12th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2008, Istanbul, Turkey, 26-30 August, 2008

IMPROVEMENT OF DIE DESIGN AND PREVENTION OF DIE FAILURE IN METAL EXTRUSION

Sayyad Z. Qamar, Rafiq A. Siddiqui, Tasneem Pervez
Box 33, Mechanical and Industrial Engineering Department, College of Engineering, Sultan Qaboos University, Al-Khodh 123, Oman; email sayyad@squ.edu.om

Anwar K. Sheikh, Abul Fazal M. Arif
Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

ABSTRACT
Performance and working life of the die and affiliated tooling are very important factors contributing to the economic success of an extrusion setup, as they directly translate into productivity and product quality. Rejection and rework of the extruded product are linked to problems faced during the tooling life-cycle: die design, die manufacture and heat treatment, die service. Efficiency and economics of any extrusion plant can be significantly improved by minimizing die defects and enhancing die life through practical measures adopted during the design and service stages of the die. Die making has been more of an art than a science, learnt through years of trial and error. Only a few extrusion die manufacturers exist around the world, religiously guarding the trade secrets to production of successful dies. Some authors have addressed individual issues in die design and die manufacture. However, no single published source appears to cover the multitude of problems that can be faced during design, manufacture, and use of an extrusion die. The current paper summarizes the results of an exhaustive review of major die problems and related preventive measures from published literature, die manufacturers, and extrusion facilities (die users).
Keywords: Metal extrusion, die design, die manufacture, product defects, prevention methods

1. INTRODUCTION
Extrusion is a widely used manufacturing method, especially for certain grades of steel, and for various aluminum alloys. The most critical component in the extrusion process is the die set, majorly contributing to productivity and profitability. Accuracy of the die and affiliated tooling ensures good quality of the extruded product and increased productivity due to uninterrupted production (reduced die correction requirements). Long die life directly translates into lower costs by avoiding frequent die replacements. That is why the knowledge of die failure and die related product defects, and associated prevention methods, is so important. Comprehensive coverage of failure modes and mechanisms of extrusion dies [1] and product defects in a typical extrusion facility [2] can be found in earlier studies conducted by the authors.

2. DIE DESIGN AND MANUFACTURING
Die design is affected by many factors such as alloy characteristics, type of extrusion process, and product specifications (such as shape, dimensions, minimum thickness, etc). Some of the main goals of a die designer are the optimization of the following factors: number of die openings (cavities) based on the shape and size of the profile and the existing tooling setup; location of the die opening with respect to billet axis; orientation of the openings around their centroids to match the handling system; optimization of bearing lengths to increase productivity while maintaining accuracy; determination of the final die opening dimensions based on thermal shrinkage, stretching allowance and die deflection.

The manufacturing process in modern die making plants is a combination of computer numerical control (CNC) saw cutting, CNC turning and milling, and spark erosion (EDM or wire EDM), together with finishing operations such as grinding. Later on, the die is subjected to various types of heat treatment and surface hardening routines to get the desired combination of toughness, hardness, etc. The exact operations and their sequence would depend on the steel type and use, die size and geometry, etc. However, the heat treatment operations of stress relieving, hardening (and quenching), and tempering are usually carried out. Surface hardening and treatment operations of nitriding, physical vapor deposition (PVD) and chemical vapor deposition (CVD) are also performed.

3. DIE PROBLEMS AND SUGGESTED SOLUTIONS

Causes that lead to failures of extrusion tooling can be classified into different categories: incorrect material selection, defects in die design, die material defects, incorrect tool manufacture, incorrect heat treatment and surface hardening, incorrect use in service, etc. Summarized below are the more significant problems (and their solutions) related to die design and manufacturing, and die operation and correction that may lead to product defects or die failure. Information has been collected, collated, analyzed, and organized after a thorough review of published sources and a survey of various commercial extrusion facilities. Each problem (in italics) is followed by its recommended solution(s), based either on mechanics of the extrusion process, or suggested by years of industrial practice.

3.1. Metal Flow Related Problems

1. Shape distortion etc due to *unbalanced flow of metal*: (i) Frictional resistance at billet-container interface slows down the metal flow near the billet surface; center of the billet thus moves faster than the periphery of the billet. Bearing length must be inversely proportional to its distance from the centre of the billet to balance the flow. To balance the flow in thinner sections, bearing length needs to be smaller, and vice versa. [3, 4, 5].
2. *To get uniform metal flow in multihole die*: Use radial layout for die openings, in which major axis of each cavity lies along a radius, giving each portion of bearing surface the same relationship to the centre of the die. This produces uniform metal flow but can lead to difficulties in controlling twisting and handling on a run out table [4].
3. *Controlling twisting and handling on a runout table for multihole die*: Use flat layout for die openings, in which major axis of each cavity is at right angles to a radius. Main advantage is ease of handling on a runout table, but it poses difficulty in die correction [4].
4. *Controlling metal flow in hollow dies*: Two different approaches are generally used. (i) Help metal to flow better under the webs using "bumps" placed on the mandrel over the bearing (not under the webs near the welding points). (ii) Control metal flow in the die-plate using the bearing together with a special device called the *piastrina*; a special pocket contouring the shape, positioned at a certain distance from the profile and having a certain depth depending on the profile's characteristics [6, 7].
5. *Correction of hollow die for twist, angularity, split corners, convex wall, concave wall, and uneven wall*: Examine the port first before working on the bearing. Ports control the volume of metal, which needs to be balanced in relation to the cross-sectional area of the extrusion that each port is feeding [4].
6. *Discontinuity in extruded product; bad billet-to-billet weld*: Caused in old flat dies because they did not have pockets. In new dies, extrusion is continuous by using pockets for good welding [6].

3.2. Hardness and Dimensional Accuracy Problems

1. *To produce extrusions having accurate shape and dimensions repeatedly with a long life; problem of die softening*: Die nitriding is the most common hardening and surface treatment method for the bearing area. Nitriding involves diffusion of nitrogen gas into the surface at a temperature ranging from 450-580^{o}C. Plasma, fluidized-bed, and nitrocarburizing are the common nitriding methods. Other methods of improving surface characteristics are physical vapor deposition (PVD) and chemical vapor deposition (CVD) [4, 8].
2. *During rehardnening process (after softening of die due to repeated hot use), grain coarsening occurs, leading to reduced toughness and increased risk of cracking*. Desired hardness is not achieved in decarburized surface zones; this leads to premature wear especially in the die

opening: During rehardening, carburization and decarburization must be avoided. Die must be previously annealed to obtain the most favorable initial structure [9].

3. *Premature plastic deformation and loss of hardness leading to reduced hot strength. Significant loss of toughness*: First problem occurs due to severe under-hardening, while the second is caused by over-hardening and inadequate preheating; double hardening can result in grain coarsening and a reduction in toughness especially with large die dimensions. Solution is careful proper hardening and adequate preheating of die; avoiding under-hardening and over-hardening [9].

3.3. Wear and Surface Texture Problems

1. *Wear-out of die land after extruding a number of billets; chemical surface adhesion*. Unoxidized aluminum is very reactive, especially at higher temperatures (500°C); it reacts with tool metal and adheres to the bearing surface. Other impurities may also cause this problem: (i) Remove alumina (A_{l2O3}) by grinding with silicon carbide abrasive paper. (iii) After extrusion of every 100 billets, die should be cleaned in 25% NaOH [10, 11, 12].
2. *Damage of die bearing surface caused by cleaning procedures*: Coating the bearing surface with a wear-resistant metal significantly reduces aluminum pickup, adhesive wear, thermal fatigue wear, friction and the tendency to stick, and also results in higher oxidation temperature (up to 750°C) and good corrosion resistance. (i) Perform surface treatment; use nitriding or duplex treatment (PVD or CVD after nitriding. This yields improved die life, better throughput of extruded aluminum, reduced die correction time, shorter cycle times, no after-process correction and (f) reduced operating costs [4, 10, 11].
3. *Flow of oxide skin of the billet surface into the extrusion (causing surface defects)*: Make sure that the material will not be drawn from the edge of the billet into the section; edge material may contain oxide layers and impurities. Use minimum clearance between the die and the container wall. Circumscribing circle diameter (CCD) of the sections in the case of multi-hole dies should not be greater than 0.85 times the container diameter [4, 13].
4. *Formation of streaks*; streaks are lines formed on the surface of extrusion: Streaks are caused by sharp changes in bearing. Blend the variation in bearing length through fillets and rounds [4].
5. *Friction between billet material and extrusion tooling* (die face, die holder, container, dummy block, and mandrel in the extrusion of hollow profile): Normal lubricants can react with billet metal at high extrusion temperature causing contamination; so they are avoided in hot extrusion. However, use of proper lubrication of container and die helps in avoiding sticking, friction and reintroduce sliding through the interface area. Lubricant material such as graphite in an oil or water-based carrier can be used [14].

3.4. Manufacturing, Material and Heat Treatment Problems

1. *Fine cracks due to spark flashover during fabrication of complex-profile dies using spark erosion*: Degree of surface damage depends on the rate of cutting. To reduce the size of the crack, spark erosion should be carried out with sufficient material for polishing. Subsequent tempering after sparking can also be a solution [9].
2. *Die fracture because of severe grain boundary carbides due to insufficient degree of solubility during heat treatment*. This grain boundary impairs the ductility and temperature fluctuation resistance and causes inhomogeneities and segregations of die material: These precipitates can be dissolved by intermediate special heat treatment after hot working. Subsequent annealing gives improved structure and homogenous metal. Inhomogeneities and segregations can be reduced by using ERS (electro-slag refining), giving better toughness values especially in the core region [9].

3.5. Puller Related Problems

1. *Dimensional problems in extruded section because of the use of puller*: Die design has to be optimized for bearing length and feeding ports and recesses to balance out the effect of puller speed [8].
2. *Bearing size problem when using pullers*: Excessive bearing length in the mandrel can cause the section to stick to the mandrel surface when puller force is applied, resulting in seriously distorted shape. Adjustment of mandrel bearing length in a hollow die has to be carried out after die trials with puller [8].

3. *Metal flow through one cavity in a multi-cavity die is difficult to start*: Use of puller can alleviate the problem by helping to get the cavity running [8].

3.6. Other Problems

1. *Proper strength to withstand the pressure applied by the billet in case of multihole die*: Minimum distance between two openings of a multi-hole die must be adequate to provide proper strength to withstand the pressure applied by the billet [4].
2. *To provide support to the die to avoid deflection*; for flat section having a long tongue or where defection is critical: (i) An insert bolster can be used, designed to match closely the aperture in the die backer, held in an insert holder. (ii) Custom backer is used with an aperture closely following the die aperture [13].
3. *Stress cracks*: Avoid high unbalanced mass variation and sharp edges in die design [9].
4. *Accuracy in fitting of die in die ring and complete die stack in die slide*: Die, die ring and backer are heated prior to loading into the press, thus increasing the dimensions accordingly. It is necessary to compromise between tight tolerance for accurate location and allowance for the variations in thermal expansion. Good tolerances can be found in references such as [13].
5. *Surface cracking; also called fir-tree cracking or speed cracking*: Can be avoided by lower temperature and slower speeds of extrusion [15].
6. *Extrusion defect; also called pipe defect, tailpipe, fishtailing.* This type of metal flow tends to draw surface oxides and impurities toward the centre of the billet, like a funnel: (i) Modify flow pattern to a less inhomogeneous one, such as by controlling friction and minimizing temperature gradients. (ii) Machine the billet surface prior to extrusion to eliminate scales and impurities. (iii) Use dummy block that is smaller in diameter than the container, thus leaving a thin shell along the container wall as extrusion progresses [15].

4. REFERENCES

[1] Arif AFM, Sheikh AK, Qamar SZ and al-Fuhaid KM “A Study of Die Failure Mechanisms in Aluminum Extrusion,” Journal of Materials Processing Technology, 134 (3), March 2003, p 318-328

[2] Qamar SZ, Arif AFM, Sheikh AK “Analysis of Product Defects in a Typical Aluminum Extrusion Facility,” Materials and Manufacturing Processes, 19 (3), July 2004, p 391-405

[3] Bauser M, Sauer G, Siegert K (ed) Extrusion, 2nd edition, ASM International, 2001

[4] Saha PK Aluminum Extrusion Technology, ASM International, 2000

[5] Aluminum Extrusion Manual, 3rd edition, Aluminum Extruders Council and The Aluminum Association, 1998

[6] Ingraldi L, Giacomelli V, Pedersoli M “Design and Correction of Hollow Dies in Europe,” 5th International Aluminum Extrusion Technology Seminar, 1992, Vol 1, p 369-383

[7] Nobrega JM, Carneiro OS "Strategies to Balance the Flow in Profile Extrusion Dies," Society of Plastics Engineers Annual Technical Conference, Charlotte, May 2006, Vol 2, p 867-871

[8] Bilén G "Die Design and Die Correction as Affected by Pullers," 4th International Aluminum Extrusion Technology Seminar, 1988, Vol 2, p 17-19

[9] Kortmann WA “Failure in Extrusion Tooling; Causes and Methods of Avoiding Failures,” International Aluminum Extrusion Technology Seminar, 1993, Vol 1, Part 5, p 219

[10] Panjan P, Cvahte P, Çekada M, Navinšek B, Urankar I “PVD CrN Coating for Protection of Extrusion Dies,” Vacuum, 61 (2001), p 241-244

[11] Björk T, Westergard R, Hogmark S "Wear of Surface Treated Dies for Aluminum Extrusion; a Case Study,” Wear, 249 (3-4), 2001, p 316-323

[12] Fontalvo GA, Humer R, Mitterer C, Sammt K, Schemmel I “Microstructural Aspects Determining the Adhesive Wear of Tool Steels,” Wear, 260 (2006), p 1028-1034

[13] Castle A, Flory R, Gagg J “Die Design and Construction in Europe,” 4th International Aluminum Extrusion Technology Seminar, 1988, Vol 2, p 25-34

[14] Benedyk JC “Review and Analysis of Emerging Extrusion Processes; Part II: The Evolving Role of Friction in Hot Extrusion,” Light Metal Age, 59 (2001), Part 9-10, p 6-14

[15] Kalpakjian S, Schmidt SR Manufacturing Processes for Engineering Materials, 4th edition, Prentice Hall, 2003