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Die Defects and Die Corrections in Metal Extrusion

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Abstract: Extrusion is a very popular and multi-faceted manufacturing process. A large number of products for the automotive, aerospace, and construction sectors are produced through aluminum extrusion. Many defects in the extruded products occur because of the conditions of the dies and tooling. The problems in dies can be due to material issues, design and manufacturing, or severe usage. They can be avoided by maintaining the billet quality, by controlling the extrusion process parameters, and through routine maintenance. Die problems that occur on a day-to-day basis are mostly repairable and are rectified through various types of die correction operations. These defects and repair operations have not been reported in detail in the published literature. The current paper presents an in-depth description of repairable die defects and related die correction operations in metal extrusion. All major die defects are defined and classified, and their causes, preventive measures, and die correction operations are described. A brief frequency-based statistical study of die defects is also carried out to identify the most frequent die corrections. This work can be of direct benefit to plant engineers and operators and to researchers and academics in the field of metal extrusion.

Keywords: metal extrusion; die defects; product defects; process parameters; die corrections; definitions; causes; classification; frequency analysis

1. Introduction

Because of its versatility and net-shape ability, extrusion is a very common manufacturing process, especially for aluminum alloys. Extruded products are widely used in the construction, automobile, and aerospace industries. The mitigation of products' defects directly leads to a reduction of rework and rejection, saving production time and cost. The die is perhaps the most vital component in extrusion because of its high cost, very fine dimensional tolerances, and good performance against repeated thermo-mechanical stresses. The accuracy and durability of a die set ensure a good product quality and reduced interruptions, leading to higher productivity and reduced costs [1–4].

Many product defects in extrusion have their root in problems related to dies and tooling. Some of these are related to die design, die material, and die manufacturing, while others occur during the service life of the die [5–10]. The latter include improper support tooling, improper temperature, erosion, pitting, billet material quality, friction, etc. [11]. Die problems can be prevented by controlling the billet quality and extrusion process parameters [12]. Many of the routine die problems are repairable and are addressed through various types of die correction operations. After some time, die corrections are no longer possible, and the die has to be scrapped. Common reasons for die failure are cracks, bearing washout, chip-off, deflection, fracture, and wear [13–16].

1.1. Current Work

There is one published study of a general nature on die defects and die failure modes in extrusion [17], while most authors have investigated only a few specific die problems. No published literature is available on correctable die defects and die correction operations performed in a metal extrusion plant. The focus of the current study is on die defects that are correctable and repairable, and the operations needed to carry out these corrections. It is based on a thorough literature review, the lead author's direct involvement with the extrusion industry for over 20 years, and detailed discussions and meetings with engineers and technicians in actual aluminum extrusion plants. Definitions and causes of all relevant die defects are presented, together with details of die correction operations needed to rectify these problems. A brief statistical analysis (frequency charts) of die defects and corrections occurring over a three-year period in a regional medium-to-large-size extrusion facility is also conducted. A discussion of die correction operations is critical for a thorough understanding of the metal extrusion process and for research and R&D targeted at the improvement of die and tooling design and the optimization of the extrusion process parameters. The current study is of direct utility for engineers and technical staff in the extrusion industry and for researchers and academics.

1.2. Die Structural Features

The terminology used in the following sections may vary a little from plant to plant. However, most of the terms are commonly used around the world. Die nomenclature generally refers to the structural features of a die. A schematic diagram of an extrusion die is shown in Figure 1a. The main features are bearing, die back clearance, step, ports, welding chamber, rib, feeding channel, and undercuts. A brief description of each feature is given below [18,19].

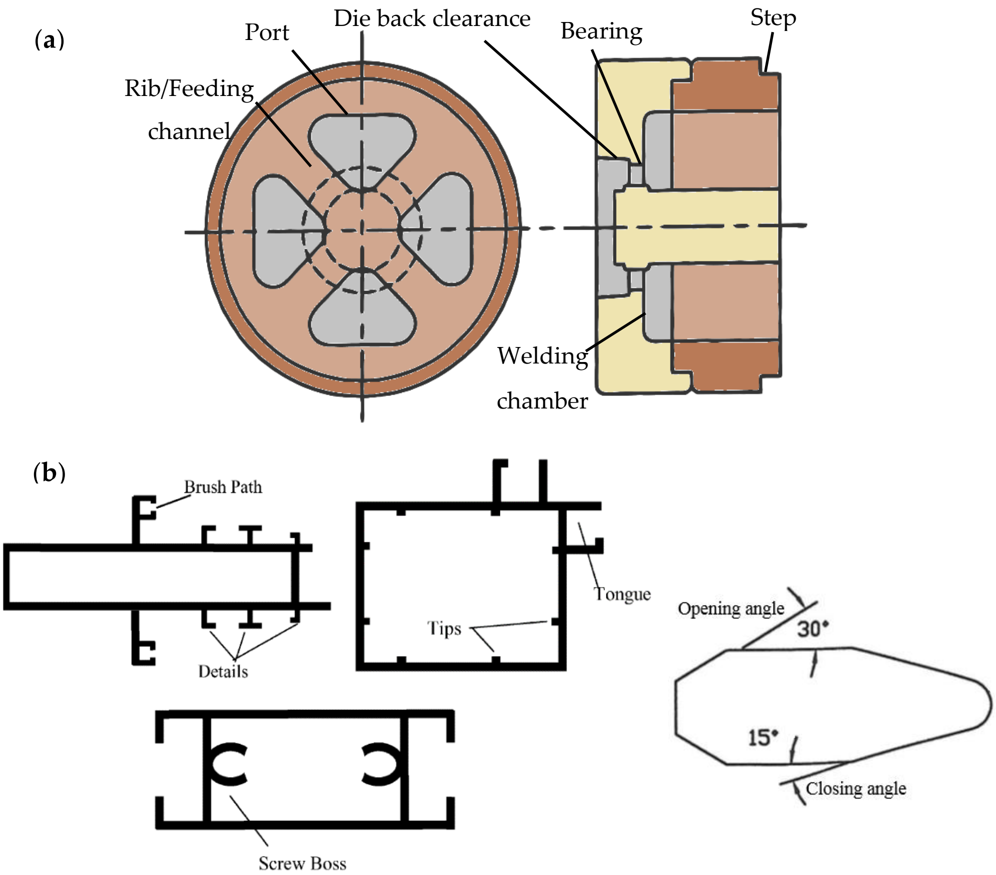

Figure 1. (**a**) Main features of a hollow-profile die; (**b**) some typical features of an extruded profile (left), and details of a rib profile (right).

The bearing forms an outline of the extrusion shape cut through the die to the highest possible precision. The bearing portion of the die determines both the profile and the finish of the extrusion. Die bearings act as the "land" which provides fine frictional control on metal flow. However, the friction of flowing metal can cause the temperature to rise. The last portion of the die is the die back, and modifications can be done on the die back clearance to influence metal flow. Reasonable support must be provided to avoid the deflection of the bearing land.

The step is the portion of the die that helps fix the die to the die holder. Ports are provided to facilitate the metal flow distribution (especially in the extrusion of hollow shapes), so that all regions of the extruded profile receive the right amount of metal. Their size is always maximized in order to feed the profile at the highest speed. The material strength of the die influences this maximum size. A large size of the ports will also allow a lower resistance to the metal flow, thereby reducing the required extrusion pressure [20].

The welding chamber is provided to facilitate the joining back of the distributed metal from the ports, before it enters the die bearing area. Deeper welding chambers help achieve higher extrusion speeds. The ribs support the mandrel portion in a hollow die, which provides the form for the inner section of the hollow profile. The die must be strong and easy to extrude at the same time. Several factors (including shear and bending stresses) must be considered and balanced in designing the die for minimum temperature increase and maximum speed. The limiting factor is the speed at which the metal can weld back after passing this rib and leg portions. The closing angle should be low enough to allow quick welding (Figure 1b).

The undercut is a step on the core of the die, just before the bearing surface. It acts as a shear edge before the metal is extruded through the die opening. In the case of hollow extrusion, a conventional straight mandrel generates heat due to friction caused by shear in the metal flowing over the mandrel. Undercutting the mandrel improves both flow and temperature distribution. It also creates a useful dead metal zone (DMZ), which allows the metal to flow much easier (with less friction) over subsequent layers. The profile features may incorporate several counter-features to generate important geometric elements (Figure 1b) of the extruded profile (such as grooves, seats, etc.) which will be required later during the installation and use of the extruded sections. The most common profile features in the die are tongue, brush path, screw boss, and tip [17].

1.3. Die Tooling

The core tooling component in extrusion is the die. The billet material (metal) is pressed through it to get the desired shape of the product. Additional tooling is required to provide sufficient rigidity to the die against the pressure applied by the ram of the extrusion press [21]. A schematic of the press and die tooling is shown in Figure 2. The common tooling components [19,22,23] are described below.

The die holder/ring holds the die, the feeder plate, and the die backer together. The die backer provides support to the die against collapse or fracture. The bolster transfers the extrusion load from the die to the pressure ring/pad. The sub-bolster is an additional (optional) tooling placed at the back of the bolster to give additional support. The pressure ring/pad (or platen plate) transfers the extrusion load from the bolster to the press platen and also guards against bolster deflection. The die carrier/slide holds together the complete die set (bolster and die ring). The feeder plate is placed in front of the die, balances the metal flow, and allows continuous extrusion without breaks. The tool stack corresponds to the full assembly containing the die, die backer, feeder plate, holder, and support tooling that fits into the die slide. The liner provides protection against thermal and mechanical stresses to the large and expensive container. The stem is fitted with the main ram to force the billet through the container. The dummy block is either floating or fitted in front of the stem and protects the life of the costly stem.

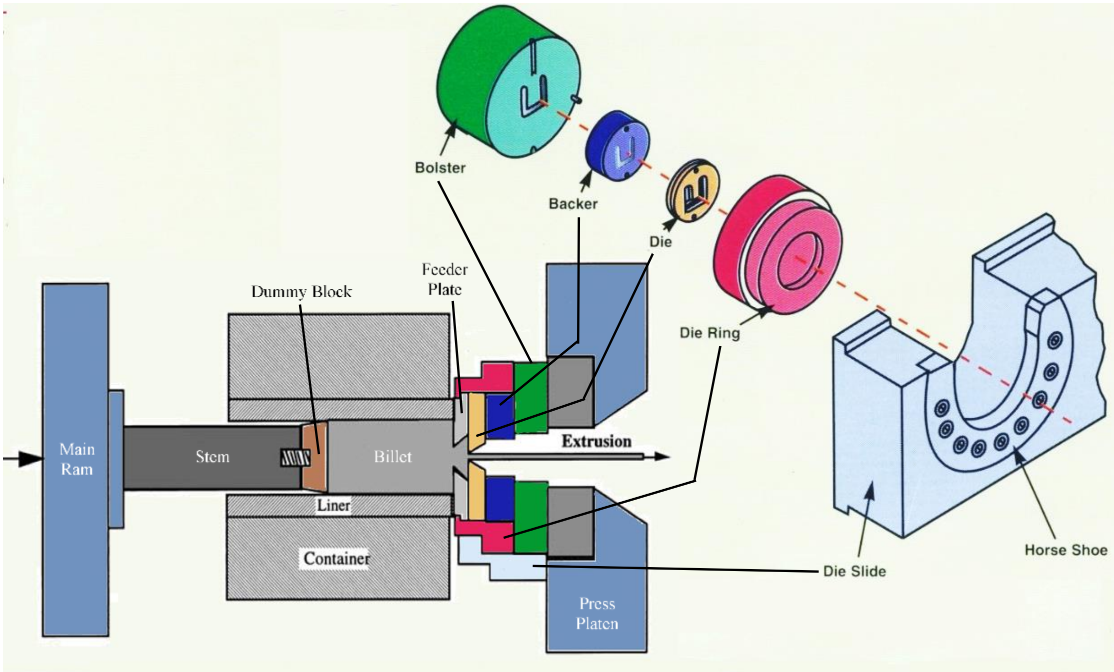

Figure 2. Schematic layout of the extrusion press and tooling.

1.4. Types of Dies

On the basis of the shape of the extruded profile, dies are generally classified into three types: solid, hollow, and semi-hollow (Figure 3). The solid profiles are usually extruded through a single-piece die, whereas the hollow shapes require a two-piece die set, known as cap and mandrel (to form the hollow profile). Semi-hollows are solid profiles (without a fully enclosed cavity) but need a cap-and-mandrel set [18,24,25].

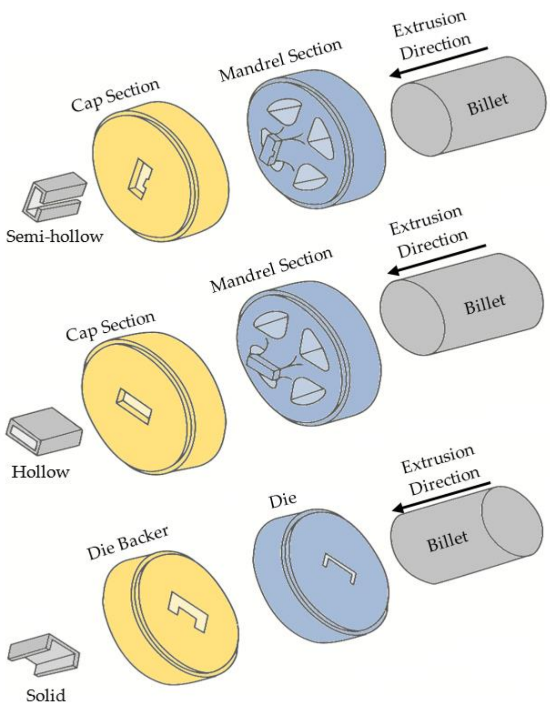

Figure 3. Schematic illustration of the extrusion setup for the semi-hollow, hollow, and solid profiles.

There are three major types of die design setups (Figure 4) for the hollow profiles. Port-hole dies are the most commonly used ones. The metal splits through the ports provided on the mandrel section, flows into the welding chamber, and then over the mandrel and into the cap section. Spider dies provide improved stability and lower load requirements for the extrusion of hard alloys. However, they are difficult to handle, especially in the case of multi-cavity dies. Bridge dies have bridges projected on the front side of the mandrel. These bridges require special rings. The bridge dies are generally favored in the case of multi-cavity dies.

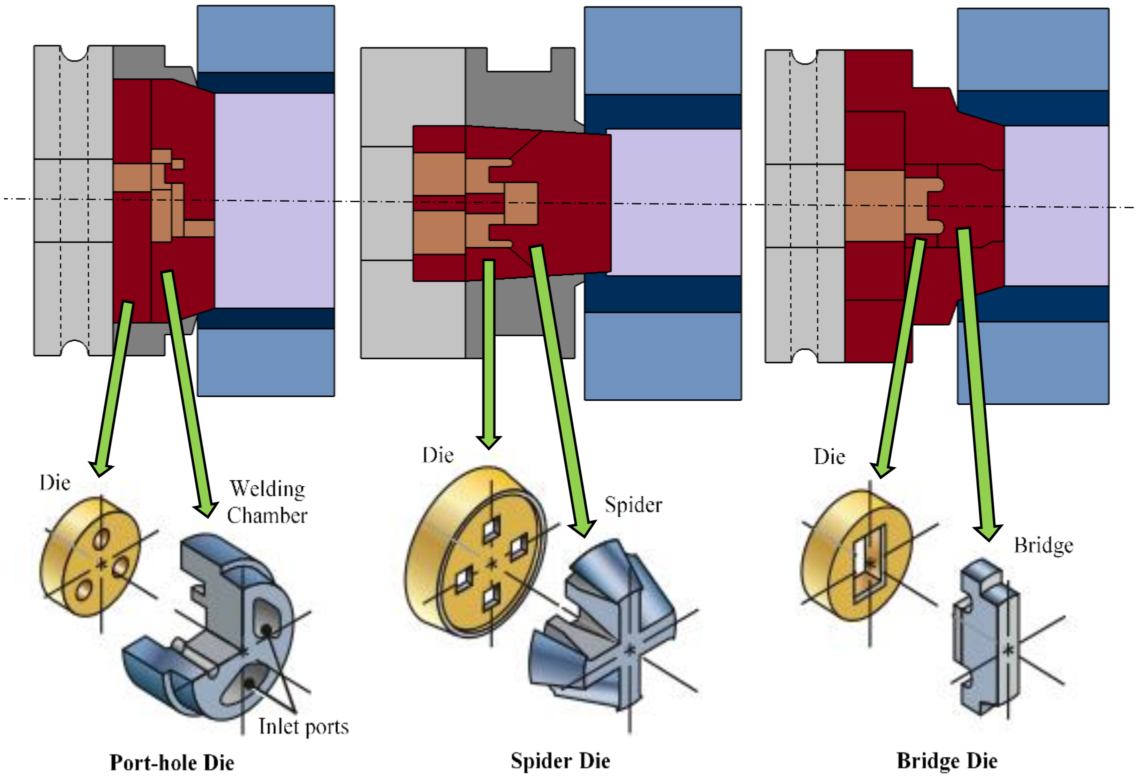

Figure 4. Three major hollow extrusion setups: port-hole die, spider die, and bridge die.

2. Materials and Methods

2.1. Die and Tooling Defects

As mentioned above, most of the die and tooling defects can be removed through operations known as die corrections. Some die defects are so critical in nature that they cannot be repaired and directly lead to die failure. In other cases, further repair is not possible after various die corrections have been done, resulting in the scrapping of the die. Many researchers have attempted to investigate or analyze individual die defects [26,27]. Arif et al. [17] conducted a more comprehensive study on die failure modes and mechanisms and presented a statistical analysis of the main die failure types and their sub-divisions. The focus in the current paper is not die failures but die corrections.

Five major categories of die defects are fracture, wear, deflection (plastic deformation), design/manufacturing, and hardness. The first three (fracture, wear, and deflection) relate to the structural and geometrical condition of the die after being used for some time and can be generally seen distinctly without the aid of a measurement device. The last two (design/manufacturing flaws and hardness problems) usually require an instrument for their detection.

Fracture defects appear as uneven crevices on the die surfaces and are caused by the large thermo-mechanical stresses combined with stress concentration locations in the profile. [15,17,28]. Rib cracks can lead to some minor deflections in the mandrel which are correctable in nature. Initiated cracks may propagate under fatigue loading over multiple extrusion cycles. The crack propagation mostly leads to ultimate brittle failure in the form of fracture of any feature of the die. Fracture is also caused by the grain boundary severity of carbides in the steel die, by reducing the ductility and resistance to temperature variations. Gradually, the inhomogeneity and segregation increase in the die material. It also occurs as a consequence of poor tooling selection, resulting in insufficient support to the die. Cracks are usually seen on bearing, mandrel, and ribs (Figure 5) that take load from the flowing metal. To prevent fracture defects, proper die hardness levels should be maintained by routine nitriding; mandrels should be designed so that they are free from high unbalanced mass variations and sharp edges, and ribs must be designed for minimum temperature increase and smoother flow.

Figure 5. Some fracture and wear defects: bearing crack leading to fracture (**top left**); crack on rib and mandrel leading to deflection (**top right**); rib crack (**bottom left**); severe bearing washout (**bottom right**).

Wear defects refer to the wear and tear of critical surfaces during service (such as the die bearing) and are typically of two types. Erosion is the deterioration or degradation of the surface, whereas washout (Figure 5) appears as craters or linear depressions accumulated in certain regions [8,29]. If the bearing washout is severe, the dimensions of the profile can change and lead the profile to go off geometry and beyond the tolerance limits. The causes of the wear defects include hard inclusions in the billet, improper setup parameters, loss of hardness, and high temperature rise due to friction. To reduce the wear problems, the die surfaces can be coated with a wear-resistant metal. This coating can reduce the uptake of hard inclusions, adhesion, thermal fatigue, and friction. Other benefits of coating include a higher oxidation temperature up to 750 °C and high corrosion resistance. The polishing of dies before each cycle can facilitate the smooth metal flow over the ribs and bearing. Wear can also be minimized by ensuring the hardness levels of critical regions of the die and mandrel.

Deflection defects are caused by the plastic deformation of the die or its features due to thermal or mechanical stresses or a combination of both [30]. Deflection in the mandrel can happen for two reasons. First, a plastic deformation can happen because of thermo-mechanical stresses occurring on the ribs and mandrel [17]. Second, when a crack or fracture occurs on the rib, the mandrel gets bent to an angle from the central axis. This will result in flow-related product defects due to the bend in the cavity. The mandrel deflection can also lead to a dimensional change (angle and wall thickness) of the profile. A feature deflection can alter the dimensions of features in the extruded product, and sometimes this dimensional change (linear or angular) may exceed the designated tolerance limit, and the product will have to be scrapped. To reduce deflection defects, enough support and rigidity should be provided to the mandrel section through a proper selection of tooling. The rib regions should be polished for a smooth metal flow. To prevent feature deflection, additional tooling may be included, such as an insert-bolster attached to an insert-holder to match the aperture of the die backer. Another measure is to use an alternative custom backer, suitable for the die backer aperture.

Some die defects are due to flaws or miscalculations in designing the die geometry, to die material issues, or to manufacturing errors. These problems are therefore categorized as design/manufacturing defects. Sometimes, they cannot be detected until after at least a few trial or actual extrusion runs [31]. Inaccurate angles can result in metal flow variations in different regions of the profile and may result in concave/convex product defects. The ribs control the flow of metal through the cavities of dies. The ribs may have excessive material (distended), and this will cause obstruction to the metal flow in the cavities. Once the flow is obstructed, the pressure will rise and may cause flashing defects (the metal passes over the die) or blocked metal flow. Distended ribs can be easily corrected by machining off the excess material. This will reduce the pressure build-up.

The two types of hardness-related die problems are low-hardness and high-hardness (Figure 6). Low hardness makes the die softer than specified, resulting in dimensional and other errors in the extruded product. High hardness makes the die over-hard and brittle, increasing the chances of chip-off and other types of breakages. Routine grinding and polishing procedures may chip off the die bearing as tiny fragments because of its high brittleness. Once the bearing is chipped, it is usually not correctable. Common causes of these defects are either over-usage or improper re-hardening operations during die corrections [32–34]. In such cases, a recalculation of the time required for periodic nitriding of the dies may be needed. The orientation of the dies while they are placed in the carbonitriding chamber must be checked for a uniform heat distribution. The preheating time of the dies should not be too long.

Figure 6. Peeling caused by hardness defect (**left**); correction error of excess chiseling (**right**).

Defects that cannot be categorized into any of the above types are named other defects. These could be a combination of the major defects or defects due to setup errors or inefficient correction operations during die maintenance (Figure 6). If the die is not corrected properly, this can cause various flow-related problems, a temperature rise, and pressure build-ups at the die–billet interface. Correction beyond the tolerance limits can result in scrapping the die. The supervision of correction works by a co-worker or supervisor is usually practiced. Training workshops can be held from time to time to instruct the workers and improve their die correction knowledge and practical experience. The die inspection tools (discussed later) must be checked periodically for errors and recalibration requirements. One of the most common setup errors is the malfunctioning of the die preheating oven (also called die furnace). Usually, the dies are preheated at 450–500 °C for a time period of two hours. If any of these parameters are not maintained satisfactorily, thermo-mechanical stress variations may occur. Billet preheating is another factor which is done at 420–450 °C. The die furnace and billet furnace should be monitored and controlled appropriately. Another setup error is related to the choice of the right type of bolster, feeder plate, and die backer, which are essential for ensuring the rigidity of the die during extrusion and avoid cracks or fracture defects. A proper and rigid setting of the tool-stack should be ensured in the die slide. The performance of selected die sets and tool-stacks should be monitored from time to time, evaluating the appearance of crack defects on the die. A classification of the defects into common sub-categories is given in Table 1.

Table 1. Major types of die defects and their common sub-categories.

Die/Tooling Defects	Sub-Categories
Fracture	Bearing crack; Mandrel crack; Rib crack; Fracture/breakage
Wear	Erosion; Bearing washout
Deflection	Feature deflection; Mandrel/cavity deflection
Design/manufacturing	Improper choke/relief; Distended rib; Improper clearance/undercut
Hardness	Soft die bearing; Peeling; Chipping
Other	Correction defects; Mixed mode; Setup damages

There are three ways by which a need for die corrections is identified. First, the new dies go through trial runs before being used for the actual production. If there are problems during these trial runs or if the extruded product from these trial runs is defective, die corrections may be needed. Second, the dies are inspected after every production run. Routine correction operations, such as die cleaning etc., are always required. Some other die corrections are done periodically, such as die re-hardening. Third, a poor product quality during actual production runs may suggest certain die corrections.

2.2. Die Corrections

As mentioned earlier, a proper condition of dies and tooling is crucial for good product quality and plant productivity. Die failures leading to rejection result in production interruptions (down-time and up-time), and the replacement of the scrapped dies further adds to the cost and time. Hence, die corrections play a crucial role in maintaining productivity and profitability by making defective dies re-usable and avoiding (or delaying) a final rejection.

A die shop is the station where the dies are routinely inspected and repaired. Broadly speaking, die corrections are of two types: pre-service corrections and post-service corrections [35]. Pre-service corrections are the ones carried out on new dies after the initial trial runs, before putting them in regular service. These corrections are mainly focused on adjusting the geometry or feed design, in case minor adjustments are needed. In some extrusion plants, it is customary to nitride (surface hardening) all the new dies before regular use. Post-service corrections are done every time the die is dismounted after being used for extrusion. They are mainly focused on correcting the flow, damage and wear, fractures, deflections, and loss of hardness. From another perspective, die correction operations can also be categorized into common corrections and task-specific corrections, described in detail below.

2.3. Die Corrector Skills

The die-shop technicians who perform die correction operations are called die correctors. They manage the die resources and are usually responsible for preparing the die assembly, performing trial runs, repairing, and maintaining the dies and related tooling [36]. These workers must possess a high level of technical skills and knowledge. One die defect may be corrected in more than one way. Some corrections can be costly and time-consuming, while improperly selected corrections can reduce the die life [37]. Another issue is that several die corrections may be required to rectify a single problem. Thus, a proper selection and execution of optimum corrective operations are very important. Some of the more critical skills that die correctors (die-shop workers) must have are listed in Table 2.

Table 2. Some of the important skills and knowledge required for a die corrector.

Skill Areas	Description/Details
Die technology	Types of dies; supporting components; die material behavior; die manufacturing and nitriding processes; die geometry parameters and their effect; die defects; extrusion process parameters
Die support technology	Compatibility of bolsters and backers; typical faults due to poor compatibility; softening of components; tolerance matching between feeder plates and die bearing
Common faults and their causes	Variations in run-out lengths; misalignment of die slides; flow speed difference; container geometry; bearing performance; surface defects; nitrided layer flaking off; blockages; breakdowns
Analysis	Die performance monitoring; recording and comparing performance and correction data; balancing speed, tonnage, and recovery rates against die corrections; identifying the need for a new die or major repairs by the manufacturer; detecting and suggesting alterations in design; documentation of changes in drawings

2.4. Principles of Die Correction

Some major principles should be generally followed in carrying out any die correction operation. Corrections should be usually carried out at the back end of the die. Working at the front end can reduce the die life. A particular die should be corrected by one specific corrector, as he/she is familiar with the die and leaves a kind of mark or handwriting. All corrections must leave sufficient room for corrections in the future. Most of the corrections are done by removing some die material, so the selection and the extent of the operation should be determined appropriately to avoid a permanent damage of the die. Even though corrections are done, it should be kept in mind that problems can recur later. All correction details and design changes must be properly documented.

2.5. Die Inspection Tools

A die correction operation or procedure is decided only after the die is inspected in detail, using the appropriate tools. Dies are continuously inspected, after being in-service and after each correction, for deviations from specified geometric and other parameters. These tolerances are generally of three types: geometric tolerances for the dimensions of all critical features (such as die bearing, ribs, ports, cavities, etc.), surface finish tolerances for the cap and mandrel areas, and die hardness requirements. The correction procedures are selected so as to attain the required specifications within the tolerance limits. The new dies are usually manufactured at bottom tolerances to ensure maximum output and to allow the correctors more space to work with. Some inspection tools (Figure 7) commonly used in the die shop are described below.

Some tools are used to check the perpendicularity of certain features. They can also act as a reference support tool while performing chiseling or choking operations. Three typical instruments are the die maker's square, try-square set, and right-angle gauge. Protractors and bevel protractors are used to measure the angles of certain features and regions. The straight edge is used for checking the straightness of the edges, bearing land, clearances, etc. The measurement of linear dimensions includes measurements of the length, width, or thickness of the die features. Typical instruments are Vernier calipers and micrometers for the measurement of both external and internal dimensions. For some specific inner dimensions, for which the above instruments cannot be used, special sets of gauges are more appropriate. Some typical gauges are the feeler gauge, go–no/go gauge, diameter gauge, pin gauge, and height gauge. A portable hardness tester is generally used, as it can measure the hardness of all accessible regions of the die [23].

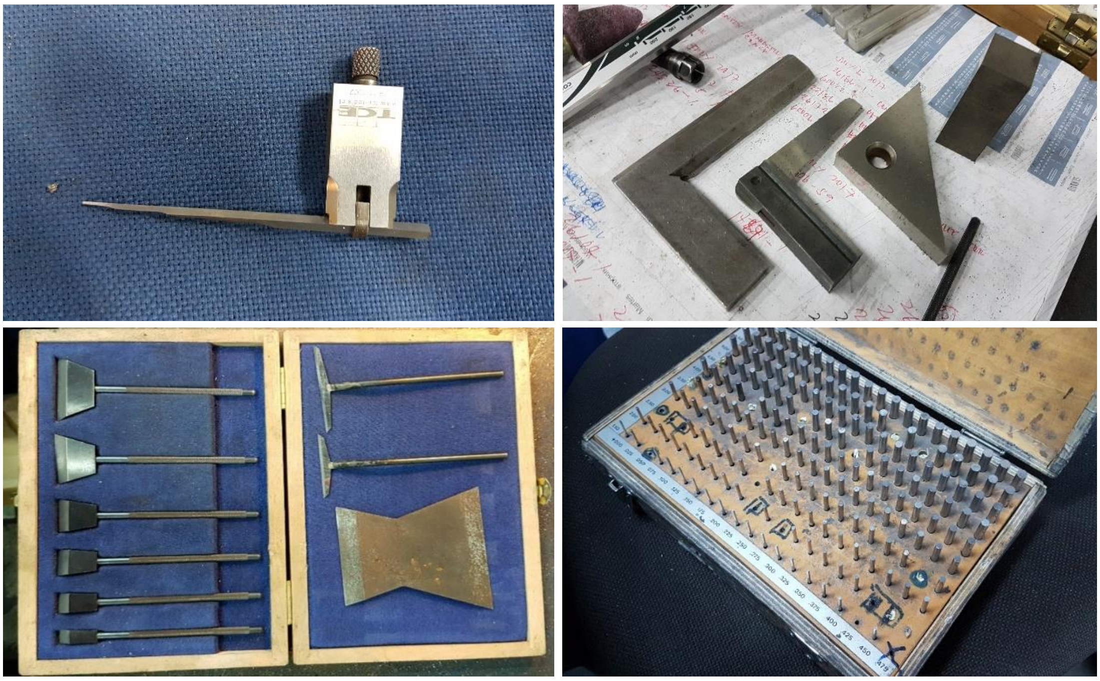

Figure 7. Common inspection tools: right-angle gauge (**top left**); try-square set (**top right**); various types of straight edges (**bottom left**); pin gauge set (**bottom right**).

2.6. Common Die Correction Operations

As the name suggests, common die corrections are the operations done on all dies on a routine basis. The first in this category is cleaning and polishing of the dies. For instance, dies in aluminum extrusion are prone to aluminum oxide build-ups on the undercuts or clearances near the bearing. Sometimes, these oxides can be found sticking inside the welding chambers and ports, or even on the die face. These build-ups are blockages that can also cause product defects like die lines and pickups, so they should be eliminated after every production run. After being used, the dies are cooled sufficiently and then immersed in a tank of caustic soda solution at 60–80 °C for about eight hours. Without proper cooling, the hot dies might crack when put in the caustic tank. Caustic soda reacts with the oxide build-ups on the die and dissolves them. These dissolved residues are then removed by thorough washing. Care must be taken to ensure the complete removal of the residues, as they can cause product defects [33,34].

After washing, a gel is applied on the die and it is polished with an emery cloth of 600–320 grade. While polishing, the emery cloth and file are aligned perfectly square with the bearing surface. If this is not done carefully, rolling or tipping may occur, and the bearing edges may get rounded off, resulting in an undesired choke or relief.

Another routine die correction is nitriding or carbo-nitriding, a type of surface-hardening or case-hardening operation [38]. This is required for new dies if they are not fully hardened by the manufacturers. The dies are also carbo-nitrided after cleaning and polishing. This hardening is also performed after a pre-specified amount of extrusion through the die, to ensure proper hardness levels. Once the dies are cleaned, polished, and nitrided, the bearing surfaces and other critical portions are protected before storing the die, using lubricating compounds such as spray paint, medium-weight oil, graphite spray, etc.

2.7. Specific Die Correction Operations

These die corrections need to be carried out for specific problems observed by the quality control or die-shop personnel. Problems in the extruded product could be due to die-related issues, wear and tear etc. of the die and tooling itself. Described below are all the major die correction operations generally carried out. Table 3 lists the die defects and product defects for which each corrective operation is carried out [1,2,35,39,40]. Later, a brief frequency-based statistical analysis of die defects is also presented, based on three-year defect data from an actual medium-to-large size commercial extrusion plant. It should be pointed out here that die corrections can be performed only a finite number of times. After repeated die corrections of the same type, the die has to be scrapped because of issues regarding its strength, dimensions, etc.

Table 3. Major die correction operations and related die and product defects.

Die Correction Operations	Related Die/Tooling and Product Defects
Shortening of bearings; Choking	**Die defects**—design/manufacturing defects, correction defects **Product defects**—concavity/convexity, twists, off angle, speed difference, ripping
Heating and realigning	**Die defects**—fracture defects, deflection defects **Product defects**—off dimension, twists and bends
Chiseling	**Die defects**—erosion, rib design defects, correction defects **Product defects**—die lines, rough surface, flashing, weld defects
Peening	**Die defects**—deflection defects, fracture defects, wear defects **Product defects**—die lines, off angle, off dimensions
Undercutting; Increasing depth; Increasing clearance	**Die defects**—design/manufacturing defects, correction defects **Product defects**—weld defects, concavity/convexity, cracks, speed difference, flashing, ripping
Welding	**Die defects**—erosion/damage, fracture defects, chipping, feature deflections **Product defects**—pick-up defect, die lines, roughness, streaks, surface cracks, etc.
Grinding; Machining and skimming	**Die defects**—wear defects, fracture defects, design and correction defects **Product defects**—die lines, streaks, pick-up defect, rough surface
Cleaning and polishing; Nitriding; Carbo-nitriding	**Die defects**—wear defects, hardness defects **Product defects**—pick-up defect, die lines, streaks, blisters/blowholes

The bearings of dies and mandrels need to be shortened when there is a requirement to increase the flow at certain regions of the profile. This "shortening of the bearings" is done by milling and grinding for corrections and hand/machine polishing for small corrections, resulting in a decrease of the frictional area of the bearing land. Product defects such as speed difference, concavity/convexity, angle-out, etc. can be rectified using this operation. An increased metal flow can also require a further fine tuning by filing the choke or relief [41].

The operation of "choking" is performed when there is a requirement to reduce the metal flow at certain portions and is mostly done on hollow dies. It is the process of giving an angle to the bearing or increasing the angle of the bearing on the inner web, to decrease the metal flow. Angle openings are very minute, and so this operation is usually done by hand-filing and not by grinding. Once the cap-bearing is choked, the same choke angle should be given to the mandrel bearing. Since it is meticulous, this operation is avoided whenever possible and is performed only by highly skilled workers when necessary. However, it is the most appropriate measure to take when mismatch occurs after shortening. Hence, choking is usually employed when there is incorrect shortening, or shortening can no longer be done.

The ridges in hollow dies may become blunt because of die wash, mostly resulting from over-usage or out-of-limit service. These ridges can be sharpened by "chiseling" the edges. This is a temporary method of fixing and cannot be generally repeated. Also, once it is done, the corrected feature will not be maintained for a long time. Die problems such as erosion, rib design defects, and correction defects can be rectified with this operation.

"Undercutting" is mostly employed for the correction of mandrels in hollow dies. Apart from blockages etc. due to usage, there may not be sufficient metal flow because of a design or manufacturing error. The flow speed and volume will increase when blockages are relieved and chambers are widened, as shown in Figure 8. Undercutting can help prevent the product defects known as ripping and flashing, in addition to speed difference and other flow-related problems. Shallow grooves are sometimes created on the die face by grinding to further control the metal flow.

Figure 8. Some die correction operations: undercutting (**top left**); milling (**top right**); welding (**bottom left**); grinding (**bottom right**).

Pockets in the die can be carved out to increase the metal flow. This "increasing of the clearance" will be done after each carving, allowing more metal to flow. This is usually done when the undercut is not sufficient.

The depth of the chamber near the bridge can be increased by milling or other machining techniques, as and where required to regulate the flow. This "increasing of depth" is usually done on the mandrels of dies for hollow profiles.

"Machining/skimming" is mostly employed on the bearings, port-holes, and ribs, for all kinds of wear and washouts and dimensional inaccuracies. Sometimes, this is done intentionally to adjust the metal flow in porthole dies, to improve the product quality (Figure 8). Because of the high hardness of H13 or similar steels, diamond tip tools are mostly used. The die corrector's skills are critical in doing a good machining. After this operation, the die will have a unique design, slightly different from the manufactured one.

The ribs and mandrels are always prone to plastic deformations after excessive use or large stresses, especially at high temperatures. These deflections are usually not correctable but can be repaired through "heating and realigning" in some cases. These corrections do not guarantee perfection and efficient functioning but make the die usable to some extent. Feature deflections related to profiles such as projections and cavities are also corrected (realigned) using this operation.

Also known as punching, "peening" involves the use of a punch and a hammer or peen. It is usually employed in the case of minor wear or deflection at the bearing edges of hollow dies, mandrels, and die surfaces. These edges and corners are peened with a hammer and a punch to impart slight adjustments. The dies can be heated (250–300 °C) and peened to prevent minute cracks, possible in cold working. However, this is generally avoided, as wrong punching pressures may destroy the design.

The die surface or edges may gradually develop cracks or tiny fissures during service. These defective regions or spots can be repaired by "welding" and machining (Figure 8). Gas tungsten arc welding (GTAW) is the method commonly used. Welding should preferably be done after annealing the die (550–650 °C) to minimize cracks from thermal stresses. Another application is to weld a feature (such as tongue) back on the die when the feature is broken off or deflected. The new feature is made of the same material as the die and machined as per the drawings. Then, it is grafted on the die by welding.

Surface "grinding" can be used to rectify wear and geometrical deflections of the cavities (Figure 8). It can also be used to modify undercuts and clearances, etc. It can also be a secondary correction operation after other procedures (such as welding).

Routine "nitriding" (or carbo-nitriding) has been described above. Here, it is discussed as a task-specific corrective operation. As a consequence of certain working conditions or after repeated usage, some damage or degrading of the top nitrided layer may occur. Low hardness (softening) may also be reported resulting from the thermo-mechanical conditions, especially in the bearing region. Such dies are re-nitrided to ensure sufficient hardness at critical regions. The Rockwell hardness of H13 steel dies after carbo-nitriding should be around 63–64 HRC. In addition to resolving low hardness problems, this process can protect and strengthen the newly welded portions after correcting deflection and fracture defects.

3. Results and Discussion

Die and product defects and related die corrections have been explained in the previous section. To achieve higher productivity and reduced rework and rejection, it is important to identify more frequent die-related problems and reduce and eliminate their occurrence. This section presents a brief frequency-based statistical analysis of actual correctable die defects. The data were collected from a regional aluminum extrusion facility, representing a typical medium-to-large size plant. This information is based on the number of dies sent for correction over a period of three years. All dies were made from H13 tool steel, and the aluminum alloy billets used were either Al-6061 or Al-6063. Major correctable die defects and die correction operations needed to rectify them are given in Table 4.

Table 4. Major correctable die defects and related correction operations.

Die Defects	Related Correction Operations	
Fracture defects	• Heating and realigning • Peening • Welding • Grinding	• Machining/skimming • Cleaning/polishing • Nitriding
Wear defects	• Chiseling • Welding • Grinding	• Machining/skimming • Cleaning/polishing • Nitriding
Deflection defects	• Heating and realigning • Peening	
Design/Manufacturing defects	• Shortening of bearings • Choking • Chiseling • Undercutting	• Increasing depth • Increasing clearance • Grinding • Machining/skimming
Hardness defects	• Welding • Nitriding	
Correction defects	• Shortening of bearings • Choking • Increasing depth	• Increasing clearance • Grinding • Machining/skimming

3.1. Overall Analysis

It should be restressed here that this data regard die corrections and not die failures. This analysis was conducted for the full three-year period, on an annual basis. The major die defect classification is the same as described above: fracture (Fr), wear (Wr), deflection (Def), design/manufacturing (D/M), hardness (Hd), and other (Oth). Figure 9 presents the data in the form of a pie chart. For the combined three-year dataset, the majority of the die corrections (around 80%) were due to the defect types of fracture, wear, and other. The most frequent single category (32%) was other defects (defects happening during correction operations, mixed-mode defects, and setup damages), followed by wear (28%), fracture (19%), problems related to design or manufacturing (14%), and hardness and deflection (7%). The annual trend of die defects was almost the same as that for the three-year period, with minor differences.

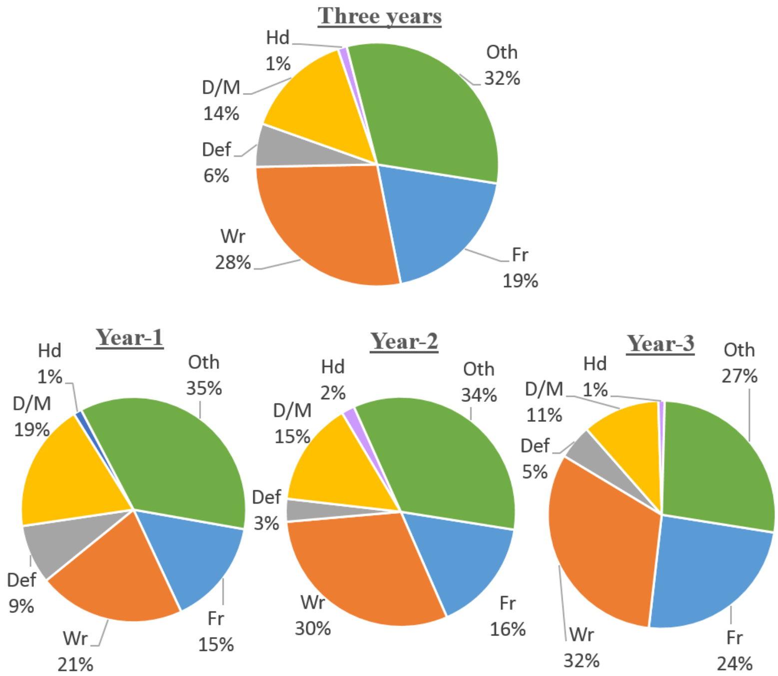

Figure 9. Overall breakdown of correctable die defects during three years (total and annual).

In the case of failed dies, the most frequent defect categories were fracture, wear, and plastic deformation (deflection). However, as observed above, the most common correctable die defects were other, wear, and fracture. The dies were brought to the die repair shop after every set of extrusion cycles, either for routine or specific repair. Small mistakes or inaccuracies in these correction operations led to further repair requirements, making "other repairs" the most common category. Fractures were not always repairable and led to complete die failure in many cases, so their frequency was less than that of wear corrections. Loss of hardness, leading to plastic deformation (deflection), was usually very difficult to correct, constituting only 7% of the correctable defects. The dies with significant deflection defects were usually scrapped (rather than repaired), as correction attempts using heating and realigning techniques mostly do not work.

3.2. Category-Wise Breakdown

The above analysis indicates that the major defect categories were other, wear, fracture, and design/manufacturing. A further break-down of each of these defects into their component categories is presented in Figure 10 for a three-year period. For other defects (Figure 10a), the major contributor was errors during die correction operations (CD-65%), followed by setup damages

(SD-20%), and combination of multiple defects (MM-15%). Correctable wear defects (Figure 10b) were due to two problems: bearing washout (BW-87%) and erosion (E-13%). In the fracture category (Figure 10c), 75% of the defects were bearing cracks (BC), 23% rib cracks (RC), and 2% mandrel cracks (MC). Design/manufacturing errors (Figure 10d) were mostly (>40%) caused by insufficient or excessive choke/relief (IC/R), improper clearance/undercut (IC/U-35%), and distended ribs (DR-24%). The distribution of these die defects and corrections on an annual basis was almost the same as that for the three-year period.

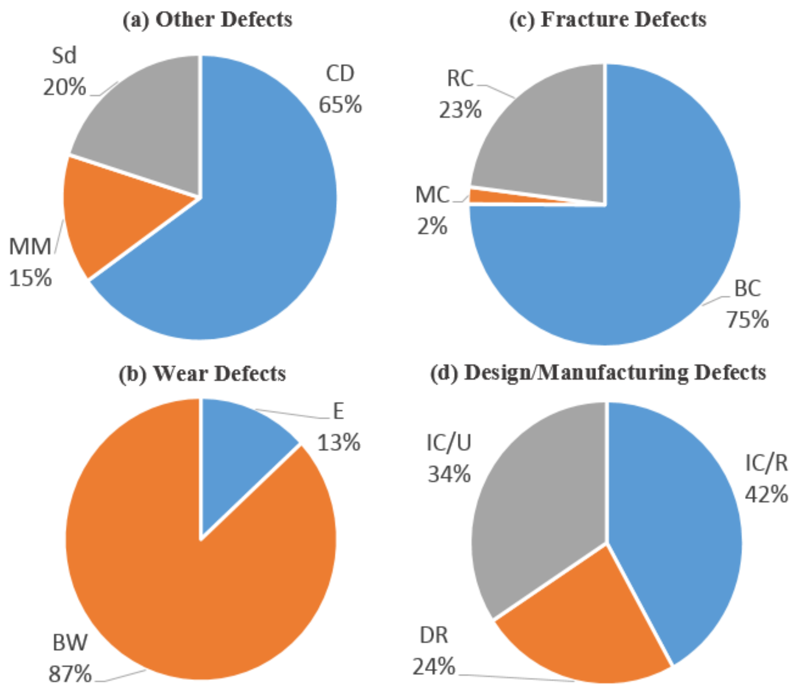

Figure 10. Breakdown of the most frequent defects in three years.

As explained in the previous section, errors during die repair are the most common cause of correctable die defects. The die bearing surface is obviously less strong than the ribs or ports. Severe wear on the bearing (washout) is therefore a bigger source of die defects than the wear of the ribs, ports, and other surfaces (erosion). The most common fracture category is "bearing cracks", because of the lower strength of the bearing compared to other die features. Most of the thermal and mechanical fatigue occurs in the bearing and rib regions. As for the design/manufacturing defects, features such as choke, relief, clearance, and undercuts are important in maintaining proper metal flow through the die cavities and in generating the correct shape and dimensions of the extruded product. Distended ribs are very critical to prevent blockages and flashing defects in extrusion.

Looking at both the annual and the three-year defects distribution, it can be clearly seen that correction defects, bearing washouts, and bearing cracks were the most prevalent three die defects. If quality control, operations, and die-shop engineers and operators in commercial extrusion plants focus on eliminating or reducing the causes of these three defects, then a large portion of repair or rejection of dies and tools can be avoided.

A notable, and perhaps surprising, finding is that the highest number of die-related problems is caused by errors in the die shop during correction operations. This finding needs to be corroborated with repair data from other medium-to-large size extrusion facilities. The regional extrusion plant from where this data were collected should exercise more care in hiring die-shop technicians and must initiate periodic re-training programs to increase the technical know-how and skills of the hired personnel. More attention should also be paid during routine inspection and repair of tools and equipment used in the die shop.

4. Conclusions

A large number of products are manufactured through the bulk deformation process of extrusion. Detection and mitigation of product defects re very important in maintaining the productivity and profitability of an extrusion plant. Die and tooling defects are one of the major sources of product defects. Corrective maintenance operations of extrusion dies are carried out on a regular basis, due to the occurrence of repairable defects. No published work presents a detailed discussion of correctable die defects and related die correction operations. The current work defines all major die defects that are correctable and discusses their causes, preventive measures (wherever possible), and required die correction operations. Also, described are inspection and correction tools, correction skills, and details of each individual correction operation. A frequency-based statistical study of correctable die defects is also presented, with the idea of identifying the most frequent problems. This work can serve as a detailed single-source reference for repairable die defects and associated corrective operations. It is useful for plant engineers and operators, students, researchers, and academics in the field of metal extrusion.

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References

1. Arif, A.F.M.; Sheikh, A.K.; Qamar, S.Z.; Raza, M.K.; Al-Fuhaid, K.M. Product Defects in Aluminum Extrusion and Their Impact on Operational Cost. In Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia, 14–17 December 2002.
2. Qamar, S.Z.; Arif, A.F.M.; Sheikh, A.K. Analysis of product defects in a typical aluminum extrusion facility. *Mater. Manuf. Process.* **2004**, *19*, 391–405. [CrossRef]
3. Nieto, J.T. Feature Based Costing of Extruded Parts. Ph.D. Thesis, University of Illinois, Champaign, IL, USA, 22 June 2010.
4. Qamar, S.Z. Introduction to extrusion: From gear manufacturing to production of cereals. In *Extrusion of Metals, Polymers, and Food Products*; Qamar, S.Z., Ed.; INTECH Open Science: Pleasanton, CA, USA, 2018; ISBN 978-953-51-3838-9.
5. Akhtar, S.; Arif, A.F.M. Fatigue failure of extrusion dies: Effect of process parameters and design features on die life. *J. Fail. Anal. Prev.* **2010**, *10*, 38–49. [CrossRef]
6. Arif, A.F.M.; Sheikh, A.K.; Qamar, S.Z.; Al-Fuhaid, K.M. Modes of Die Failure and Tool Complexity in Hot Extrusion of Al-6063. In Proceedings of the 16th International Conference on Production Research (ICPR-16), Prague, Czech Republic, 29 July–3 August 2001.
7. Arif, A.F.M.; Sheikh, A.K.; Qamar, S.Z.; Al-Fuhaid, K.M. Variation of pressure with ram speed and die profile in hot extrusion of aluminum-6063. *Mater. Manuf. Process.* **2001**, *16*, 701–716. [CrossRef]
8. Li, T.; Zhao, C.; Guan, Y.; Sun, X.; Li, H. Effect of process parameters on die wear behavior of aluminum alloy rod extrusion. *Mater. Manuf. Process.* **2013**, *28*, 312–318. [CrossRef]
9. Aue-u-lan, Y.; Khansai, K.; Sinpayakun, P.; Tragangoon, C. Investigation of the parameters affecting the die failure in high extrusion ratio of aluminum square hollow profile by using viscoplastic finite element modelling. *Int. J. Appl. Sci. Technol.* **2013**, *6*, 27–33.
10. Qamar, S.Z. Modeling and Analysis of Extrusion Pressure and Die Life for Complex Aluminum Profiles. Ph.D. Thesis, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, June 2004.
11. Yilbas, B.; Arif, A.F.M.; Akhtar, S. Finite element simulation of the effect of Al-6063 billet quality on the extrusion die performance. *Ind. Lubr. Tribol.* **2013**, *65*, 78–90. [CrossRef]

12. Qamar, S.Z.; Sheikh, A.K.; Arif, A.F.M. *Modeling and Analysis of Aluminum Extrusion: Process, Tooling, and Defects*; LAP Lambert Academic Publishing: Saarbrücken, Germany, 2011; ISBN 9783844331585.
13. Lepadatu, D.; Hambli, R.; Kobi, A.; Barreau, A. Statistical investigation of die wear in metal extrusion processes. *Int. J. Adv. Manuf. Technol.* **2006**, *28*, 272–278. [CrossRef]
14. Kazanowski, P. *Die Performance Optimization through Understanding of the Surface Features of Fatigue Fractures*; Hydro Aluminum Cedar Tools: Cedar Springs, MI, USA, 2008.
15. Qamar, S.Z. Fracture life prediction and sensitivity analysis for hollow extrusion dies. *Fatigue Fract. Eng. Mater. Struct.* **2015**, *38*, 434–444. [CrossRef]
16. Zhang, C.; Zhao, G.; Li, T.; Guan, Y.; Chen, H.; Li, P. An investigation of die wear behavior during aluminum alloy 7075 tube extrusion. *J. Tribol.* **2013**, *135*. [CrossRef]
17. Arif, A.F.M.; Sheikh, A.K.; Qamar, S.Z. A study of die failure mechanisms in aluminum extrusion. *J. Mater. Process. Technol.* **2003**, *134*, 318–328. [CrossRef]
18. Sheppard, T. *Extrusion of Aluminum Alloys*; Kluwer Academic: Dordrecht, Germany, 2013.
19. Laue, K.; Stenger, H. *Extrusion: Processes, Machinery, Tooling*; American Society for Metals: Metals Park, OH, USA, 1981.
20. Qamar, S.Z.; Arif, A.F.M.; Sheikh, A.K.; Pervez, T. Effect of process parameters on metal flow and dead metal zone in extrusion. *Arch. Mater. Sci.* **2008**, *28*, 118–123.
21. Bauser, M.; Siegert, K. *Strangpressen*, 2nd ed.; Aluminium Verlag: Munich, Germany, 2001.
22. Mielnik, E.M. *Metalworking Science and Engineering*; McGraw-Hill: New York, NY, USA, 1991.
23. Lange, K. *Handbook of Metal Forming*; McGraw-Hill: New York, NY, USA, 1985.
24. Saha, P.K. *Aluminum Extrusion Technology*; ASM International: Materials Park, OH, USA, 2000; ISBN 9781615032457.
25. Qamar, S.Z.; Sheikh, A.K.; Arif, A.F.M.; Pervez, T. Defining shape complexity of extrusion dies—A reliabilistic view. *Mater. Manuf. Process.* **2007**, *22*, 804–810. [CrossRef]
26. Chang, K.H.; Shih, C.W.; Tzou, G.Y. Defect improvement of extrusion dies using combination of fem stress analysis with the taguchi method. *Trans. Can. Soc. Mech. Eng.* **2015**, *39*, 729–738. [CrossRef]
27. Zhang, C.; Zhao, G.; Guan, Y.; Gao, A.; Wang, L.; Li, P. Virtual tryout and optimization of the extrusion die for an aluminum profile with complex cross-sections. *Int. J. Adv. Manuf. Technol.* **2015**, *78*, 927–937. [CrossRef]
28. Qamar, S.Z.; Pervez, T.; Al-Moharbi, A.D. Fracture Prediction of Extrusion Die Modeled as Pressurized Cylinder with Internal Crack. In Proceedings of the 15th International Research/Expert Conference on Trends in the Development of Machinery and Associated Technology (TMT 2011), Prague, Czech Republic, 12–18 September 2011.
29. Qamar, S.Z.; Arif, A.F.M.; Sheikh, A.K.; Younas, M.; Pervez, T.; Siddiqui, R.A. Simulation of Fatigue and Wear Life of Extrusion Dies. In Proceedings of the 10th International Research/Expert Conference on Trends in the Development of Machinery and Associated Technology (TMT 2006), Barcelona, Lloret de Mar, Spain, 11–15 September 2006.
30. Qamar, S.Z.; Arif, A.F.M.; Sheikh, A.K.; Al Fuhaid, K.M. Some Observations on Pressure Distribution and Die Failure Modes in Hot Extrusion. In Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia, 14–17 December 2002.
31. Qamar, S.Z.; Siddiqui, R.A.; Pervez, T.; Sheikh, A.K.; Arif, A.F.M. Improvement of Die Design and Prevention of Die Failure in Metal Extrusion. In Proceedings of the 12th International Research/Expert Conference on Trends in the Development of Machinery and Associated Technology, Istanbul, Turkey, 26–30 August 2008; pp. 869–872.
32. Schey, J.A. *Introduction to Manufacturing Processes*, 3rd ed.; McGraw-Hill: New York, NY, USA, 2000; ISBN 978-0070311367.
33. Kalpakjian, S. *Manufacturing Processes for Engineering Materials*, 6th ed.; Addison-Wesley: Menlo Park, CA, USA, 2017.
34. Groover, M.P. *Fundamentals of Modern Manufacturing: Materials, Processes and Systems*, 5th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2012.
35. Qamar, S.Z.; Pervez, T.; Chekotu, J.C. Correctable Die Defects in Aluminum Extrusion. In Proceedings of the World Congress on Mechanical and Mechatronics Engineering, Dubai, UAE, 16–17 April 2018.
36. Fielding, R.A.P.; Johannes, V.I. The evolution and changing role of die correction in the production of extrusions. *Light Met. Age* **2005**, *63*, 6–21.

37. Qamar, S.Z.; Sheikh, A.K.; Arif, A.F.M.; Younas, M.; Pervez, T. Monte carlo simulation of extrusion die life. *J. Mater. Process. Technol.* **2008**, *202*, 96–106. [CrossRef]
38. Qamar, S.Z. Optimum heat treatment of extrusion die steel. *Adv. Mater. Res.* **2014**, *911*, 215–219. [CrossRef]
39. Qamar, S.Z. Product Defects in Commercial Aluminum Extrusion: Review and Analysis. In Proceedings of the International Conference on Advances in Materials and Processing Technologies (AMPT 2016), Kuala Lumpur, Malaysia, 8–11 November 2016.
40. Qamar, S.Z.; Chekotu, J.C.; Pervez, T. Mitigation of Major Product Defects in Aluminum Extrusion. In Proceedings of the 14th International Conference and Exhibition on Materials Science and Engineering, Las Vegas, NV, USA, 13–15 November 2017.
41. Qamar, S.Z. Shape complexity, metal flow, and dead metal zone in cold extrusion. *Mater. Manuf. Process.* **2010**, *25*, 1454–1461. [CrossRef]