution in Extrusion Through Conical Dies, *J. Eng. Ind. (Trans. ASME)*, 1968 doi: 10.1115/1.3604584

20. Y. Tashiro, H. Yamasaki, and N. Ohneda, Extrusion Conditions and Metal Flow To Minimize Both Distortion and Variance of Cross-Sectional Shape, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, 1992

21. P.K. Saha, Temperature Distribution in Extrusion, M.S. thesis, University of Calcutta, India, 1977

22. P.K. Saha, and R.K. Ghosh, Temperature Distribution During Hot Extrusion of Aluminum—Theoretical Evaluation, *Indian J. Technol.*, Vol 17, 1979

23. P.K. Saha, Influence of Plastic Strain and Strain Rate on Temperature Rise in Aluminum Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Extruders Council and the Aluminum Associations, Inc., May 1996

24. P.K. Saha, Factors Affecting Speed and Pressure in 6063 Aluminum Extrusion, *Proc. Aluminum 2000—3rd World Congress on Aluminum*, 1997 (Cyprus), Interall Publications

Chapter 2: Thermodynamics in Extrusion

References

1. A.R.E. Singer and J.W. Coakham, Temperature Changes Occurring during the Extrusion of Aluminum, Tin and Lead, *J. Inst. Met.*, Vol 89, 1961–1962

2. R. Akert, A Numerical Analysis of Temperature Distribution in Extrusion, *J. Inst. Met.*, Vol 95, 1967

3. G.D. Lahoti and T. Altan, Prediction of Metal Flow and Temperatures in Axisymmetric Deformation Processes, *Proc. of the 21st Sagamore Army Materials Research Conference*, 1974

4. G.D. Lahoti and T. Altan, Prediction of Temperature Distribution in Tube Extrusion Using a Velocity Field without Discontinuities, *Proc. of the Second North American Metalworking Research Conference*, 1974

5. A.R.E. Singer and S.H.K. Al-Samarrai, Temperature Changes Associated with Speed Variations during Extrusion, *J. Inst. Met.*, Vol 89, 1960–1961

6. T. Altan and S. Kobayashi, A Numerical Method for Estimating the Temperature Distribution in Extrusion Through Conical Dies, *J. Eng. Ind.* (Trans. ASME), 1968 doi: 10.1115/1.3604584

7. A.F. Castle and T. Sheppard, Hot Working Theory Applied to Extrusion of Some Aluminum Alloys, *Met Technol.*, Vol 3(No. 10), 1976 doi: 10.1179/030716976803391485

8. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

9. G.E. Macey and M. Salim, Numerical Simulation of Two-Dimensional Hot Extrusion of Aluminum, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1988

10. A.F. Castle, Temperature Control in Aluminum Extrusion, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1992

11. Y. Tashiro, H. Yamasaki, and N. Ohneda, Extrusion Conditions and Metal Flow To Minimize Both Distortion and Variance of Cross-Sectional Shape, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1992

12. V.I. Johannes and C.W. Jowett, Temperature Distribution in Aluminum Extrusion Billets, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

13. V.H. Pham, Heat Transfer Model for Temperature Profile of Extruded Sections at the Extrusion Press Exit, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

14. P.K. Saha, Influence of Plastic Strain and Strain Rate on Temperature Rise in Aluminum Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1996

15. H.S. Carslaw and J.C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press, London, 1959

16. P.K. Saha, “Temperature Distribution in Extrusion,” M.S. thesis, University of Calcutta, India, 1977

17. P.K. Saha and R.K. Ghosh, Temperature Distribution during Hot Extrusion of Aluminum—Theoretical Evaluation, *Indian J. Technol.*, Vol 17, 1979

18. E.G. Thomsen, C.T. Yang, and S. Kobayashi, *Mechanics of Plastic Deformation in Metal Processing*, Macmillan Co., 1965

19. A.F. Castle, Temperature Changes in the Extrusion of Aluminum Alloys, *Proc. Third International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1984

20. M. Lefstad, Die Temperatures in Aluminum Extrusions, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1988

21. W.R. Barron, Non-Contact Temperature Measurement of Aluminum: Its Design Performance and Function for Aluminum Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

22. E. Glasman, R. Goshen, B. Harel, A. Neboshchim, and E. Hodos, New Optical Pyrometer for Measuring the Temperature of Aluminum Alloys, *Aluminium 2000 3rd World Congress*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1997

23. G.J. Dail, M.G. Fuhrman, and D.P. DeWitt, Evaluation and Extension of the Spectral-Ratio Radiation Thermometry Method, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1988

24. M.L. Mester, A.H. Kahn, and H.N.G. Wadley, Measuring Internal Temperatures of Aluminum Extrusions, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1988

25. P.K. Saha, Thermodynamics and Tribology in Aluminum Extrusion, *Wear*, 1998 doi: 10.1016/S0043-1648(98)00210-5

26. T.J. Ward, R.M. Kelly, G.A. Jones, and J.F. Heffron, The Effects of Nitrogen—Liquid and Gaseous—on Aluminum Extrusion Productivity, *J. Met.*, Dec 1984 doi: 10.1007/BF03339208

27. K. Laue, Isothermal Extrusion, *Z. Metallkd.*, Vol 51, 1960

28. R. Chadwick, Developments and Problems in Package Extrusion Press Design, *Met. Mater.*, 1969

29. J. Kelly and F. Kelly, Simulated Isothermal Extrusion, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

30. J. Kialka, Isothermal Extrusion of Aluminum Alloys by Employing Force-Ram Speed Feedback, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

31. M. Pandit and K. Buchheit, A New Measurement and Control System for Isothermal Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

32. D. Jenista, Taper Quenching: A Cost-Effective Tapering Method for Isothermal Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

33. I. Venas, J. Hergerg, and I. Shauvik, Isothermal Extrusion Principles and Effect on Extrusion Speed, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

34. A.K. Biswas and B. Repgen, Isothermal and Isopressure Extrusion Results of Process Optimization in Various Extrusion Plants, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

35. OPTALEX Technical Brochure, Alu-Mac, Denmark, 1996

36. A.J. Bryant, W. Dixon, R.A.P. Fielding, and G. Macey, Isothermal Extrusion, *Light Met. Age*, April 1999

Chapter 3: Extrusion Press and Auxiliary Equipment

References

1. R.A.P. Fielding, How to Operate Extrusion Presses Well, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

2. R.A.P. Fielding, The Maintenance of Extrusion Plant: Operating Extrusion Presses for Maximum Efficiency, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

3. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

4. W.F. Larson and R.A. Bland, Developments in Indirect Extrusion Presses, *Light Met. Age*, 1977

5. V.L. Berezhnoy, Extrusion with Active Friction Forces as an Innovation in Light Alloy Metallurgy, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

6. V.N. Shcherba, Extrusion with the Use of Active Friction Forces (EwAFF), *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

7. H. Maeda, Ube Technical Features for Large Capacity Extrusion Presses, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

8. A.F. Castle, Fixed Dummy Block Extrusion, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1988

9. G.B. Clecim, The Fixed Dummy Block, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1988

10. A.F. Castle, Improving Fixed Dummy Block Performance, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

11. W. Johnen, Induction Billet Heaters with Hot Log Shears and Integrated Shock Heating System and Self-Contained Induction Shock Heaters, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

12. C.B. Gentry and J.C. Bugai, Mr. Profile's New Extrusion Line, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

13. R.A.P. Fielding and G. Macey, A Review of System for Heating Extrusion Dies, *Light Met. Age*, August 1998

14. F. Gramaticopolo and A. Kennedy, Modifications to the Extrusion Press and Handling System for Increased Reliability and Productivity, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

15. C. B. Gentry, The "Double Puller" Offers Three Major Advantages, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

16. F. Gramaticopolo, A No-Man Extrusion Handling System, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

Preview for: *Aluminum Extrusion Technology*, by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

Chapter 4: Extrusion Die and Tooling

References

1. V. Nagpal, C. Billhardt, T. Altan, and R. Gagne, Automated Design of Extrusion Dies by Computer, *Proc. Second International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1977

2. C. Purnell and D. Males, Extrusion Die Design by Computer, *Light Met. Age*, April 1980

3. C.T. Post, The Strong Link That Ties CAD to CAM, *Iron Age*, 22 Aug 1977

4. C.F. Billhardt, V. Nagpal, and T. Altan, "A Computer Graphics System for CAD/CAM of Aluminum Extrusion Dies," *Paper MS78–957*, Society for Manufacturing Engineers, 1978

5. V. Nagpal, and T. Altan, Design and Manufacturing of Dies for Lubricated Extrusion of Shapes, *J. Mech. Work. Technol.*, Vol 1(No. 2), Nov 1977 doi: 10.1016/0378-3804(77)90005-5

6. V. Nagpal, C. Billhardt, and T. Altan, Lubricated Extrusion of "T" Sections from Aluminum, Titanium and Steel Using Computer-Aided Techniques, *J. Eng. Ind. (Trans. ASME)*, Vol 101, Aug 1979 doi: 10.1115/1.3439513

7. R.A.P. Fielding, Computer Aided Design and Manufacturing of Extrusion Dies, *Light Met. Age*, April 1979

8. C.O. Stockdale, The Application of CAD/CAM to Extrusion Die Design, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

9. M.Y. Shridhara, CAD/CAM Systems for Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

10. J.-P. Hardouin, Bearing Length Calculation by Control of Metal Flow, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

11. T. Altan, S.-L. Oh, and H.L. Gegel, *Metal Forming*, American Society for Metals, 1983

12. P. Rodriguez and A. Rodriguez, System to Calculate Chambers and Feeds to Obtain a Minimum Single Bearing, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

13. P.T.F. Machado, Extrusion Die Design, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

14. L. Ingraldi, V. Giacomelli, and M. Pedersoli, Design and Correction of Hollow Dies in Europe, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

15. Die Design and Technology—*Proc. of the Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, 1996

16. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

17. L Bello, Aluminum Extrusion Die Correction, 1st ed., Fellom Publications, San Francisco

18. F.P. Bens and D. Peckner, Hot-Work Die Steels, *The Tool and Manufacturing Engineer*, May 1966

19. L. Jonson, L-A. Norstrom, and O. Sandberg, A New Precipitation Hardening Steel For Aluminum Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

20. A. Czelusniak, M.J. Korwin, and Y. Robert, Economics of NITREG Process Use in Nitriding of Aluminum Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

21. D. Pye, Plasma Nitriding, An Alternative Nitriding Method for Aluminum Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

22. R. Gonzales, User Experience with Fluidized-Bed Nitriding and Nitrocarburizing of Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

23. B.J. Janoss, Surface Enhancement Technology for Metal Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1996

24. M. Sundqvist, T. Bjork, S. Hogmark, and I. Srinivasan, Tribological Evaluation of Surface Treatments for Extrusion Dies, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1996

25. A.B. Mew and D.M.M. Guyoncourt, The Evaluation of Some Surface Treatments for Aluminum Extrusion Dies, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

26. I.B. Kelley, N.Y. Melville and W. Misiolek, Plasma Sprayed Ceramic Coatings for Extrusion Dies, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1996

27. J.A. Schey, *Tribology in Metalworking*, American Society for Metals, 1983

28. W.W. Thedja, B.K. Muller, and D. Ruppin, Tribological Process on the Die Land Area during Extrusion of AA6063 Alloy, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1992

29. P.K. Saha, Thermodynamics and Tribology in Aluminum Extrusion, *Wear*, Vol 218, 1998, p 179–190 doi: 10.1016/S0043-1648(98)00210-5

Chapter 5: Billet Casting Principles and Practice

References

1. A. Nussbaum, Recent Advances in Vertical Direct Chill Casting Equipment for Extrusion Billet Production, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

2. D.T.T. Auchterlonie, N.B. Bryson, G. Leblanc, and V.J. Newberry, Modular Mold System for Casting Extrusion Ingots, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992.

3. R.B. Wagstaff and J.M. Ekenes, Innovations in Hard Alloy Hot Top Casting Systems, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

4. V.L. Hammersmith, Materials for Casting Equipment, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

5. P.D. Harvey, Aluminum Casting Principles, *Aluminum and Its Alloys*, American Society for Metals, Course 26 (Lesson 5), 1979

6. R.J. McHale and D.W. Sites, Implementing Purchased Scrap Into An Aluminum Operation, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

7. L.A. Strom, J.W. Black, R.I.L. Guthrie, and C. Tian, Filtration Efficiency and Engineered Performance Improvements of Fully Sintered Reticulated Ceramics for Nonferrous Alloy Filtration, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

8. M. Bertoli and G. Bosetti, Improvements in Extrusion Properties and Practice Through the Use of SNIF In-line Refining, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

9. A.O. Aarflot, S.T. Johansen, and K. Venas, New In-Line Technology Combining Degassing and an Efficient Removal of Non-Metallic Inclusions by Gas Fluxing, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

10. J.R. Davis, Ed., *Aluminum and Aluminum Alloys, ASM Specialty Handbook*, ASM International, 1993

11. D.J. Deball and B.L. Kidwell, Method for Evaluating Grain Refiner Rod, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

12. J.H. Liu, F. Lin, and W.K. Lin, Study on the A1-Ti-B-Re Alloys as Grain Refiner to Al and its Alloys, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

13. L.S. Aubrey, M.A. Cummings, C.L. Oliver, and M. Chow, The Development and Performance Evaluation of a Dual-Stage Ceramic Foam Filtration System, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

14. M.J. Ekenes and F.E. Wagstaff, Expanding Capabilities of the AirSlip Air-Casting Process, *Light Met. Age*, Vol 43, April 1985

15. J.A. Brock and R.R. Avery, Production of High Strength Aluminum Alloys with Wagstaff MaxiCast System, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

16. M. Arase, N. Ohhaatake, and Y. Nagai, Development of High Speed Horizontal Continuous Casting in 6063 Billets and Billet Quality, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

17. F. Niedermair and G. Hertwich, Compact Type Remelt Plant with Horizontal DC Casting and Continuous Homogenization, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

18. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

19. N. Dahl, T.E. Johnsen, B.R. Henriksen, and E.K. Jensen, Precipitation of Mg_2Si in AlMgSi-Alloys During Cooling from Homogenization Temperature, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

20. J. Mahoney, Improved Methods of Log Cooling, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

21. A. Jackson and T. Sheppard, Structural Modifications Occurring during Homogenization of Some 7*xxx* Alloys, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

22. O. Reiso, U. Tundal, and S.J. Andersen, The Effect of Cooling Rate After Homogenization and Billet Preheating Practice on Extrudability and Section Properties of an AlMgSi Alloy, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

23. T. Oka, M. Yanagawa, and M. Hirano, The Effect of Homogenizing Heat Treatment Practice on the Productivity of Al-Mg-Si System Alloy, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

24. A.N. Anderson, Physical Metallurgy and Extrusion of 6063 Alloy, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

25. P. Cook and I. Musulin, PHOENICS Model for a Billet Homogenization Furnace, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

26. P. Garcia and G. Hertwich, The Hertwich Continuous Homogenizing System Operating at Inespal, Aviles (Spain), *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

27. D. Alabran, Improved Operating Efficiency of Log Homogenizing Furnaces, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

28. R.A. Ricks, N.C. Parson, H.L. Yiu, and S.A. Court, Microstructural Optimization for Extrusion of 6063 Alloys, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

Chapter 6: Extrusion of Soft- and Medium-Grade Alloys

References

1. L.F. Mondolfo, A.R. Peel, and J.A. Marcantonio, *Met. Technol.*, Vol 433(No. 9), 1975 doi: 10.1179/030716975803276970

2. L.F. Mondolfo and A.R. Peel, *Light Met. Age*, Vol 30(No. 4), 1978

3. J. Zasadzinksi, W. Libura, J. Richert, and W.Z. Misiolek, Modeling of Temperature-Speed Parameters In Aluminum Extrusion, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

4. O. Reiso, The Effect of Billet Preheating Practice on Extrudability of AlMgSi Alloys, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1988

5. Aluminum Extrusion Alloys, Kaiser Aluminum & Chemicals, Inc., Oakland, CA, 1964

6. Metal Working with Aluminum, 2nd ed., The Aluminum Association, 1975

7. K. Laue, “Moglichkeiten werkstoffgerechter Getsaltung von Leichtmetmetallprofilen, Z.f. Metallkunde 54, 1963

8. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

9. P.K. Saha, Influence of Plastic Strain and Strain Rate on Temperature Rise in Aluminum Extrusion, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1996

10. P.K. Saha, Factors Affecting Speed and Pressure in 6063 Aluminum Extrusion, *Aluminum 2000 3rd World Congress*, Vol 3, 1997

11. E. Kursetz, “Die Problematik der Fertigung von Hohlprofilen und Rohren beim Warmstrangpressen von Aluminium, Blech 16, 1969

12. W. Strehmel, M. Plata, and B. Bourqui, New Technologies for the Cooling and Quenching of Medium-To-Large-Sized Aluminum Extrusions, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

13. Plata *et al.*, Spray Unit for Cooling Extruded Sections, U.S. Patent 5,413,314, 1994

14. J.R. Davis, Ed., *ASM Specialty Handbook: Aluminum and Aluminum Alloys*, ASM International, 1993

15. R. Ramanan and A. Dery, How to Obtain the Most from Your Ageing Ovens, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

16. N.C. Parson, J.D. Hankin, and A.J. Bryant, The Metallurgical Background to Problems Occurring during the Extrusion of 6*xxx* Alloys, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

17. T. Ramanan, Helping the Customer, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

18. N.C. Parson, C.W. Jowett, C.V. Pelow, and W.C. Fraser, Surface Defects on 6*xxx* Alloy Extrusions, *Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

19. M. Tokizawa and N. Takatsuji, Effects of the Die Condition and Billet Composition on the Surface Characteristics of the Extruded 6063 Aluminum Alloy, *Trans. Jpn. Inst. Met.*, Vol 29(No. 1), 1988 doi: 10.2320/matertrans1960.29.69

20. W.W. Thedja, B.K. Muller, and D. Ruppin, Tribological Process on the Die Land Area during Extrusion of AA6063 Alloy, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1992

Preview for: *Aluminum Extrusion Technology*, by Pradip K. Saha, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.aet.9781627083362

Chapter 7: Extrusion of Hard Alloys

References

1. A. Wilm, *Metall.*, Vol 225(No. 8), 1911

2. T. Sheppard, On the Relationship between Extrusion Conditions, Mechanical Properties and Surface Acceptability in Some Hard Alloys, *Aluminum 2000 3rd World Congress*, Vol 1, 1997

3. P.P. Mozely, *J. Aeronaut. Sci.*, Vol 10(No. 6), 1943, p 180

4. E.H. Dix, *Trans. AIME*, Vol 130(No. 35), 1945

5. L.F. Mondolfo, *Manganese in Aluminum Alloys*, Manganese Center, London, 1958

6. D.J. Strawbridge, W. Hume-Rothery, and A.T. Little, *J. Inst. Met.*, Vol 191(No. 74), 1947–1948

7. J. Hatch, Ed., *Aluminum: Properties and Physical Metallurgy*, American Society for Metals, 1984

8. *Aluminum Extrusion Alloys*, Kaiser Aluminum & Chemicals, Inc., Oakland, CA, 1964

9. J. Zasadzinski and W. Misiolek, Estimating Optimal Speed/Temperatures to Maximize Hot Extrusion Exit Speed, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1988

10. K. Asboell, O. Jensrud, O. Reiso, and D. Jacobsen, Extrudability and Mechanical Properties of Some 7*xxx*-Series Alloys, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1996

11. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

12. J.R. Davis, Ed., *Aluminum and Aluminum Alloys*, ASM International, 1993

13. W. Dixon, Extrusion of 2*xxx* and 7*xxx* Alloys, *Proc. Seventh International Aluminum Extrusion Technology Seminar*, 2000, accepted for publication

14. G.E. Dieter, *Mechanical Metallurgy*, McGraw-Hill, Inc., 1961

15. B. Avitzur, *Metal Forming—Processes and Analysis*, McGraw-Hill Publishing Co., 1968

16. G. Sachs and K.R. VanHorn, *Practical Metallurgy*, American Society for Metals, 1940

17. J.L. Brandt, *Aluminum*, K.R. VanHorn, Ed., American Society for Metals, 1967, p 1–30

18. U.S. Patents 2,885,313; 2,885,315; and 2,885,316, 5 May 1959

19. P.K. Saha, Sources of Blister in 7075 Thin Gage Extrusion in Fabrication, *Seventh International Aluminum Extrusion Technology Seminar*, 2000, accepted for publication

20. M.S. Hunter, A.M Montgomery, and G.W. Wilcox, *Aluminum*, K.R. VanHorn, Ed., American Society for Metals, 1967, p 55–78

21. A.J. Bryant, W. Dixon, and R.A.P. Fielding, The Prevention of Metallurgical Defects in Medium- and High-Strength Aluminum Extrusions, *Light Met. Age*, June 1999, p 30–54

22. W. Dixon, Further Developments in the Extrusion of Aluminum-Based Metal Matrix Composites, *Proc. Sixth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1996

23. W. Dixon, Extrusion of Particulate-Reinforced Aluminum-Based Metal Matrix Composites, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

24. S. Brusethaug, O. Reiso, and W. Ruch, Extrusion of Particulate-Reinforced Aluminium Billets Made by D.C. Casting, *Proc. Fabrication of Particulates Reinforced Metal Composites*, J. Masounave and F.G. Hamel, Ed., ASM International, 1990, p 173–180

25. P.W. Jeffery and S. Holcomb, Extrusion of Particulate-Reinforced Aluminum Matrix Composites, *Proc. Fabrication of Particulate Reinforced Metal Composites*, ASM International, 1990

26. J. Zhou, J. Duszczyk, P. Houdijk, H. Zitman, and A.J. Walstock, Extrusion of an Aluminium Matrix Composite with Hard Metal Dies, *Aluminium 2000 3rd World Congress*, Vol 3, 1997

27. D.J. Lloyd, Aspects of Fracture in Particulate Reinforced Metal Matrix Composites, *Acta Metall.*, Vol 39, 1991 doi: 10.1016/0956-7151(91)90328-X

28. T.F. Klimowicz, W. Dixon, and S. Inouye, The Effect of Cold Drawing on the Elastic Modulus of Aluminum Composite Drive Shaft Tube, *Proc. of the 10th Annual ASM/ESD Advanced Composites Conference*, 1994

29. J.L. Cook and W.R. Mohn, MMCs Whisker-Reinforced, *Composites*, Vol 1, *Engineering Materials Handbook*, ASM International, 1987

30. R. Dashwood and T. Sheppard, Extruded Aluminum Alloys Produced from the Powder Phase, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 2, Aluminum Association and Aluminum Extruders Council, 1992

Chapter 8: Process Control in the Aluminum Extrusion Plant

References

1. P. K. Saha, Process and Quality Control in an Aluminium Extrusion Plant, Part I, *Aluminium Extrusion*, Year 1(No. 2), INTERALL Srl, Italy, 1996, p 26–33

2. P. K. Saha, Process and Quality Control in an Aluminium Extrusion Plant, Part 2, *Aluminium Extrusion*, Year 2(No. 3), INTERALL Srl, Italy, 1997, p 18–21

3. K. Laue and H. Stenger, *Extrusion*, American Society for Metals, 1981

Chapter 9: Statistical Process and Quality Control

References

1. V.R. Bird, Use of Statistically Designed Experiments in an Extrusion Plant, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1988

2. R.F. Wolf, Statistical Process Control Application to the Aluminum Extrusion and Drawn Tube Process, *Proc. Fourth International Aluminum Extrusion Technology Seminar*, Aluminum Association and Aluminum Extruders Council, 1988

3. W.C. Boatman, Applications of Statistical Process Control and Continuous Improvement Philosophy in an Extrusion Plant, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

4. D.B. Rogers, Practical Application of Statistical Process Control in the Aluminum Cast Shop, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

5. M.J. Schwarz, Quality Improvements in an Aluminum Extrusion Billet Casting Facility, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

6. M.J. Schwarz, The Implementation of Statistical Process Control, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

7. R.G. Holder, Total Quality Management: Survival and Success in Today's Extrusion Industry, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992.

8. A. D. Steadman, The Philosophy behind Management Control Systems and the Achievement of An Extrusion Management Control System, *Proc. Fifth International Aluminum Extrusion Technology Seminar*, Vol 1, Aluminum Association and Aluminum Extruders Council, 1992

9. J.M. Juran and F.M. Gryna, *Quality Planning and Analysis*, Tata McGraw-Hill, New Delhi, 1988, p 125–130

10. J.M. Juran, *Juran on Planning for Quality*, Free Press, New York, 1988

11. R.S. Burington, *Handbook of Probability and Statistics with Tables*, 1970

12. I. W. Burr, *Engineering Statistics and Quality Control*, McGrawHill

13. A. J. Duncan, *Quality Control and Industrial Statistics*, Richard D. Irwin Inc., 1959

14. L.M. Tobin, The New Quality Landscape: Total Quality Management, *Journal of System Management*, Vol 41(No. 11), 1990, p 8–14

15. B.J. Witcher, Total Marketing: Total Quality and the Marketing Concept, *The Q. Review of Marketing*, Winter 1990