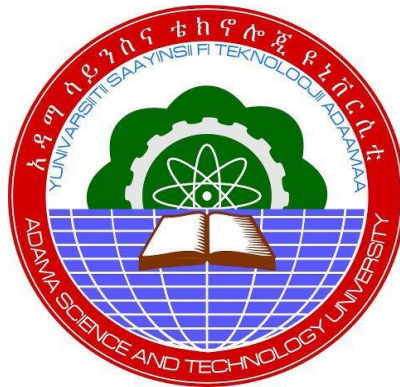


**ENHANCEMENT OF PROCESS CAPABILITY ON AA6063
ALUMINIUM ALLOY THROUGH MULTI-HOLE EXTRUSION
PROCESS**

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PGR/18210/11

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Department of Mechanical Design and Manufacturing Engineering
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Adama

Jan 2021

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A thesis submitted in partial fulfillment of the requirements for the degree of
MSc in Manufacturing Engineering

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Approval Page

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DECLARATION

I declare that the thesis entitled “**Enhancement of Process Capability on AA6063 Aluminium Alloy Through Multi-Hole Extrusion Process**” submitted in partial fulfillment of the requirements for the award of the degree of Masters of Science in Manufacturing Engineering is an authentic record of my work carried out, under the advisor **P.J. Ramulu (Ph.D.)** and co-advisor **D.K. Sinha (Ph.D.)**, Mechanical Design and Manufacturing Engineering Program, Adama Science and Technology University, Adama, Ethiopia. I have not submitted the matter embodied in this thesis for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

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Abstract

The fabrication of aluminium alloy products through the hot extrusion process has been a forwarding and promising method for most manufacturing industries. In the extrusion process, process enhancement has been taken care of to improve the productivity of the multi-hole extrusion process. Since the improper selection of process parameters leads to poor quality and yield, an attempt was made to simulate hot direct extrusion of AA6063 alloy using DEFORM-3D, the optimal process parameters were selected through Taguchi-based grey relational analysis with a multi-response optimization technique. And the results were analysed using ANOVA to check the significance of process parameters. The experimental works also conducted to investigate the validation of simulation results and extrusion behaviour of AA6063 aluminium alloy rods under heating conditions i.e. 400 to 500°C by using multi-hole extrusion dies. For the experimentation, ram, container and multi-holes dies were designed and fabricated as per the standard specifications. The results showed that the order of significance was the number of holes, extrusion temperature and ram speed, at 4-number of holes, 7mm/s ram speed, and 500°C extrusion temperature the optimum multi-hole extrusion process enhancements have been obtained. The experimental results show that microstructural damage on extrudates and ram force for multi-hole extrusion is improved through the multi-hole extrusion of AA6063 aluminium alloy. Therefore, the manufacturing firms or any industries that intend to work in the extrusion of aluminium material will enhance their productivity and product quality by using a multi-hole extrusion process with the implementation of FEM and DoE methods.

Keywords: GRA; hot extrusion; FEM; DOE; multi-hole extrusion.

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ABBREVIATIONS

FEM	Finite Element Method
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
DoE	Design of Experiment
GRA	Gray Rational Analysis
GRC	Grey Rational Coefficient
GRG	Grey Rational Grade
ANOVA	Analysis of Variance
SEM	Scanning Electron Microscope

NOMENCLATURE

A	Pocket angle
L	Length of the die
M	Friction factor
A_0	Billet area
A	Area of extrudates
$\sigma_{ij,j}$	Stress tensors
$\bar{\sigma}$	Effective stress
$\bar{\epsilon}$	Effective strain
$\dot{\epsilon}$	Strain rate
ϵ	Strain
$\dot{\bar{\epsilon}}$	Effective strain rate

Chapter One

1. Introduction

1.1. Background of the Study

The conversion of raw materials to finished products for a specific application concerns a shape, properties and structures of a product required manufacturing process. This conversion into finished products are accomplished using a variety of manufacturing processes that utilize energy to produce controlled changes in the configuration properties of materials (Mani et al., 2015). Increasing production efficiency while using the maximum effort to utilize energy and improve qualities of products is a difficult task for industries and manufacturing firms Figure 1.1 illustrates the product capability and enhancement limitations during the manufacturing process. Especially if the products are working under pressure, there might be a huge probability for finished products to fail in their applications. Therefore, to study and improve technological processes to advance the product quality, durability, sustainability, energy utilization and equipment productivity; There is a formation of a work team inside the industries.

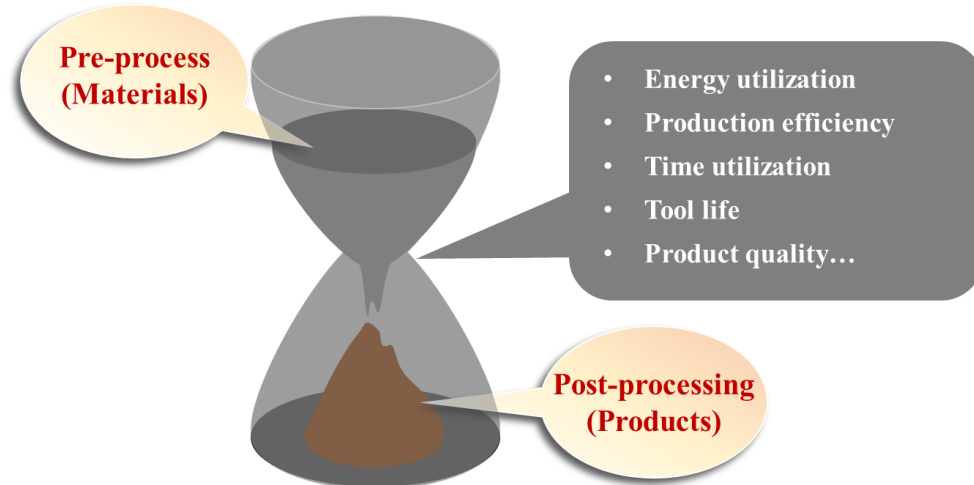


Figure 1.1 Product capability and enhancement limitations.

But with some exceptional cases in developing countries like Ethiopia, such investigative team inside industries are not oftenly seen while participating or working on product quality improvements or process capability enhancements. Among the manufacturing processes extrusion is one of the process which needs process capability enhancement and improvements. Since the industrial development extrusion process has shown its advantage in bulk metal forming process. Product quality enhancement, mechanical property improvements

specifically in strength of extruded products are the benefit of extrusion process. Extrusions are produced by pushing solid material through an opening called a die to form parts with complex cross sections. Due to its good corrosive resistance, structural rigidity, good appearance and ease of post fabrication process the aluminium extruded profiles have a huge interest across architects and the structural engineers. The extrusion process makes aluminum an extremely versatile material for structural design. Rather than being limited to the standard rolled shapes, designers can concoct their own cross sections, putting material where it is needed. Solid and hollow cross sections, even sections with multiple hollows, can be readily extruded.

In metal extrusion, the raw material is forced through a die to produce long, straight, semi-finished metal products such as bars, solid and hollow sections, tubes, wires, and strips (Dixit et al., 2009). Schematic diagram of extrusion process is shown in Figure 1.2.

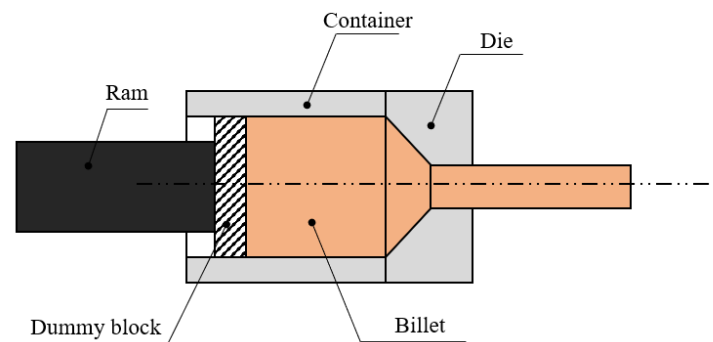


Figure 1.2 Schematic diagram of extrusion process.

The extrusion process consists of four major components, hydraulic press (ram), die, container, and billet casted or rolled. The billet (block of metal) is forced to flow through the die openings to form a final product of extrudates. For direct extrusion process the compressive forces are developed by the reaction of the workpiece (billet) with the container and die, when these forces reach its maximum values; The reaction of the billet (work piece material) 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. 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.

The better mechanical properties and the quality of the extruded products have proved the importance of this process (Kumari et al., 2018). Since a single ram can be used to form many

materials in different size and profiles only by changing the die and other toolings with it, extrusion can be treated as flexible manufacturing process (Chahare & Inamdar, 2016). There are several advantages of the modern process: A variety of shapes are especially with hot extrusion, grain structure and strength properties are enhanced in cold and warm extrusion, fairly close tolerances are possible, especially in cold extrusion and in some extrusion operations, little or no wasted material is created. However, a limitation is that the cross section of the extruded part must be uniform throughout its length (Groover, 2008).

Extrusion can be performed either hot or cold, depending on work metal and amount of strain to which it is subjected during deformation. Metals that are typically extruded hot include aluminum, copper, magnesium, zinc, tin, and their alloys. These same metals are sometimes extruded cold. Steel alloys are usually extruded hot, although the softer more ductile grades are sometimes cold extruded (e.g., low carbon steels and stainless steel). Aluminum is probably the most ideal metal for extrusion (hot and cold), and many commercial aluminum products are made by this process (structural shapes, door and window frames, etc.) (Groover, 2008).

1.1.1. Extrusion of soft and medium grade alloys

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. According to the study of the bulk of structural aluminum profiles used in the construction industry is produced through hot extrusion. 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.

Extrusion of aluminum alloy shapes represents the most advanced technology in terms of alloy making, press design, tooling, and die design. The billet chemistry determines the type of alloy and its applications. The 6000-series alloys are widely used based on their having the best technical and economic characteristics, including ease of extrudability into hollow and complex shapes, simplicity in heat treatment, good electrical conductivity, satisfactory mechanical properties, good surface finish quality, high corrosion resistance, and good weldability for a wide variety of applications.

Several million tons of 6000-series alloy extrusions are produced every year (Saha, 2000). Applications include bars and rods to intricate shapes such as door and window frames,

automobile trim, building structures, electrical bus bars, heat exchangers and so on (Saha, 2000). Because it is easy to work with 6000 series alloys, development of many derivatives of 6000 series alloys continues in order to fulfill the requirements of different customer applications throughout the world. Some 6000 series alloys have a higher level of alloying elements to achieve higher strength for structural and semi structural applications.

1.1.2. Alloys and extrudability

Since extrusion is a compression process in which the work metal is forced to flow through a die opening to produce desired cross sectional shape, extrudability is the basic property in which metal extrusion needed to have.

AA6063 aluminum alloys extruded by conventional hot extrusion are widely used for the fabrication of high strength and lightweight structures (Zhao et al., 2013). AA6063 aluminum alloys of high strength AlMgSi are suitable for different miscellaneous structural applications in building, automotive see Figure 1.3, and aircraft industries. Due to their strong modification of strength induced by precipitation phenomena which is accompanied by a low density, good corrosion properties and good weldability.

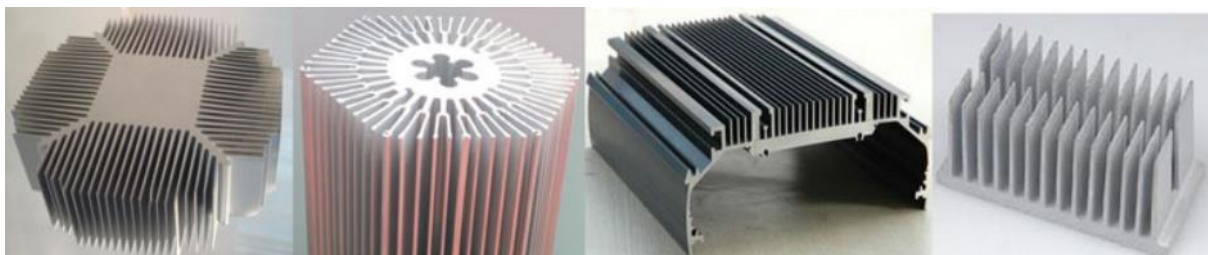


Figure 1.3 Typical aluminium alloy radiators (Cunsheng et al., 2016).

Extrudability, which can be measured by the maximum extrusion speed, is one of the most significant factors influencing cost and efficiency of the extrusion process. Temperature and speed parameters, together with the state of stress in the deformation zone, mainly in the die region, play a significant role in improving extrudability of a given alloy. A simple, practical method of extrudability testing is to vary extrusion ratios while holding other process parameters unchanged, the maximum extrusion speed without cracks being the measure of extrudability. Figure 1.4 shows the simulation and experimental demonstration of extruded radiator regarding to ram speed difference across the radiator profile.

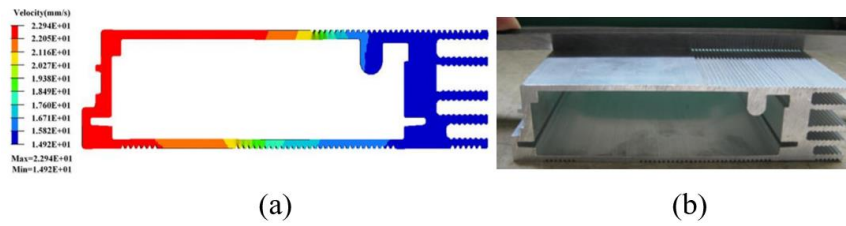


Figure 1.4 (a) Simulation and (b) fabricated demonstration of extruded radiator (Cunsheng et al., 2016)

1.1.3. Multi-hole extrusion

Multi-hole extrusion is the process in which the raw material is pushed through a die having more than one hole. This process is highly productive for producing parts of smaller length and cross-section. For the given billet and final product size, the requirement of the ram force is lesser in the multi-hole extrusion than in the single-hole extrusion. The process has great importance for producing micron size parts (Dixit et al., 2009).

For increase in productivity, multi-hole extrusion process is a better alternative. But different process parameters such as extrusion ratio, hole locations on the die, extrusion speed, lubrication and die land length effect the quality of the extruded products.

1.1.4. Process parameters

Extrusion is an extremely flexible manufacturing process, as a single press can be used to extrude various materials and a large number of profiles by simply changing the die and the associated tooling with it. Extrusion Process is highly influenced by the process parameters required for determining the quality of process and extrude. The following factors influence the productivity and quality of the products in the extrusion process (Tyrer & Waheed, 2006): Initial billet temperature and the radial and axial temperature profiles, time for the transport of the billet from the furnace to the loader, dwell time in the billet loader, mean container temperature and temperature distribution, thermal capacity of the container (mass of the container) compared to the thermal capacity of the billet, number and location of the heating elements in the container, and the ability to switch individual heaters on and off (Tyrer & Waheed, 2006).

The process parameters such as billet pre-heating temperature, container temperature, die temperature, extrusion ratio, ram speed, die pre-heating temperature, number of cavities in the die, etc. control the process, which ultimately affects the productivity and quality of the extrude.

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 (Saha, 2000).

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.

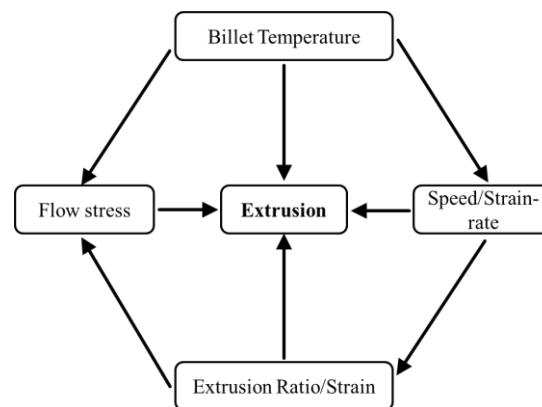


Figure 1.5 Effect of principal variables on extrusion (Saha, 2000).

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.

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 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, σ , is important because in flow curve because it gives the stress required to cause the metal to flow plastically to any given strain (Saha, 2000).

Temperature and strain-rate sensitivity have been incorporated into the flow stress. The thermodynamics model predicts the influence of plastic strain and strain rate on temperature

rise in extrusion. A summary of the effects of different factors on extrusion and their inter-relationship are shown in Figure 1.5 as a closed loop chain.

1.1.5. Numerical analysis and simulation

Numerical and analytical modelling of manufacturing processes together with microstructure investigations have great potential to increase process productivity and product quality. Aluminium hot extrusion is one main metal forming process largely applied in manufacturing bars and products with complex cross section shape. Traditionally, metal forming analysis has been performed by upper-bound, slab, slip-line methods and also, more recently, through computational methods such as the finite element method (FEM). It has been widely accepted FEM is a powerful numerical tool for design and analysis of metal forming processes. Simulations of manufacturing processes reduce the need of costly shop floor trials and redesign of tooling and accessories.

FEM is nowadays very popular and widely employed to metal forming process analysis by commercial codes such as ABAQUS, DEFORM and FORGE.

1.2. Statement of the Problem

Increasing production efficiency while using the maximum effort to utilize energy and quality of products is a complicated task for industries and manufacturing firms. Specially, if the products are working under pressure their failure will be catastrophic. According to most researchers the composition of engineering material will not be the only factor for such dynamic failures, the production method will also employ for their engineering failures.

A material like aluminum which have been a tremendous engineering application, light in weight and flexible for manufacturing processing will engage easily in such catastrophic failures due to its effortlessly deformable characteristics; hence it is expedient to investigate the productivity and mechanical property improvement of this material. AA-6XXX aluminium alloy series are the best suited aluminum materials which are mostly used in production of architectural frames, structural members, screw machine products, nuts, oil line fittings, hinge pins, decorative hardware and appliance fittings, etc. These products are an incredible application in human existence, as a result most manufacturer prefer extrusion process for production of these products. Therefore, this study characterized and analyzed different extrusion process parameters which affect the product capability and property of extruded AA6063 alloy through multi-hole extrusion die.

1.3. Objectives

1.3.1. General Objective

The general objective of this thesis is to enhance the multi-hole extrusion process capability of AA6063 aluminium alloy through different process parameters and optimization.

1.3.2. Specific objectives

The specific objectives of this thesis are to:

- Simulate different extrusion process parameters using multi-hole die.
- Optimize multi-hole extrusion process parameters using DoE techniques and FEM analysis.
- Perform experimental investigations for selected parametric combinations to assess the product capability.
- Test mechanically the properties of extruded products through multi-hole dies and also to characterize them.
- Compare the experimental and numerical investigations of multi-hole extruded products to validate the simulation results.

1.4. Significance of the study

For their massive engineering applications, the structural engineers and architects in Ethiopia preferred imported aluminum profiles rather than locally fabricated ones. Such rebuff of locally fabricated products will impact the national GDP of countries and it will lock the investment opportunity for metal manufacturers; the reason behind such rejection will be insufficient of product supplies and substandard qualities of aluminium extruded profiles. Therefore, this study will enhance the capability of locally fabricated aluminum profile through multi-hole extrusion process.

1.5. Scope and Limitations

This study mainly focuses on numerical and experimental investigation of multi-hole extrusion process. The study establishes the numerical approach and experimental validations. In this investigation testing and characterization of solid circular section extrudates have used to study the microstructural and mechanical properties of the samples. The machine utilized for this study was scanning electron microscope and Vickers hardness testing machines. Die design and analytical approaches are beyond the scope of this study. Due to difficulty of getting

extrusion setups, this study is limited to small number of extrudate sample preparation. The limitations that have been faced during this study is listed below:

- During the COVID-19 pandemic, it was difficult to get materials and workshop accessories easily, as a result, this research couldn't be finished as per the proposed plans.
- Since there weren't small scale extrusion setups it was difficult to use a hydraulic press as an extrusion setup to investigate the experimental work.
- During the COVID-19 pandemic, it was difficult to perform some mechanical tests due to the strain of accessing laboratories.

1.6. Organization of the Thesis

This thesis is composed of 5-chapters. The first chapter introduces the concept of multi-hole die extrusion process and discuss the soft materials which are mostly engaged in making extruded products. Literature survey in chapter two with its summary and gap have been presented. The third chapter presents the material and methodology section of the work. Chapter four presents the major finding and results of numerical and experimental investigations conducted with their implication. The last chapter includes the conclusion of the whole work and recommendation for further study.

Chapter Two

2. Literature reviews

2.1. Introduction

Many researches and developments in extrusion process enhancement have been done in the past years to improve this competitive manufacturing process. There have been several improvements and technical specifications implemented to enhance the process parameters in extrusion processes and still lots of investigators are try to improve the efficiency and optimization of extrusion process. In this section previous works associated with extrusion processes, for both direct and indirect extrusion, extrusion of soft and medium alloys, extrusion process parameters, and experimental and numerical investigations were reviewed. finally, the summary of all the literature and its gap is also included.

2.2. Extrusion

It has been more than two century since the extrusion industries are introduced for this globe (Okokpujie & Akinlabi, 2018; Saha, 2000). But it has been observed that the benefits of extrusion process have increased tremendously in the past 60 years due to advancement in technology gotten from the practical knowledge and various fundamental search into the process of extrusion, tooling, metal forming, and metal flow (Okokpujie & Akinlabi, 2018). Extrusion process is a well established metal forming process used world wide for manufacturing of major metallic and non metallic components. The better mechanical properties and the quality of the extruded products have proved the importance of this process (Kumari et al., 2018). Another advantages of extrusion process over other metalworking processes are that varieties of sections can be achieved through hot extrusion, the grain structure and desired strength are enhanced, and close tolerance can be obtained and there is usually little or no material wastage (Okokpujie & Akinlabi, 2018).

Extrusions are produced by pushing solid metalic material (billet) through an opening called a die to form parts with complex cross sections. Materials that are commonly extruded include polymers, metals, concretes, ceramics, and foodstuffs. Metals that could be extruded are alloys of aluminium, tin, lead, copper, etc (Okokpujie & Akinlabi, 2018). The pushing of the material being extruded through the shape forming aperture of the extrusion die enables cross sectional shapes to be produced that cannot be manufactured by any other hot working process (Tyrer & Waheed, 2006). Extrusion may be performed either hot or cold, hot extrusion is commonly

employed for many metals to reduce the forces required, eliminate cold working effects, and reduce directional properties. Extrusion is used to produce semifinished products in the form of bar, strip, and solid sections as well as tubes and hollow sections. The high mean compressive stresses in the deformation zone of the container enable materials to be worked that cannot be processed into semifinished products by other hot working processes, for example rolling, because of their limited workability (Tyrer & Waheed, 2006).

In metal extrusion, a common arrangement is to have a heated billet placed inside a confining chamber. A ram advances from one end, causing the billet to first upset and conform to the confining chamber. As the ram continues to advance, the pressure builds until the material flows plastically through the die and extrudes, as depicted in Figure 2.1. The stress state within the material is one of triaxial compression. (Kohser, 2012)

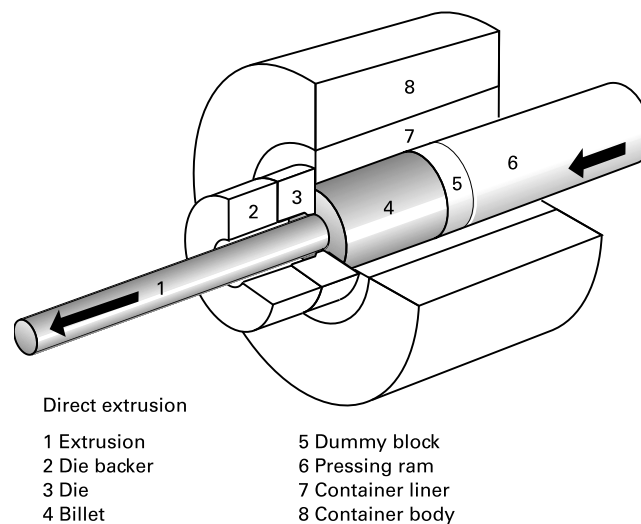


Figure 2.1 Direct extrusion schematic showing the various equipment components (Kohser, 2012).

Aluminum, magnesium, copper, lead, and alloys of these metals are commonly extruded, taking advantage of the relatively low yield strengths and low hot working temperatures. Steels, stainless steels, nickel based alloys, and titanium are far more difficult to extrude. Their yield strengths are high, and the metals tend to weld to the walls of the die and confining chamber under the required conditions of temperature and pressure (Kohser, 2012). The extrusion process also enables semifinished products to be produced from powder metallurgy based materials, composite materials, and the production of semifinished products from clad composites with material combinations including aluminum/copper and aluminum/steel using the cladding process (Tyrer & Waheed, 2006).

As shown in Figure 2.2 , almost any cross-sectional shape can be extruded from the nonferrous metals.

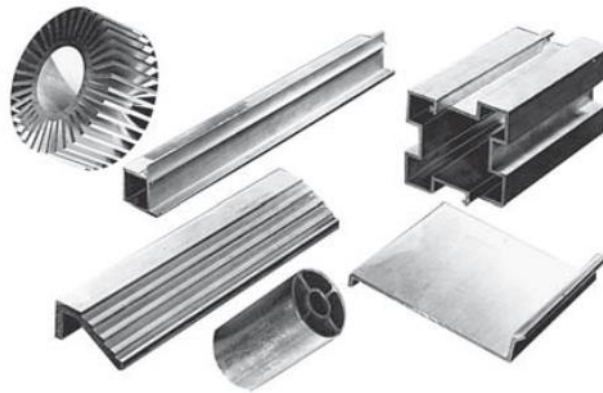


Figure 2.2 Typical shapes produced by extrusion (aluminum products) (Kohser, 2012).

Extruded products have good surface finish and dimensional precision. For most shapes, tolerances of 0.003 cm/cm with a minimum of 0.075 mm are easily attainable. Grain structure is typical of other hot worked metals, but strong directional properties (longitudinal versus transverse) are usually observed (Kohser, 2012). Standard product lengths are about 6 to 7 m, but lengths in excess of 12 m have been produced. Because little scrap is generated, billet to product yields are rather high.

2.2.1. Direct and Indirect extrusion

Extrusions can be produced by various techniques and equipment configurations. Hot extrusion is usually done by either the direct or indirect method, both of which are illustrated in Figure 2.3 In direct extrusion, a solid ram drives the entire billet to and through a stationary die and must provide additional power to overcome the frictional resistance between the surface of the moving billet and the confining chamber (Kohser, 2012). In direct extrusion, the direction of metal flow will be in the same direction as ram travel. The most important and common method used in aluminum extrusion is the direct process (Sheppard et al., 1982). The direct extrusion process is the most widely used method of producing complex shapes in the non-ferrous metals industry. The main application of the direct extrusion is the extrusion of semifinished products of aluminum. However, all other metallic materials including steel, copper, brass, lead, and zinc can be deformed by the direct extrusion process (Tyrer & Waheed, 2006). It is clear that the pressure requirement for direct extrusion is higher than that for the indirect process, primarily because billet/container friction forces must be overcome: these are, of course, absent in the indirect.

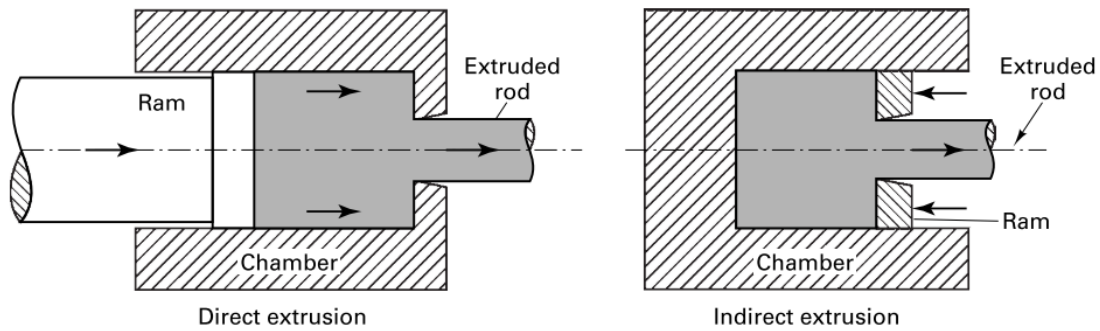


Figure 2.3 Direct and indirect extrusion (Kohser, 2012).

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 Figure 2.3. There is industrial interest in the process of indirect extrusion because lower pressures are required and the greater homogeneity of deformation produces a surface structure which is less heavily worked than in the direct process (Sheppard et al., 1982). With indirect extrusion, also called reverse, backward, or inverted extrusion, a hollow ram pushes the die back through a stationary, confined billet. Because there is no relative motion, friction between the billet and the chamber is eliminated. The required force is lower, and longer billets can be used with no penalty in power or efficiency (Kohser, 2012). However, there are disadvantages to the indirect process, the major problems being; the maximum circumscribed circle diameter of the extruded shape is limited by the inner diameter of the hollow stem; and the outer periphery of the billet forms the surface of the extrude and hence any surface casting defects are reflected in the extrudate surface (Sheppard et al., 1982).

During direct extrusion, the load or pressure-displacement curve most commonly has the form shown in Figure 2.4 . Traditionally, the process has been described as having three distinct regions (Sheppard et al., 1982). In the first stage the billet is upset, and pressure rises rapidly to its peak value. And in the second stage the pressure decreases, and what is termed “steady state” extrusion proceeds. Finally, the pressure reaches its minimum value followed by a sharp rise as the “discard” is compacted.

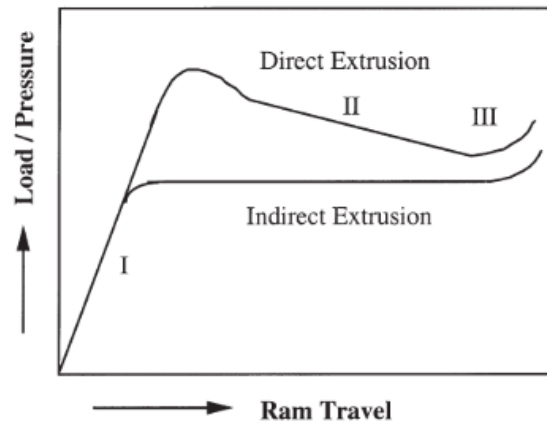


Figure 2.4 Variation of load or pressure with ram travel for both direct and indirect extrusion process (Saha, 2000)

The areas below the lines have units of Newton-meters and are, therefore, proportional to the work required to produce the part (Kohser, 2012). The area between the two curves is the work required to overcome the billet chamber friction during direct extrusion an amount that can be saved by converting to indirect extrusion. Unfortunately, the added complexity of the indirect process (applying force through a hollow ram, extracting the product through the hollow, and removing residual billet material at the end of the stroke) serves to increase the purchase price and maintenance cost of the required equipment.

2.2.2. Billet material

The extrusion process consists of four major components, hydraulic press, die, tooling, and billet casting. Billet quality directly controls or may affect extrusion productivity and quality (Saha, 2000). The profitability of the extrusion is derived from the cost of the billet. The cost of casting and the quality of the billet are two very important considerations for the extrusion producer. But the technology is changing and improving toward higher productivity and quality.

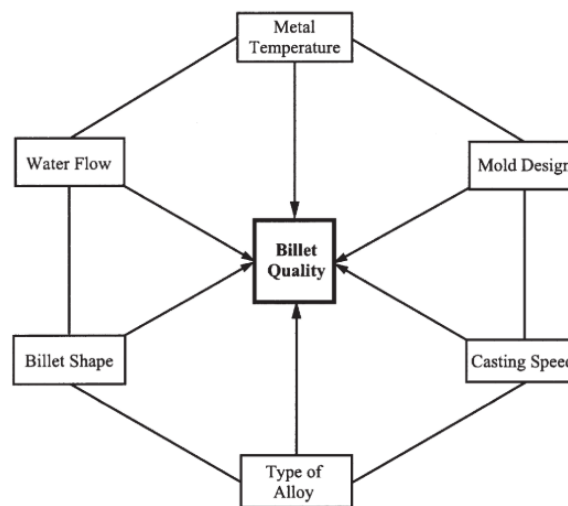


Figure 2.5 Effect of principal variables on billet quality (Saha, 2000).

As stated by (Saha, 2000) the overall production performance and quality of billets are influenced by the factors that are connected with a closed loop chain as shown in Figure 2.5

2.2.2.1. Extrusion of soft and medium grade alloys

Aluminum alloys have significantly higher elastic or energy absorption capacity relative to steel because of their low elastic modulus. This is an advantage that should not be undervalued for aluminum designs subjected to impact loads, for example, in rail or road transport vehicles (Tyrer & Waheed, 2006).

A number of unique and attractive properties account for the engineering significance of aluminum. These include its workability, light weight, corrosion resistance, good electrical and thermal conductivity, optical reflectivity, and a nearly limitless array of available finishes (Kohser, 2012). Aluminum has a specific gravity of 2.7 compared to 7.85 for steel, making aluminum about one-third the weight of steel for an equivalent volume.

The mechanical properties of the aluminum alloys used for the production of large aluminum profiles are adequate for most applications where good design enables the profile geometry to be adequately dimensioned. Nevertheless, difficult to extrude and, to some extent, moderately difficult to extrude aluminum alloys (those with a higher alloy content) do not offer the same profile geometry options as the low alloyed and easily welded aluminum alloys such as AlMgSi0.5 and AlMgSi0.7 (Tyrer & Waheed, 2006).

The main application of the hot-working process extrusion is in the general production of bars, tubes, and wire in aluminum alloys and, in particular, the manufacture of aluminum sections. Acceptable materials properties and modulus of elasticity, weight saving from the low density,

good surface quality, good dimensional accuracy and minimum subsequent machining, and ease of recycling make aluminum alloys both economically and environmentally interesting (Tyrer & Waheed, 2006). These properties, as well as the largely unrestricted shape of the cross section geometry, are the basis for the trend to the development of ever more functional components with good appearance and corrosion resistance.

2.2.2.2. Alloys and extrudability

Extrudability, which can be measured by the maximum extrusion speed, is one of the most significant factors influencing cost and efficiency of the extrusion process. Temperature and speed parameters, together with the state of stress in the deformation zone, mainly in the die region, play a significant role in improving extrudability of a given alloy. A simple, practical method of extrudability testing is to vary extrusion ratios while holding other process parameters unchanged, the maximum extrusion speed without cracks being the measure of extrudability. (Zasadzinski et al., 1992) studied improved extrudability (as measured by maximum exit speed) through the control of deformation geometry and accurate selection of temperature and speed process parameters. The advantage of the approach is its practicality. They used an inexpensive method by changing the die design using a direct extrusion press and developed an algorithm for calculating the optimum temperature and speed conditions for a given extrusion.

(Reiso, 1988) investigated billet preheating practices in an industrial environment for two different AlMgSi alloys to determine extrudability. It was shown that extrudability, as well as the mechanical properties and surface quality, may be significantly improved by using billet preheating practices different from accepted normal production practices. At high billet temperatures, a sharp increase in extrudability was recorded (30% and 60% for the two alloys investigated), and a further gain in extrudability was obtained by homogenizing the billets, followed by cooling into the normal temperature range, prior to extrusion. The obtained increase in the extrusion speed was found to be alloy dependent. Furthermore, the extrusions with the highest extrusion speeds also had better mechanical properties and improved surface quality compared with those from billets heated directly in the normal preheating temperature range.

The relative extrudability ratings of some soft and medium grade alloys are given in Table A1. The alloys are classified into three different groups according to their extrudability (Saha, 2000). Alloys easy to extrude: pure aluminum, AlMn, AlMg1, AlMgSi0.5, and AlMgSi0.8.

Alloys moderately difficult to extrude: AlMg2-3, AlMgSi1, AlZnMg1. Alloys difficult to extrude: AlCuMg, AlCuMgPb, AlZnMgCu, AlMg>3%Mg

Alloys under groups easy to extrude and and II are considered to be soft and medium grade alloys. The alloys generally used for the principal types of extruded aluminum products are listed in APPENDIX-A (Table A2).

2.2.2.3. Aluminium 6XXX series

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. According to the study of the bulk of structural aluminum profiles used in the construction industry is produced through hot extrusion (Saha, 2000). 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. Significance of improving the material processing techniques for aluminium alloy has been felt due to its enormous application in various key industries. The process of aluminium alloy extrusion has gained great popularity in recent years due of its simplicity and low cost (Saha, 2000).

Extrusion of aluminum alloy shapes represents the most advanced technology in terms of alloy making, press design, tooling, and die design. The billet chemistry determines the type of alloy and its applications. The 6000-series alloys are widely used based on their having the best technical and economic characteristics, including ease of extrudability into hollow and complex shapes, simplicity in heat treatment, good electrical conductivity, satisfactory mechanical properties, good surface finish quality, high corrosion resistance, and good weldability for a wide variety of applications (Saha, 2000).

Several million tons of 6000-series alloy extrusions are produced every year (Saha, 2000). Applications include bars and rods to intricate shapes such as door and window frames, automobile trim, building structures, electrical bus bars, heat exchangers and so on (Saha, 2000). Because it is easy to work with 6000-series alloys, development of many derivatives of 6000-series alloys continues in order to fulfill the requirements of different customer applications throughout the world. Some 6000-series alloys have a higher level of alloying elements to achieve higher strength for structural and semi structural applications.

2.3. Process parameters

Quality is the basic marketing factor in the aluminum extrusion industry. Quality is a key factor leading to business success, growth, and an enhanced competitive position. There is a substantial return on investment from an effective quality improvement program that provides increased profitability to the company that effectively employs quality as a business strategy (Saha, 2000). Consumers believe that the products of certain companies are substantially better than those of other companies, and they make purchasing decisions accordingly. Effective quality improvement programs can result in increased market penetration, higher productivity, and lower overall costs of manufacturing and service (Saha, 2000). Consequently, companies with such programs can enjoy significant competitive advantages.

The quality of extrusion is totally dependent on the functions of the process control of each head of the functional block diagram of the quality control system shown in Figure 2.6.

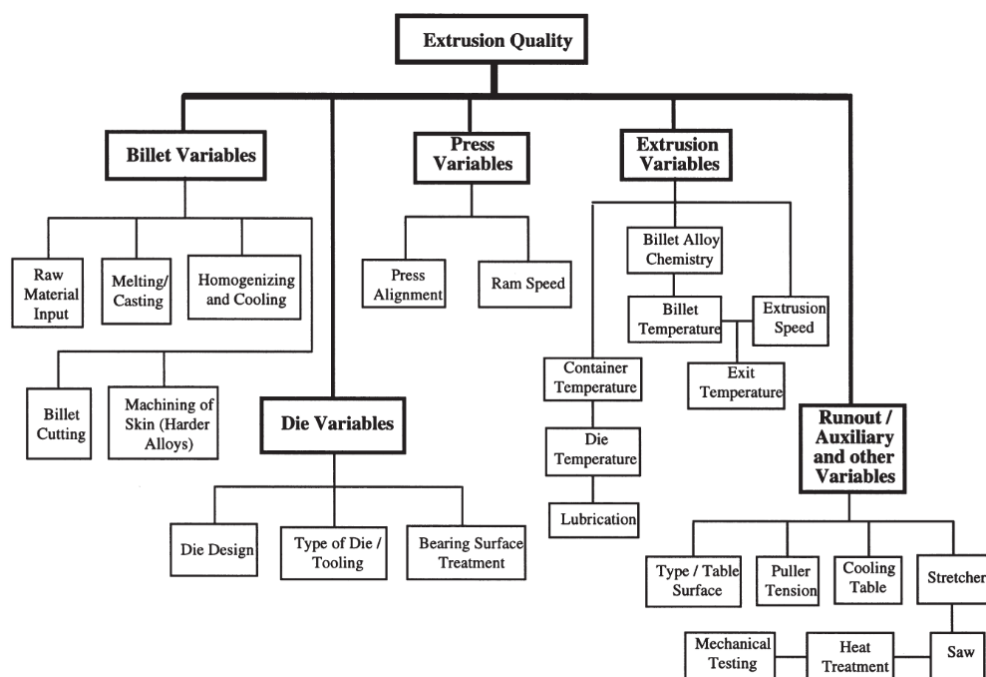


Figure 2.6 Typical flow diagram of an extrusion quality control system (Saha, 2000).

Extensive review of past literature reveals that for better product quality and product efficiency pre-heating temperature, ram speed, extrusion ratio, cone half angle, bearing length, etc. are the process parameters mostly needed to be optimized during extrusion processes. However in most extrusion process these sensitive processes parameters have been determined depending on the experience, intuition or analogy of workers and many times trails-and-errors (Chen et al., 2007). These leads to defects in extrudates such as; crack or surface burning, twist

deformation, variation in material flow, wave, and bend appear, and actual production has to be stopped or postponed (Chen et al., 2007; Li et al., 2003; Zhang et al., 2012). During the hot extrusion process of aluminum alloy 6061, the process parameters significantly affect the mechanical properties of extruded products (Prabhu et al., 2011). For better extruded components, these process parameters needed to be optimized. Extrusion parameters (e.g., billet temperature and extrusion speed) are fully dependent on the chemistry of each alloy. The container temperature is controlled based on the initial billet temperature (Saha, 2000).

Different optimization technique will be implemented to study the effects and relations of process parameters. (Sharififar et al., 2015) studied the effect of extrusion process parameters and die geometry on extrusion force using Taguchi method and genetic algorithm to produce the rectangular waveguides.

2.3.1. Billet pre-heating temperature

According to the study of (Zhou et al., 2009) among the multiple process parameters in aluminium extrusion, the extrudate temperature is the most important one to watch, because it determines the quality of the product and indicates the possibility of increasing extrusion speed. When it exceeds a critical value, surface defects appear in the form of hot shortness or cracking. Even below this critical value, high temperature may lead to local recrystallisation and grain growth, detrimental to the mechanical properties of the extruded product. For feature angularity of a two-track top profile used in commercial window assembly, (Inamdar & Chahare, 2017) found that billet pre-heating temperature is the significant factor among different extrusion process parameters.

For another type of aluminium alloy extrusion also (twist extrusion) temperature have a significant influence to tensile strength and hardness of extrudates. An investigation on AA6061-T6 alloy of a twist extrusion process by (Iqbal et al., 2016) found that for higher temperature and more number of passes, the tensile strength and hardness increased by 8–10%. (Ramya & Sreedevi, 2016) predict the extrusion load and stress during the hot extrusion process of 6061 Aluminium Alloy by using Deform-3D simulation. According to their studies 500 °C is best processing parameters in extrusion process with minimum reduction ratio 10:1 when ram speed 2.5 mm/sec is required.

As stated by (Saha, 2000) the metal flow through multi-hole die is dependent on many variables such as shape, number and layout of die openings, extrusion temperature, and section thickness.

Hence, it is mandatory to consider the extrusion temperature when multi-hole die extrusion investigation is performed.

2.3.2. Ram speed

Since it is an important affecting parameter on the profile quality and extrusion productivity, the ram speed should also be well controlled during the extrusion process of aluminum alloy. In aluminium extrusion process feature angularity of products is one of the defects faced by aluminium manufacturers. The experimental investigation of (Prabhu et al., 2011) clearly predict and gave a direction for reduction of feature angularity by optimizing the extrusion process parameters. During the study ram speed was found to be the highest contributor among billet pre-heating temperature and container temperature, and it is found that the optimum ram speed to reduce feature angularity is 6.0 mm/s. Billet pre-heating temperature also plays an important role in reduction of extrusion load (Ramya & Sreedevi, 2016). According to (Ramya & Sreedevi, 2016) billet pre-heating temperature of 500°C is the best temperature value in reduction of ram force.

The effects of ram velocity on some evaluation parameters of pyramid die extrusion, such as the material flow behavior, extrudate temperature, extrusion force, transverse weld, quality of longitudinal weld, and back end defect, have been investigated by (Guoqun et al., 2015). Their result confirmed that, the flowing velocity, extrudate temperature, extrusion force, and welding pressure tend to increase as the increase of ram velocity, while the length of transverse weld is reduced at higher ram velocity.

2.3.3. Friction model

Another useful extrusion mathematical model is friction model. During simulation work the value of friction should be selected carefully, a detail friction model presented by the work of (Liliang & Haoliang, 2012) presented the three basic friction models for aluminium extrusion. Among different friction model's coulomb friction model overestimate the friction stress this over estimation enables the coulomb friction model to be infrequently used in finite element simulation. (Sanabria et al., 2015) developed a new friction model which occurs between aluminium alloys EN AW-6060 and hot working steel.

(Jajimoggala et al., 2019) found that coefficient of friction is one of a significance extrusion process parameter on extrusion quality and product enhancement. According to their grey relational grade (GRG) analyze coefficient of friction had 7.52% contribution on the product

quality of extrudates. And they found that the optimum coefficient of friction for hot extrusion is 0.1.

2.4. Extrusion die

Die design plays a critical role in aluminium alloy profile production, which directly influences the quality of the final products and the service life of the die. During the extrusion process of aluminium alloy profiles, scientific and reasonable design of extrusion dies affects directly on the product qualified rate, production efficiency, and cost (Zhang et al., 2017). (Ter et al., 2017) studied the relationships between the design of dies for aluminium hot extrusion, the contact pressures on the die's bearing surface, the length of the bearing surface, the quality of the nitride layer and the service lifetimes of nitride dies. As a result, they propose an approach for optimization in a prolongation of the service lifetimes of the dies.

(Cunsheng et al., 2016) used four different die modifications (resizing the porthole structure, chamfering the mandrel support, adding baffle plates, and adjusting bearing lengths) to improve material flow uniformity during the extrusion process. With the modified extrusion die, a sound radiator is extruded with the desired size and geometry. Finally, the extrusion die modification rules are summarized for similar radiators of their study. Another authors (Liu et al., 2012) proposed and simulate four kinds of structure optimizations for a large, multi-cavity aluminium profile extrusion, the modifications was the same as (Cunsheng et al., 2016). The simulation was taking care of by using the Arbitrary Lagrangian Eulerian (ALE) algorithm. Their result shows that through the effective prediction of flow velocity in the simulation extrusion, the qualified profiles with few trial and error extrusions were manufactured successfully. The case study demonstrates that the ALE method is a viable predictive tool for die design, and the approach is applicable to the extrusion of other alloys for any other extrudate shapes.

The temperature monitoring during aluminium extrusion is a crucial task performed in order to avoid profile defects, to increase the die life and to optimize the process productivity. Among the different available systems used to control the process temperatures, in the last decade, the die cooling through liquid nitrogen has been installed on several extrusion plants (Reggiani & Donati, 2019). A numerical model of the extrusion that accounts for liquid nitrogen cooling has developed by (Reggiani & Donati, 2019), in their result they found that a significant impact of the design aspects of channel on the thermal efficiency of the cooling and an important heat removal when the liquid nitrogen cooling is used.

2.4.1. Multi-Hole dies

The appropriate die design for multi-hole extrusion is still a challenging task because of the complicated circumstances and large material deformation during extrusion process (Fang et al., 2020). (Liang et al., 2014) studied the effects of eccentricity ratio, shape of the second-step welding chamber, and uneven bearing length on the exit velocity distribution of extrudate. Their work suggested a logical and effective route for designing multi-hole porthole dies for die designers.

From the recent study of (Kumari et al., 2018) on a finite element analysis and experiments of multi-hole forward, backward and combined forward and backward extrusion, they found that The extrusion load increases with in extrusion ratio, die land length and the extrusion speed. The extrusion ratio and the die land length are found to be more significant on the extrusion load as compared to the extrusion speed. The coefficient of variation of the extruded parts is less for low die land length and low extrusion speed.

(Fang et al., 2020) designed and numerically simulate a porthole die for a multi-hole extrusion process of a thin-walled flat multi-port tube. The result indicates that, with the optimized die, a highly qualified tube with good appearance, desired dimensional accuracy, fine-grained microstructure, and high-pressure bearing capacity is manufactured successfully, and the die failure is delayed effectively.

An investigation by (Mueller & Sanabria, 2018) on four-hole die with pair wise parallel and choked long channels showed that, profiles extruded through parallel channels flowed faster than those through choked, therefore dissimilar grain structures will be generated. Hence the above author concludes that speed and temperature are the most influential parameters to define the product microstructure.

A recent study by (Xue et al., 2018) investigated the role of die structures on metal flow balance in multi-output porthole extrusion of thin-walled profile. They found that the optimized design of a multi-output porthole extrusion die structure to improve the extrudate quality.

2.4.2. Pocket, Porthole and feeder on die design

The material flow balance in extrusion die cavity (e.g. porthole, welding chamber, etc.) plays a crucial role in the extrusion process and product quality of hollow aluminum alloy profiles. Therefore, the structures of porthole and welding chamber are always the keys for designing extrusion dies (Zhang et al., 2016). Porthole die extrusion has been more and more utilized to produce hollow complex cross-section profiles. The porthole die is characterized by complex

shapes and various geometric variables have to be set properly for the process optimization. Numerical simulations combined with optimization methods are effective strategies, which can be used for a proper die design reducing the experience and “trial and error” sequences.

The virtual tryout of the extrusion process of a large hollow aluminium profile is carried out by using numerical simulation. Firstly, a porthole die is designed based on the theory of metal plastic forming, and a finite element model of the extrusion process is established (Ji et al., 2017). (Mahmoodkhani et al., 2014) developed and validated a comprehensive numerical model of the hot extrusion process for aluminium alloys, which shows that the die feeder design has a significant effect on the transverse weld formation with tapered dies showing lower transverse weld lengths compared to regular feeder plates. Compared to conventional single-output porthole extrusion, multi-output porthole extrusion leads to a substantial enhancement of the real productivity and a lower required extrusion force for a given size of billet and profile (Xue et al., 2018).

A study by (He et al., 2009) on porthole die with pockets show that the pockets could be used to effectively adjust the metal flow and especially benefit to the metal flow under the legs. In addition, the maximum temperature at the die bearing and the peak extrusion load decrease, which indicates the possibility of increasing the extrusion speed and productivity. (Reggiani et al., 2015) conducted a multi-objective optimization for a porthole extrusion die used to manufacture a thick AA7003 round tube. The aim of their work was to increase the seam weld quality, the die lifetime, the production rate and at restraining the die yielding and the peak process load with respect to an initial already optimized solution, their proposed approach to the extrusion process optimization could provide an effective automated guidance for practical productions to be used at the die and process design stage in order to maximize process performances both for die makers (die strength) and extruders (profile quality).

The extrusion ratio will be the clear indication to the amount of mechanical working that will occur as the shape is being extruded. 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 (Saha, 2000).

(Ji et al., 2017) optimized the extrusion die and microstructure analysis for a hollow aluminium alloy profiles. In their result they showed that, the uneven deformation caused by the difference in wall thickness is the main factor that causes the uneven distribution of grain sizes in the cross-section of the product. When the material flows out of the die orifice and undergoes uneven temperature distribution at the profile section, the grain growth rates become different.

(Gagliardi et al., 2018) investigated the optimum process parameters for port hole extrusion, in their studies they used the required ram load, the maximum pressure inside the welding chamber, and the material flow homogeneity to study an optimum geometric variables for port hole extrusion.

(Zhang et al., 2017) used the response surface method (RSM) and mesh deformation technique (MDT) to automatically optimize the feeder chamber of the extrusion die. With implanted material physical properties and constitutive model of aluminium alloy, the numerical simulation of the extrusion process is firstly carried out and experimentally verified.

In the aluminum porthole extrusion process, excessive wear occurs on the surface of mandrel. A 3D printing process known as direct metal depositing (DMD) technique will be used for repairing the hot extrusion die. (Sang-Kon et al., 2018) evaluate the die repairing technique for hot aluminium extrusion process. In their study the wear characteristics of three die repairing methods (parent-STD61, DMD-STD61, and welded-STD61) were compared through a high-temperature pin-on-disk wear test. Their result confirmed that DMD results in superior wear characteristics when compared to overlay welding repair method.

2.5. Numerical and simulation works

Now a days, computer simulations based on the finite element method (FEM) has been increasingly applied to the aluminium extrusion process. FEM allows geometrical complexities to go beyond the capabilities of the conventional analytical methods (Bingol et al., 2014). A recent literatures showed that numerical and analytical modelling of manufacturing processes together with microstructure investigations have been great potential to increase process productivity and product quality, as well as to reduce development and production costs (Bressan et al., 2015; Kanghua et al., 2012; Madej et al., 2015; Sanabria et al., 2015).

(Zhou et al., 2009) used 3D FEM simulation to investigate the effect of steps in the die pocket on metal flow to produce two chevron profiles with unequal thicknesses through two-hole dies. Since they found the simulation work and experimental results were in good agreement for their study (Zhou et al., 2009), they suggested that 3D FEM demonstration is a powerful tool in optimizing die design and decreasing the number of trials in extrusion process. (Das et al., 2014) also found that the effective strain, which provides the information about the work hardening of the material during the extrusion process is dependent of the ram speed, extrusion load, and die pocket in their FEM analysis. A numerical description made by (Bressan et al., 2015) also formulated a mathematical relation for strain rate, stress and velocity fields of axisymmetric hot extrusion process using finite volume methods (FVM). The formulation of their work proposed a new numerical scheme to calculate stress and velocity fields of metal flows in the axisymmetric extrusion process under steady state of aluminium alloy 6351. On the another investigation (Sinha et al., 2009) estimates the desirable ram force for multi-hole extrusion by using upper bound method, which was taking as an assumption of single hole conical die. The analytical result of their work shows over estimation of ram force compared to the experimental results; this defines that the estimation of ram force enables the designed component of extrusion to work under safer conditions.

A simulation work and numerical relation of arbitrary Lagrangian-Eulerian (ALE) by (He-nan et al., 2012) also predicted the extrusion process defects, which is experimental verified in their result.

2.6. Literature summery

The above literature shows that the ram force required for single-hole extrusion is higher than multi-hole extrusion, and the multi-hole extrusion is more productive than single-hole extrusions. Beside the productivity and ram force differences, the following studies have been conducted in extrusion process and results have been obtained:

- With an increase in the temperature, speed, and ratio of extrusion, the grain sizes and area fraction increased as a result of the temperature rise at the deformation zone caused by deformation heating, the yield strength decreased but the elongation increased when the temperature, speed, and extrusion ratio increased.
- During the extrusion process of aluminium alloy profiles, scientific and reasonable design of extrusion dies affects directly on the product qualified rate, production efficiency, and cost of the production.

- A numerical approach has been employed to calculate strain rate, stress and velocity fields in extrusion process which is in good agreement with the finite element analytical solutions.
- Now a days, computer simulations based on the finite element method (FEM) has been increasingly applied to the aluminium extrusion process. FEM allows geometrical complexities to go beyond the capabilities of the conventional analytical methods.
- Numerical and analytical modelling of manufacturing processes together with microstructure investigations have been great potential to increase process productivity and product quality.
- With the help of Lagrangian-Eulerian (ALE) adaptive remeshing technology and advanced simulation software's, the bulk metal forming investigation can be capable to simulate defects in extrusion.
- A recent study suggests that a liquid nitrogen cooling is effective for hot extrusion of aluminums alloys.

2.7. Literature gaps

Many investigations have been conducted in extrusion processes according to the survey of this study. Most of the objectives of this study directly or in directly studied, but these gaps have been a void as per the best of this literature review. Hence, in this study the author will try to fill these gaps.

- Most investigators in aluminium extrusion have been studied each extrusion process parameters individually. There was a little study on the interaction of extrusion process parameters.
- The multi-response parametric optimization of hot extrusion process for some of AA6XXX alloy have been studied but most of the studies were limited to simulation works only.
- There have been little investigations performed regarding to multi-hole extrusion process combined with capability and product enhancements.

Therefore, this study focuses on multi-response parametric optimization of multi-hole extrusion product capability enhancement, and also the experimental investigation performed to check the mechanical properties of extruded products.

Chapter Three

3. Materials and Methodologies

3.1. Introduction

The present study applies numerical simulations, theoretical and experimental analysis as a main approach which is used as a methodology. Figure 3.1 describes the pictorial description of various steps involved in present study and their sequence. Before analyzing the experimental results, there are three major steps which can be classified as introducing the investigation, methodology and design of experiments and simulation (which is part of the methodology section). The subsequent sub-sections will explain these steps in detail.

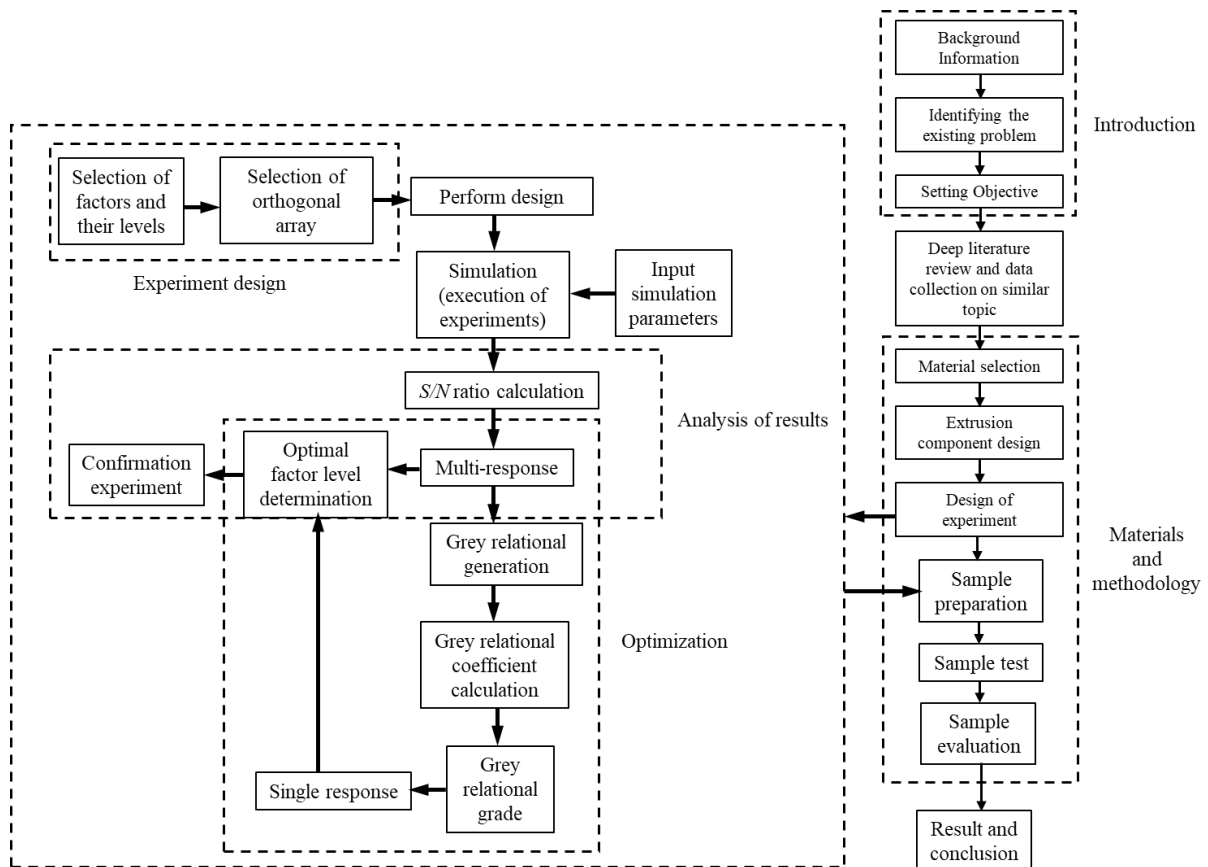


Figure 3.1 Procedure implemented in this study

3.2. Material selection

The dies used for the extrusion of aluminum alloys and copper alloys are generally made from AISI H11, H12, or H13 tool steels (Park, 2005).

Table 3.1 Typical materials and harnesses for tools used in hot extrusion (Park, 2005)

Tooling application	Tool materials and hardness level for aluminium and magnesium extrusions	
	Tool material	Hardness (HRC)
Dies, for solid and hollow extrusion	H11, H12, H13	47-51
Dummy block, backers, blosters and die rings	H11, H12, H13	46-50
Mandrel	H12, H13	46-50
Mandrel tips and inserts	T1, M2	55-60
Liners	H11, H12, H13	42-47
Ram	H11, H12, H13	40-44
Containers	4140, 4150	35-40

3.2.1. Billet (6063 aluminium alloy)

AA6063 aluminium alloy, as a deformed aluminium alloy which can be strengthened by heat treatment, is widely used in the automotive industry with medium strength, good formability and corrosion resistance.

The billet material selected for this study is AA6063, which is an aluminium alloy with magnesium and silicon as the alloying elements. It is similar to the British aluminium alloy HE9. AA6063 is the most common alloy used for aluminium extrusion. It allows complex shapes to be formed with very smooth surfaces fit for anodizing and so is popular for visible architectural applications such as window frames, door frames, roofs, and sign frames.

3.3. Tool materials

In the process of manufacturing an aluminium extrusion die, the selection of a die material and its specific properties are critical factors. Since the hot aluminium extrusion process is investigating on this study which ranges up to 500°C, the most frequently used die material is die steel AISI H13 (Saha, 2000; Ter et al., 2017).

The performance of the extrusion die is normally limited by typical material related failure mechanisms. In aluminium extrusion, the most common die failure mechanisms are hot wear,

plastic deformation, and cracking. In order to offer good resistance against these failure mechanisms, the die material should have the following properties:

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

3.3.1. Top die (ram)

In direct extrusion, top die (ram) is used that must be suitable for a specific press load. They do not take any direct role in the hot working process. Therefore, the selected ram material for this study is H13 (Park, 2005).

3.3.2. Bottom die

As per (Park, 2005) the selected die material for this study is H13 tool steel. Due to its high cost, based on special material and processing, very fine tolerances, and high demands on repeated thermo-mechanical performance, the most critical extrusion component is perhaps the die. APPENDIX-B shows the CAD modeled using Solidwork 2019 and fabricated die at Ethiopian engineering group (EEG). The mechanical and physical properties of the die materials for this study is stated in.

3.3.3. Container

Due to subjection of high heat from billet and external sources the container material should work under different heat fluctuations. Therefore, this study selects AISI 4150 material for their special working conditions in hot forming process.

3.4. Die design

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

close working relationship between designer, die maker, press operator, and die corrector is needed to check tolerances and production performance (Saha, 2000).

Therefore, due to its complexity and exclusion of this study scopes. The task for die designing and fabrication is given to the huge national manufacturing company Ethiopian Engineering group (formerly known as Hibret machining and machine building industry). To start with the design of a die, the designer needs fundamental information regarding the geometry of the shape, alloy to be extruded, size of the press, billet size, runout required by the customer, support tooling like backer or bolster to be used, the weight of extrusion per unit length, and so on (Saha, 2000).

3.4.1.1.Geometry of Die

Design of a die with single-hole is simpler than a die with multi-hole. During the designing of a multi-hole die, it is required to decide the number of the openings and how to be placed a geometric layout on the surface of the die, Figure 3.2 shows the CAD model and fabricated 4-hole die.

To obtain a regular metal flow in the die, some of the rules are decided by the die designers. In the multi-hole dies, the center of gravity of each section should be more or less coincident with the center of gravity feeding the opening portion of billet (Bingol et al., 2014).

Die Layout

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

- Proper clearance, between the die opening and the container wall, and also proper distance, between the openings. At the same time, the 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. Sufficient strength in the die may avoid cracking and deflection in the die.
- Balanced metal flow to avoid any distortion of the shape
- Ease in die design and manufacture
- To avoid overlapping and scratching a particular part of the extrusion on the runout table

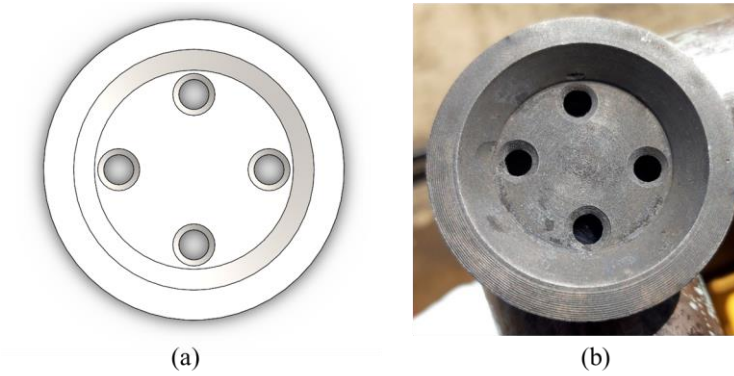


Figure 3.2 Layout of multi-hole die (a) CAD model and (b) fabricated.

Eccentric ratio

According to the recent study conducted by (Fuh-Kuo et al., 2008) the material flow in the multi-hole extrusion can be affected by the geometry of the die. A fully symmetric geometry is considered as the most desirable die design. However, for multi-hole extrusion, a fully symmetric die shape is not obtainable. The eccentric arrangement of holes may cause unbalanced flow at the exit of extrusion die. For multi-hole extrusion the above authors recommended that eccentric ratio to be below 0.3 to minimize the bending angle at the out late of extrusion Figure 3.3 depicted the sectional view and schematic of 3-hole die.

Eccentric ratio can be calculated as follow;

$$e = b/(a + b) \quad (1)$$

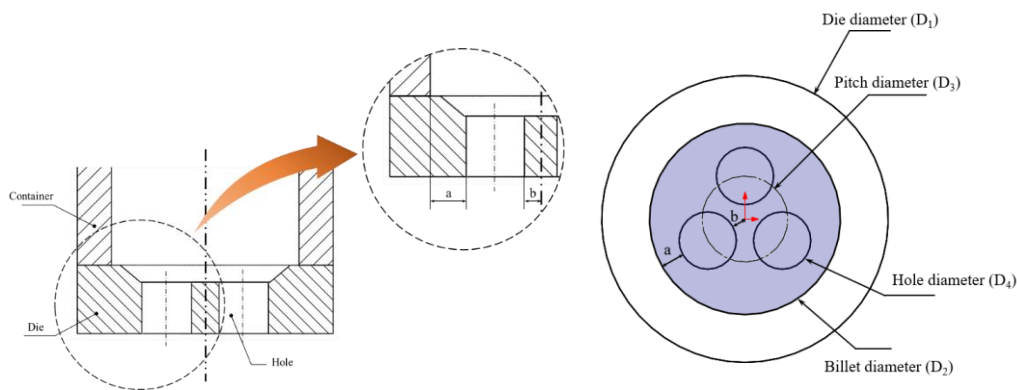


Figure 3.3 Hole eccentricity diagram sectional view and schematic of the die.

Where:- e is eccentric ratio, a and b is a distance from container and center of the die.

Since the workpiece material for this study is fixed to 40 mm in diameter, the pitch diameter and hole diameter of the bottom die can be calculated by as follow.

Since $e = \frac{b}{a+b} = 0.3$

$$b = 0.3(a + b),$$

$$\therefore D_3 = 0.6(R_2 - D_4) + D_4 \quad (2)$$

When the hole diameter is set to 5 mm;

$$D_3 = 11.15 \text{ mm} \approx 11 \text{ mm}.$$

Where: -D₁ is die diameter, D₂ is billet diameter, D₃ is pitch diameter, D₄ is die-hole diameter.

Design of the pockets

In the design of die pocket, it is important to realize that the geometrical parameters of the pocket, including width, depth and outline (contour), have varied effects on metal flow. Pocket angle may be used to integrate the effects of pocket width and depth on metal flow. Fang, *et al.* (Zhou et al., 2009) drive a geometric relation between cone half angle and distance of holes from container wall for two hole extrusion. This geometric relation explains the geometric description of multi pocket feature on multi-hole extrusions. the pocket angle α illustrated in Figure 3.4 , is described as

$$\alpha = \arctan \frac{W_{P1}}{D_P} + \arctan \frac{W_{P2}}{D_P}. \quad (3)$$

where W_{p1} and W_{p2} are the widths of the pocket and D_p is the depth of the pocket.

$$\therefore \alpha = 80^\circ$$

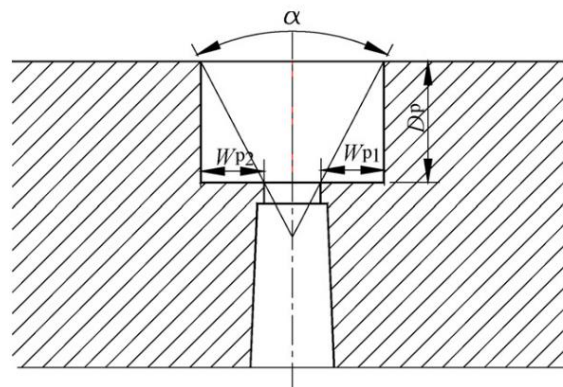


Figure 3.4 Definition of the pocket angle (Zhou et al., 2009)

In a pocket, the metal in the area where the pocket angle is larger flows faster. Changing the pocket width and introducing multiple steps are effective means to change the pocket angle.

Compared with a square pocket (single-step), a multi-step pocket reduces the dead metal zone in the pocket (Li et al., 2003) and facilitates metal flow. Thus, at a given pocket angle, steps may be effectively used to adjust metal flow. The position of the pocket relative to the die orifice is also important for a uniform velocity distribution. To determine the pocket contour, the following method was adopted. At the corners, enlarged circles were placed and linked with tangent lines. In addition, a circle with a larger diameter was placed at the corner where the section was thinner and far from the die center, so as to facilitate the metal flow there.

Extrusion ratio

The extrusion is the ratio of the area of the work billet cross section to that of the extrusion ratio or reduction ratio, in case of multi-hole extrusion expressed as (Saha, 2000):

$$\text{Extrusion ratio} = \frac{A_o}{A}. \quad (4)$$

Where A_o is billet area to be extruded, and A is area of extrudates after extrusion (in case of multi-hole extrusion A becomes the summation of all hole areas in the die).

For 2-hole die the extrusion ratio becomes

$$\text{Extrusion ratio} = \frac{40^2}{2 * 5^2} = 32 \quad (5)$$

For 3-hole die the extrusion ratio becomes

$$\text{Extrusion ratio} = \frac{40^2}{3 * 5^2} = 21.3 \quad (6)$$

For 4-hole die the extrusion ratio becomes

$$\text{Extrusion ratio} = \frac{40^2}{4 * 5^2} = 16 \quad (7)$$

The extrusion ratio for this study is between the range of 16:1 to 32:1 which is more optimum condition for soft metal like aluminium.

Bearing length

The function of the bearing is to control size, shape, finish, and speed of extrusion. The bearing also determines the life of the die. Friction at the die land is the controlling factor for retarding the metal flow. The length of bearing at any location of the die opening depends upon the extent

to which the metal flow must be retarded at that point Figure 3.5 shows the bearing surface of the sectional view for multi-hole die.

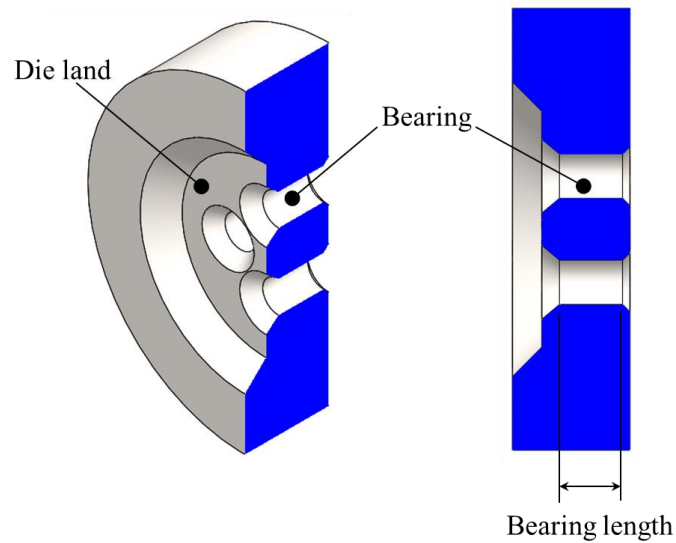


Figure 3.5 die section view

In order to obtain straight extrusion products without defection, the die designer must ensure that the workpiece flows uniformly through the die exit. Generally, the designer can control the material flow by constraining the flow in thick sections by increasing the bearing length (Lee & Im, 2002). In other words, variation of the bearing length is the main method of controlling the material flow and feed.

There are no absolute rules for calculating appropriate bearing lengths, but the general procedure is to increase the bearing length in thicker sections and to reduce the length with increasing distance from the center of the die. Also, the bearing length should be reduced at the end regions of the die opening to decrease friction levels which are usually high in such regions.

But in this study a uniform cross section of circular profiles will be obtained, therefore the metal flow character will not be affected constant in any case of bearing length therefore the bearing length taken as 2.8 mm. see APPENDIX-B

3.4.1.2.CAD model

The CAD model for the die is prepared by using Solidworks 2019 software, which is one of the best software in CAD/CAM. In Solidworks there is a global valuable option which helps the designer to perform his/her design with equation driven relations. As it is can be seen in the figure below the sigma notation indicates the equation which was used in the CAD model (part design). Therefore, by changing one of the variables (D_2 or D_4) the pitch diameter can be

obtained automatically. The three die types of die used for this study is illustrated in Figure 3.6.

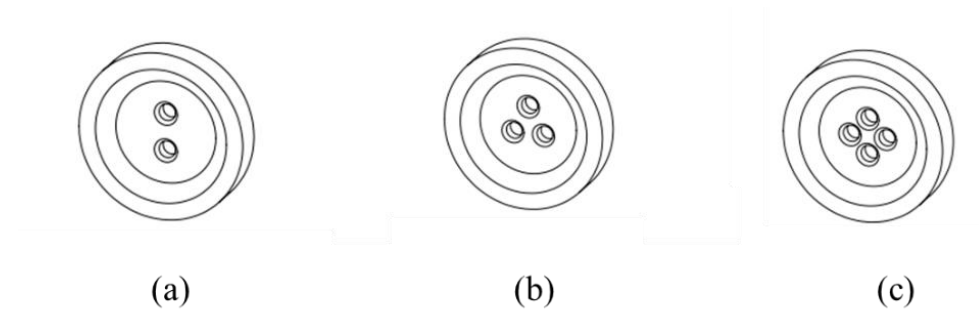


Figure 3.6 3D Models of bottom dies, (a) 2-holes, (b) 3-holes and (c) 4 holes.

3.5. Methodology for numerical simulation

3.5.1. Numerical investigation

(Md Israr & Rajkumar, 2016) found that DEFORMTM 3D is an effective tool to investigate the effect of design and process parameters on metal forming. Hence the present study of simulations carried out through a commercial software package DEFORMTM-3D 11.0 software developed by Scientific Forming Technology Corporation (SFTC) in the US. With this program, thermomechanical coupling, automatic meshing and adaptive remeshing, all essential for meaningful simulation of the extrusion process, are built in. HP15da1xxx PC with four-CPU's and 8GB RAM was used to run the simulations. In addition, the parallel computing Message Process Interface (MPI) was carried out to save calculating time. The simulations were limited to the extrusion process in the transient state. If the simulation had been allowed to proceed well into the steady state of the process, the computing time would have been too long and the data files generated would have caused a storage problem. This simulation was at present engaged with the process of hot extrusion for AA6063 aluminium alloy. Unlike the general-purpose codes used for FEM, DEFORM was developed for deformation of modelling with a friendly user graphical interface which provides an easy data survey and preparation.

By simulating manufacturing processes on a computer, this advanced tool allows designers and engineers to:

- Reduce the need for costly shop floor trials and redesign of tooling and processes.
- Improve tool and die design to reduce production and material costs.
- Shorten lead time in bringing a new product to market.

Among the vast range of capabilities some capabilities of the DEFORM tool are as follows:

- Coupled modeling of deformation and heat transfer for simulation of Cold, Warm and hot forming processes.
- Extensive material database for many common alloys
- Contour plots of temperature, strain, stress, damage etc.
- Self-contact boundary conditions with robust remeshing allows a simulation to continue to completion even after a lap or fold is formed.

The DEFORM system uses time dependent non-linear problems by generating a series of FEM solutions at discrete time increments (in step control section). At each time increment, the velocities, temperatures, and other key variables of each node in the finite element mesh are determined based on boundary conditions, thermo mechanical properties of the work piece materials and possibly solutions at previous steps.

The two basic formulations used in finite element technique are Eulerian and Lagrangian. In Eulerian formulation, the domain is fixed region in space (called control volume). However, in a Lagrangian formulation the domain consists of a set of material particles that changes its shape continuously with the deformation. The updated Lagrangian formulation is an incremental method in which the domain is updated incrementally. Further, the measure of deformation used in Eulerian formulation is the rate of deformation tensor and the constitutive equation is expressed in terms of the stress and rate of deformation tensors. On the other hand, in Updated Lagrangian formulation, the measure of deformation is an incremental stress and incremental strain tensors. Like that of Eulerian formulation, the governing equations of the updated Lagrangian formulation also are non- linear and need an iterative scheme to obtain a solution.

3.5.1.1.Finite element formulation

This study applies commercial finite element code DEFORM-3D to simulate the plastic deformation behavior during the multi-hole extrusion process.

The basic equations of the rigid-plastic finite element are as follows:

Equilibrium equation:

$$\sigma_{ij,j} = 0 \quad (8)$$

Compatibility and incompatibility equations

$$\dot{\epsilon}_{ij} = \frac{1}{2}(u_{ij} + u_{ji}) \quad (9)$$

$$\dot{\epsilon}_v = u_{ij} = 0 \quad (10)$$

Constitutive equations:

$$\sigma'_{ij} = \frac{2\bar{\sigma}}{2\bar{\epsilon}} \dot{\epsilon}_{ij}, \bar{\sigma} = \sqrt{\frac{3}{2} \dot{\sigma}_{ij} \dot{\sigma}_{ij}}, = \sqrt{\frac{3}{2} (\dot{\epsilon}_{ij} \dot{\epsilon}_{ij})} \quad (11)$$

Boundary conditions:

$$\sigma_{ij} n_i = F_j \text{ on } S_F, u_i = U_i \text{ on } S_U \quad (12)$$

Where σ_{ij} and $\dot{\epsilon}_{ij}$ are the stress and the strain rate, respectively, $\bar{\sigma}$ and $\bar{\epsilon}$ are the effective stress and the effective strain rate, respectively, F_j is the force on the boundary surface of S_F , and U_i is the deformation velocity on the boundary surface of S_U . The weak form of rigid-plastic FEM can be determined by applying the variational method to Eqs. (8-12), i.e.

$$\int_V \bar{\sigma} \delta \bar{\epsilon} dv + K \int \epsilon_v \delta \epsilon_v dV - \int_{S_F} F_i \delta u_i dS = 0 \quad (13)$$

Where V and S are the volume and the surface area of the material, respectively, and K is the penalty constant. The most important and crucial part of simulation in software is the selection of appropriate material model. DEFORM-3D contains various material models (for elastic-plastic, rigid-plastic and porous material), and each model has different suitability, so selection of correct material model as per the requirement is the prime necessity to get the accurate results.

Most of the material models require detailed material properties such as young's modulus of elasticity, strain hardening exponent, and strength coefficient, etc., as input to preprocessor before running the solver. In addition to material properties, preprocessor also require input of detailed process parameters such as friction coefficient, extrusion wheel velocity, heat transfer coefficients etc. Yielding criteria which is used for solving of problem is Von Mises (in the Deform 3D). Eqs. (14) and (15) show effective strain and effective stress respectively.

$$\bar{\epsilon} = \frac{\sqrt{2}}{3} \sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2} \quad (14)$$

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (15)$$

Where ε_i and σ_i are principle strain and principle stress in direction i respectively.

3.5.1.2. Simulation procedure

For carrying out a continuous extrusion process simulation, first it needs to represent the metal forming system to be simulated in its detailed geometry content, i.e., to create the computer models of the deformation system and the metal forming process.

The work piece has been meshed with tetrahedral mesh elements in the continuous extrusion process simulations. Sparse FE solver and Newton-Raphson iteration method has been used to the elastic-plastic material as a work piece. Deformation and thermal boundary condition have been added in the simulation.

Sparse solver package, in conjunction with several finite element strategies, has been used for the numerical simulation like deformation of Rigid Visco-Plastic materials. Some of the features of the solver are: It is able to deal with large systems of equations arising from finite element problems, takes into account the structural symmetry of the finite element matrices, It is able to reproduce fractional –step schemes blue at the solver level, the computational cost increases close to linearly with the number of unknowns, the parallelization of the code is under development.

Assumptions made during simulations of Continuous Extrusion process are as follows:

- a. Work piece material is assumed to be Rigid Visco-Plastic materials
- b. Due to the nature of work piece to be Rigid Visco-Plastic materials coulomb friction coefficient has been used.
- c. No sticking friction condition is assumed.

Pre –Processor includes simulation control which can control the numerical behavior of the simulation. Main controls deal with specifying the simulation title, unit system, geometry type, etc.

Stopping and step controls are used to specify the time step, the total number of steps and criteria used to terminate the simulation. Processing conditions like the environment temperature, convection coefficient can be specified under processing conditions.

The DEFORM system uses time dependent non-linear problems by generating a series of FEM solutions at discrete time increments (in step control section). At each time increment, the

velocities, temperatures, and other key variables of each node in the finite element mesh are determined based on boundary conditions, thermo mechanical properties of the work piece materials and possibly solutions at previous steps. The iteration controls specify criteria for the FEM solver which uses to find a solution at each step of the problem simulation. For most of the problems, the default values should be acceptable. The sparse solver is a direct solution that makes use of the sparseness of FEM formulation to improve the solution speed. The conjugate-gradient solver tries to solve the FEM problem by iteratively by approximating to the solution. For certain problems, this solver offers tremendous advantages over the sparse solver.

An iteration method is the manner in which the simulation solution is updated (or iterated upon) to try to approach the converged step solution. The Newton –Raphson method is recommended for most problems because it generally converges in less iteration than the other available methods. However, solutions are more likely to fail to converge with this method than with other methods.

The Direct method is more likely to converge than Newton-Raphson, but will generally require more iteration to do so. In the case of porous materials, the direct method is the only method currently available. Recommended solver for general forming with Rigid Visco-Plastic materials objects is Sparse FE solver.

The sparse solver is a direct solution that makes use of the sparseness of FEM formulation to solve for the temperature and heat transfer problems. Currently, this is the only solver available for solving thermal problems.

Computer aided engineering (CAE) simulation procedure

Figure 3.7 shows the general procedure of proposed CAE process. To conduct CAE simulation, it is first to be represented in detail i.e., in geometry content, and therefore, a CAD model in a suitable format is made for the metal forming simulation systems. The CAE engineers need to create the simulation test models for a given deformation system. The physical model idealizes the real engineering problems and abstracts to comply with certain physical theory with assumptions.

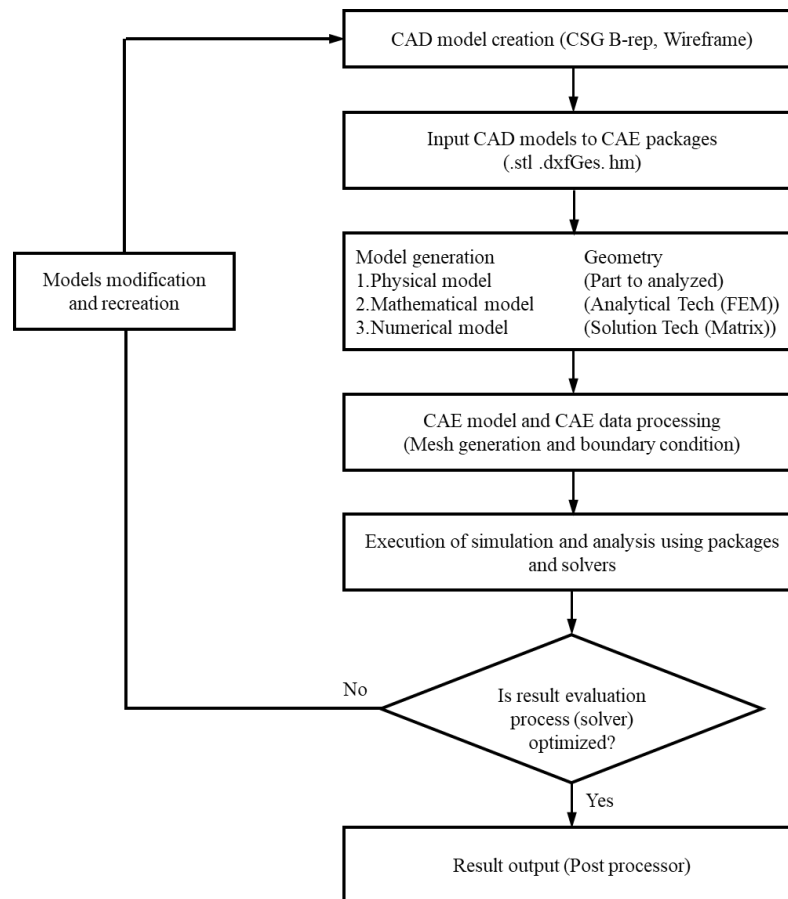


Figure 3.7 General procedure of CAE process

The mathematical model specifies the mathematical equations such as the differential equations on FEM analysis along with detailed boundary and initial conditions and their constraints. The numerical model describes the element type, mesh density and solution parameters. Usually, most CAE packages have part of built-in content of these models, but users still need to prepare and input most of the model information into a CAE system.

The CAE simulation process consists of four main steps (1) pre-processing (2) simulation engine (3) post processing and (4) result analysis and evaluation. After the simulation, the calculated results need to be analyzed and evaluated. If the results and solutions are satisfactory the suggested changes and modifications for the metal forming system (part design, tooling design, process configuration and material selection) can be made for next round of simulation. The process is therefore, iterative in nature (Fu et al., 2007).

The integrated numerical simulation of continuous extrusion process, including metal forming process and tooling deformation provides a systematic approach for simultaneously modeling of mechanical deformation behaviors, metallurgical phenomena and thermal phenomenon of the metal forming processes. Besides, the interaction and interplay of these

physical behaviors and phenomena, their interaction to each other are also taken into consideration. On the other hand, the simulation and analysis of tooling deformation and stress strain distribution during the process can be conducted simultaneously along with the simulation.

I. Details of simulation steps

The FEM package DEFORM-3D is used to simulate multi-hole extrusion process of AA 6063 aluminium alloy. The finite element result is used to investigate the damage, displacement, ram force, and exit temperature under various process parameters conditions.

The simulation process consists of following five steps:

1. Initial geometry- In this step CAD model of the work piece, extrusion wheel, coining wheel, extrusion shoe, abutment and die as .stl file is imported into the pre-processor of the simulation package (DEFORM-3D).
2. Material data and Meshing- In this step, already existing file material and their material properties are assigned to previously imported products. Also, there is a provision for defining new raw materials. The material properties available from the literature can be imported easily in this step. Meshing can be done with the use of tetrahedral elements.
3. Defining the boundary conditions-Different types of boundary conditions such as velocity of extrusion and coining wheel. Coefficient of friction between extrusion wheel and coining wheel and temperature of the work piece are applied. Several possible combinations of these boundary conditions are tested to get the best possible results. Finally, a data base file (.db) is generated. This file is run in the simulation engine.
4. Simulation engine-Performs the numerical analysis and writes the information in the data base file.
5. Post-processing-this is used to extract the information from data base file. In this step different types of defects, load requirement and torque required for extrusion are studied. Effective stress, effective strain, velocity distribution and damage distribution are also found. This step gives the modifications required in geometry or boundary conditions to obtain the optimum result.

As per Table 3.2 the dimension was considered for geometries of billet, ram and the bottom die at different number of holes were produced in Solidworks 2019 which are displayed in Figure 3.8 (a), (b), and (c). Then the inception temperatures and mesh size of both die's and billet are set from Table 3.2, and the billet was taken as plastic in a circular form and the

properties of materials were assigned as per the material model. According to (Jajimoggala et al., 2019) the heat transfer coefficient between billet and tool was set as 11 N/smm°C. The parameters and remaining boundary conditions required for present simulations were executed according to Table 3.2.

Table 3.2 Component description and boundary conditions

Components	Size	Boundary conditions
Billet	40mm dia, 50mm length	Pre heat temperature (400, 450, and 500) °C Meshing type Tetrahedral ^(a)
Container	50mm outside dia, 40mm inside dia, 60mm length	Pre heat temperature 250°C. Heat transfer coefficient 11 N/s.mm.°C. Coefficient of friction 0.1
Ram	40mm dia, 60mm length	Pre heat temperature 250°C. Ram speed (6, 7 and 8) mm/sec Heat transfer coefficient 11 N/s.mm.°C. Coefficient of friction 0.1.
Bottom die	50mm outside dia, 40mm inside dia, 9mm length 2-holes, 3-holes and 4-holes with an equal hole diameter of 5mm	Pre heat temperature 250°C. Heat transfer coefficient 11 N/s.mm.°C. Coefficient of friction 0.1.

^(a)Tetrahedron elements, easy to discrete an object with an irregular shape, were assigned to the workpiece (Zhou et al., 2009).

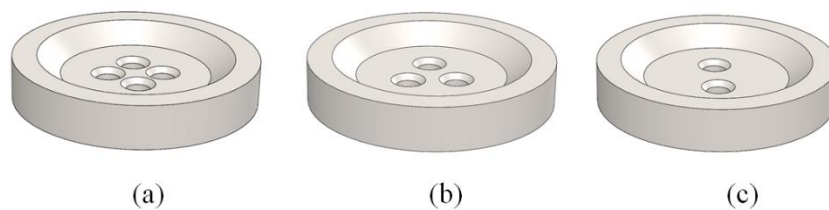


Figure 3.8 CAD model of dies. (a) 4-hole die, (b) 3-hole die (c) 2-hole die.

To save calculation time and data storage space, the mesh density distributions of the work piece and die were optimized. In the areas near the die bearing, finer meshes were assigned, while coarser meshes were placed in the other areas. Thus, varied mesh densities were distributed throughout the workpiece in accordance with the extent of local deformation. Mesh density windows were defined to determine mesh sizes, when the DEFORM 3D software remeshed the workpiece automatically. The meshed billet, die and other extrusion tooling are shown in Figure 3.9.

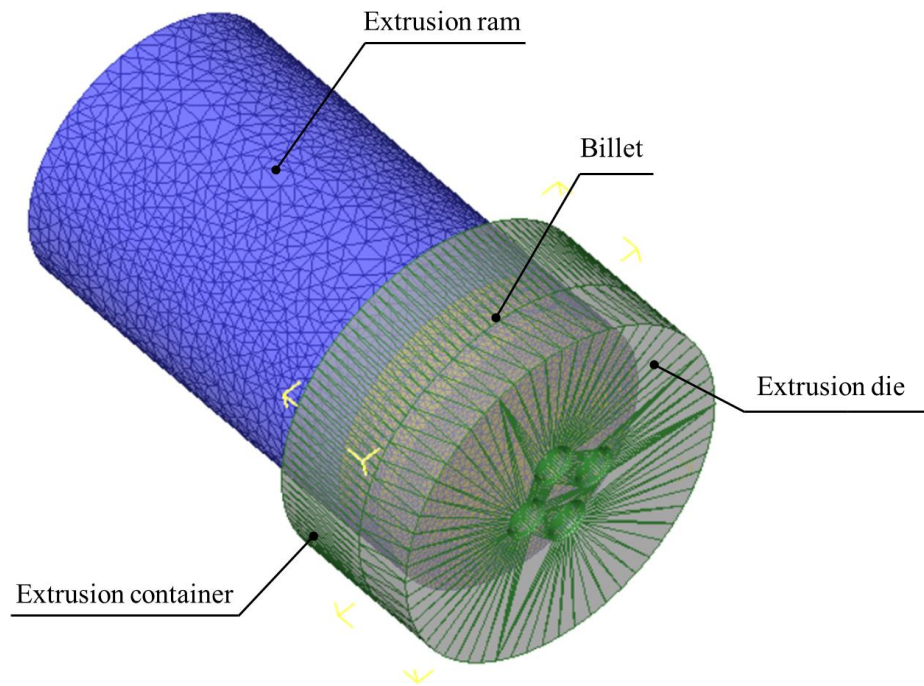


Figure 3.9 Geometry models and meshes of the billet, die and other extrusion tooling.

Figure 3.10 describes the meshed model of billet and both dies. Accurate simulations can be procured by proper generation of mesh. The material deformation usually managed by the proper reformulation of mesh at every single time on the steps.

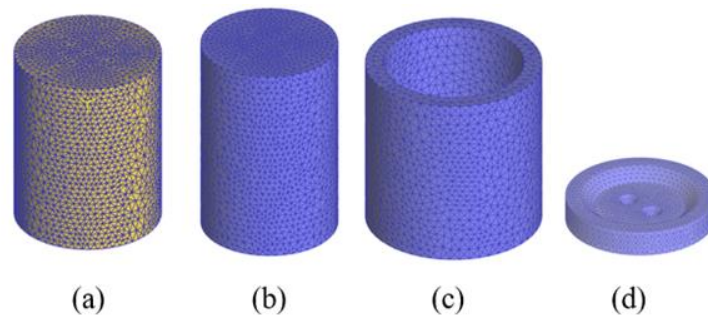


Figure 3.10 Meshed model of (a) billet (b) ram (c) container (d) 2-hole die

The schematic demonstration for the extrusion setup was implemented to carry simulation after the billet got integrated with die as shown in Figure 3.11.

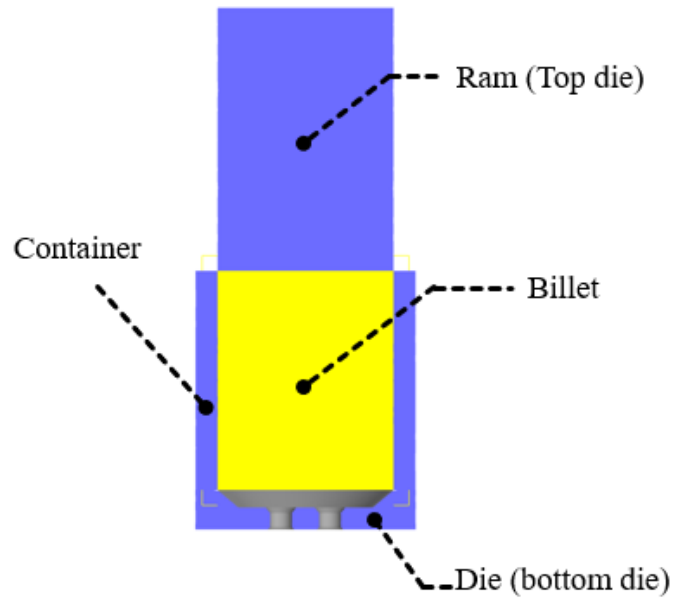


Figure 3.11 Schematic of extrusion process setup.

Material models

The most common aluminium alloy for extruded products, AA6063, was used as the billet material in the present FEM simulations.

A deep understanding of hot deformation behavior of a material plays a crucial role in determining process parameters and designing extrusion dies during the extrusion process of the aluminum alloy profiles (Dong et al., 2016).

Flow stress is defined as the instantaneous value of stress required to continue plastically deforming the material to keep the metal flowing. The flow stress for a given material in continuum mechanics is dependent upon the temperature, true strain, and strain rate, Therefore, it can be written as a function of those parameters:

$$\bar{\sigma} = f(\epsilon, \dot{\epsilon}, T) \quad (16)$$

In bulk metal forming process the flow stress value and calculation will have a great influence on the process of the operation.

A recent study on hot deformation behavior and processing map of AA6063 aluminium alloy (Wang et al., 2019) established the constitutive equation of AA6063 aluminium alloy based on the Arrhenius hyperbolic sine function as follow:

$$\dot{\epsilon} = 8.99 \times 10^{13} [\sinh(0.01499\sigma)]^{7.28391} \times \exp\left(\frac{261848}{8.314T}\right) \quad (17)$$

Where $\dot{\epsilon}$ is strain rate of AA6063 aluminium alloy billet, σ flow stress, and T is temperature in K.

3.5.2. Process parameter selections

Temperature

Billet pre-heating temperature, container temperature and ram speed are the most influencing parameters during extrusion of aluminium alloys to obtain defect free and high quality of product with improved efficiency of the extrusion process. Homogenization of billet by pre-heating is an essential part of hot extrusion to reduce the geometrical deviation during extrusion process. High extrusion temperature leads to increase in ductility of the alloy to reduce the force required for extrusion, whereas low extrusion temperature helps to achieve good geometrical tolerances. Therefore, there is a need to obtain an optimum heating temperature to achieve geometry as well as reduced force. (Inamdar & Chahare, 2017)

Billet temperature

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.

AA6063 Aluminium alloy is one of the representative aluminium alloys. This alloy has an attractive combination of characteristics such as high specific strength, high corrosion resistance and easy workability, which make it an ideal choice for structural applications. It is well known that plastic deformation conditions, such as temperature, have an important influence on the deformation behavior of AA6063 alloy. Therefore, it is of vital importance to thoroughly study the high temperature deformation behavior of AA6063 alloy for the purpose of the deformation parameter optimization. The temperature at which extrusion is performed depends on the material being extruded. Table 3.3 Shows billet temperatures for hot extrusion of different materials.

Table 3.3 Typical billet temperatures for hot extrusion (Park, 2005)

Materials	Billet temperature °C
Lead alloys	90-260
Magnesium alloys	340-430
Aluminium alloys	340-510
Copper alloys	650-1100
Titanium alloys	870-1040
Nickel alloys	1100-1260

Ram speed

Ram speed is another major contributing factor required to achieve high production rate. High ram speed reduces the contact area leading to reduction in friction between the die and the billet and ultimately reducing the temperature variation due to friction. Thus, uniform temperature reduces the defects in the final product. On the other hand, low ram speed increases the time of contact and thus leading to temperature variation along the cross-section of the extruded profile. Therefore, optimum ram speed is to be achieved. (Inamdar & Chahare, 2017)

3.5.2.1. Selection of hot extrusion process parameters

Developing optimum process parameters was the major step of producing quality product. So selection of process parameters acts/acted as salient role. Usually in an extrusion process, ram speed, extrusion temperature, billet diameter and extrusion ratio) were critical and basic process parameters that have great control on the product efficiency, the die life time and energy consumption etc. (Jajimoggala et al., 2019). Therefore, this study will investigate the process performance capability of multi-hole extrusion process on AA6063 alloys, which optimizes the parameter of ram speed, number of holes, and extrusion temperature.

From an extensive review of literatures an assumptions have been taken and the variant levels of parameters are selected which are displayed in Table 3.4. The effect of these process

parameters on damage, ram load, exit temperature and, displacement is studied. According to pilot experiments, processing control parameters ranges is considered.

Table 3.4 Process parameters and their levels

Process parameters	Level 1	Level 2	Level 3
Number of holes (A)	2	3	4
Ram speed (mm/s) (B)	6	7	8
Extrusion temperature (°C) (C)	400	450	500

3.6. Experimental design

3.6.1. Taguchi method

Taguchi's methods are the one which was extensively used methods to resolve the optimization difficulties which are influenced by multiple variables of multiple objectives. In this method, designing the parameter is the main phase, which was employed to acquire the process parameters of optimal levels for generating the quality characteristics. It hires an orthogonal array (OA) which was used for learning the entire process parameters spacing with least experiments only. Based on Taguchi's OA, experiments that lead in increasing of cost and time will maximum reduced.

In the construction of DOE by the technique of Taguchi, a special OA was used in elucidating the problems created during the study of numerous processing control parameters in an experiment. In the process of hot extrusion AA6063, the three process parameters were chosen, namely, (A) number of holes, (B) ram speed and (C) extrusion temperature. L_{27} OA was taken and the 27 experimental procedures were directed from the combinations specified in the Table 3.5. This table shows only the particular level of the variant process parameters at which experimental pilot was conducted.

Table 3.5 Experimental Taguchi's L₂₇ (OA)

Exp.Run	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)	Exp.Run	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)	Exp.Run	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)
1	2	6	400	10	3	6	400	19	4	6	400
2	2	6	450	11	3	6	450	20	4	6	450
3	2	6	500	12	3	6	500	21	4	6	500
4	2	7	400	13	3	7	400	22	4	7	400
5	2	7	450	14	3	7	450	23	4	7	450
6	2	7	500	15	3	7	500	24	4	7	500
7	2	8	400	16	3	8	400	25	4	8	400
8	2	8	450	17	3	8	450	26	4	8	450
9	2	8	500	18	3	8	500	27	4	8	500

Column 1 represents experiments in serial order wise. Columns A-C represents various parameters of levels according to OA. This table does not state any observed data. Design parameter in the technique of Taguchi would transform the objective responses into a S/N numerical ratio, which is the evaluation index of the quality feature. In this method, the word 'signal' was mentioned as (mean) desirable effect and the word 'noise' was mentioned as (signal disturbance) or undesirable effect of output feature. Least variation as well as optimal design was drawn from S/N ratio, which includes lower-the-better, higher-the- better and nominal-the-better.

- Lower the better

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (18)$$

- Higher the better

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (19)$$

Where, 'y_i' represents the value of calculate response for ith, 'n' represents the total number of trail runs and 's' represents standard deviation. S/N ratio values of extrusion load, temperature, displacement and damage are computed through the equation 18, 19 and reported in Table 4.2.

The determined values of S/N were being used in next calculations that are the grey relation coefficients (GRC). The method of Taguchi was used for optimizing single independent-objective function not for multiple responses complication. The theory of Grey concept was stated by Julong (Julong, 1989). From the survey of literature, it was appeared that the GRA was the more desirable approach in order to optimize multiple responses in the different fields

(Lal et al., 2015; Md Israr & Rajkumar, 2016). So, it was needful for identifying optimal level of factors which simultaneously maximize the displacement and minimize the extrusion load, exit temperature and damage value. To get desired objective, four responses were reformed into single-responses that is GRG using the procedure explained in below section.

3.6.2. Gray rational analysis

GRA was an enhanced methodology for discriminating and scrutinizing critical system factors and is helpful for variable independence analysis. Rather than performing a trail to search out the proper solution, grey analysis provides techniques for determinative an honest solution, that is, an acceptable solution for the problems of the world. In operating grey relational creation, normalization is done first for experimental data starting from 0 to 1.

Grey relational creation expresses the alteration between an ideal value and an experimental value. For GRA there were exists 3 types for optimization such as 'Higher the better', 'nominal the better' and 'Lower the better'. In the current work, 'Lower the better' for extrusion load, exit temperature, damage and 'Higher the better' for displacement are taken for better extrusion achievement. The normalized value of exit temperature, extrusion load, displacement and damage are computed by the equation 20 and 21, the data also exhibited in Table 4.6.

- Lower the better

$$X_{ij} = \frac{\max Y_{ij} - Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \quad (20)$$

- Higher the better

$$X_{ij} = \frac{Y_{ij} - \max Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \quad (21)$$

The GRC (ξ_{ij}) was calculated to describe the connection between reference and experimental (actual) normalized data. The GRC are often determined as follows

- Minimization

$$\xi_{ij}(k) = \frac{\Delta_{\min} - \xi \Delta_{\max}}{\Delta_{ij} - \xi \Delta_{\max}} \quad (22)$$

Where $\Delta_{ij} = |X_{oi} - X_{ij}|$

- Maximization

$$\xi_{ij}(k) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{ij} + \xi \Delta_{max}} \quad (23)$$

Where $\Delta_{ij} = |X_{ij}|$

Where, X_{oj} are the best data or the reference data, Δ_{max} exhibit the value for maximum of Δ_{ij} , Δ_{min} exhibits for minimum of Δ_{ij} and ξ_{ij} was the recognition or (distinguishing) coefficient and their values were laid in between zero to one. Generally, the distinguishing coefficient or (identification coefficient) are assumed at 0.5 to fit the practical necessities. The data in Table 4.2 do not require any units because it only represents the evaluated values of S/N ratio, values of normalization and the GRCs for extrusion load, damage and displacement. After analyzing the GRC, the GRG is computed from the equation (24) to find single GRG by determining the average of overall GRC related to every single individual response characteristic. For 'ith' experiment the γ_i was assessed as follows.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_{ij}(k) \quad (24)$$

Where, (γ_i) exhibits the GRG, 'n' exhibits number of response characteristics. The resultant values of GRG were scrutinized for the response characteristic extrusion load, exit temperature, displacement and the damage.

3.7. Methodology for experimental investigation

In this section the methodology for sample preparation and characterization is presented. For sample preparation from process identification to finishing.

3.7.1. Extrusion component fabrication

The task for fabrication of extrusion component is given to Ethiopian engineering group (EEG) formerly name Hibret machining and machine building industry. Figure 3.12 depicted that the procedural order of die manufacturing sequences during fabrication of dies. The information that helps the manufacturer to fabricate the extrusion components is listed and given as a procedural guide. These lists are as follow:

- The process that the component used for
- Geometrical layout of each components
- Measurements

- Materials for each component
- Desirable mechanical properties

The manufacturing industry gathers all the information about the tools including the 2D and 3D drawings.

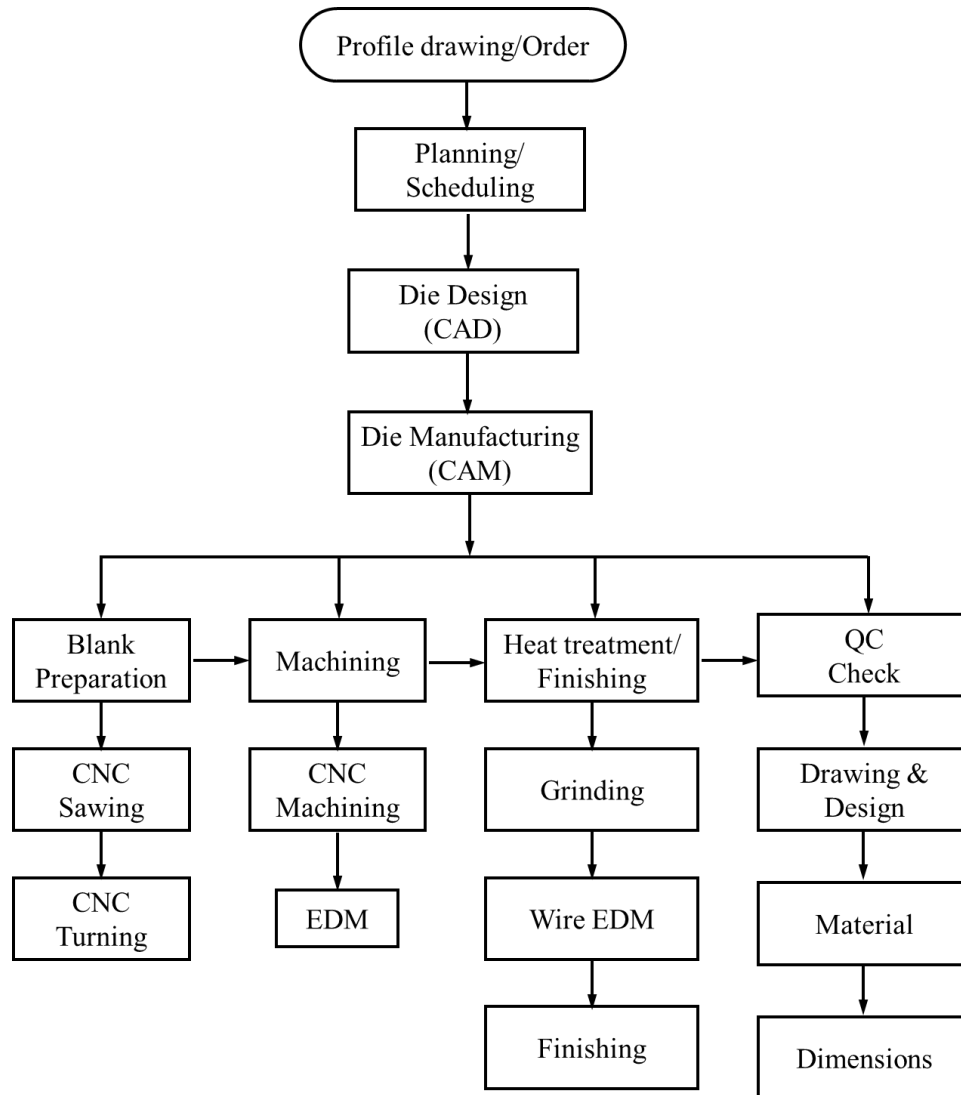


Figure 3.12 Die manufacturing steps and processes (Tyrer & Waheed, 2006)

3.7.2. Sample preparation

Due to sensitivity of extrusion process parameters and difficulty of extrusion setup arrangement the sample preparation takes a longer period of time to accomplish.

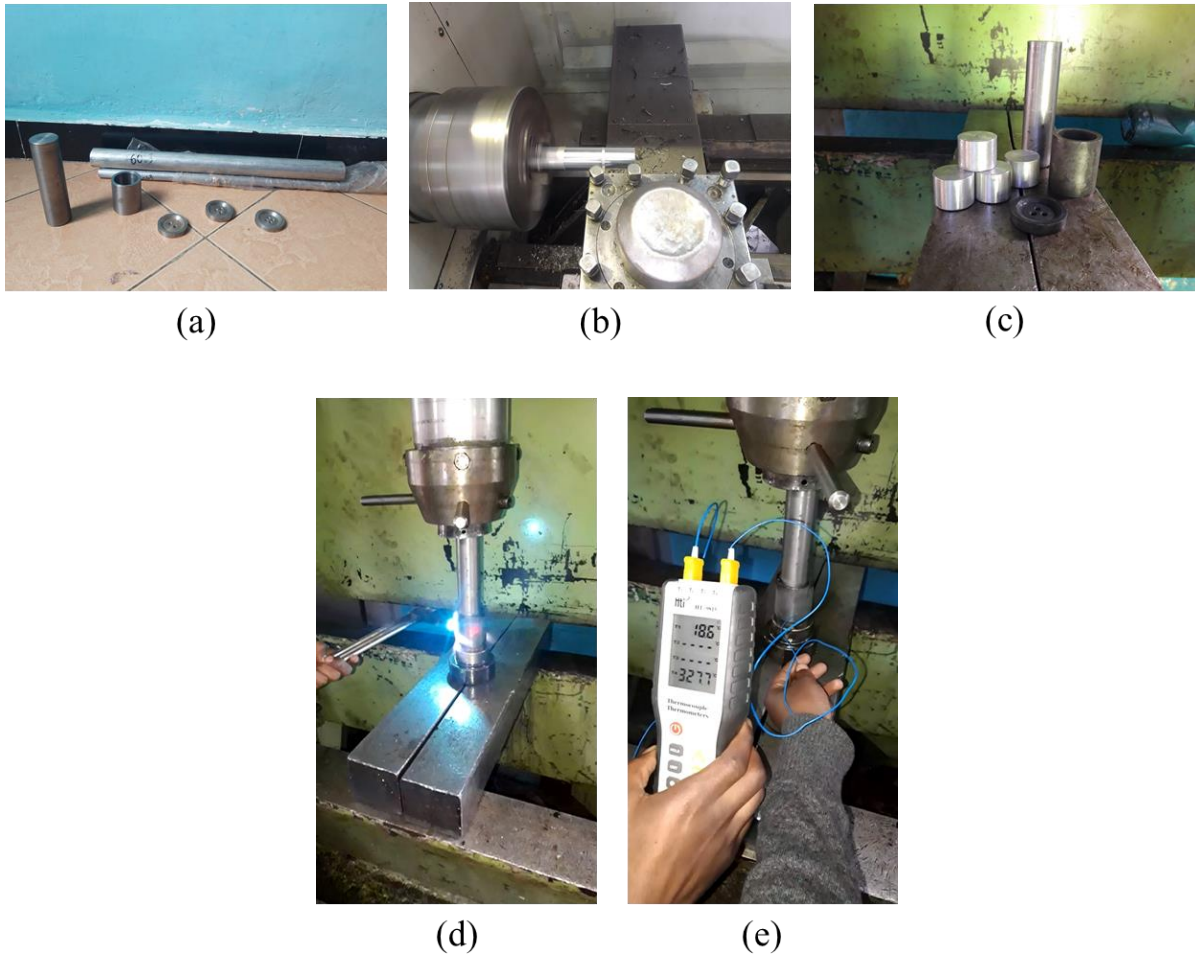


Figure 3.13 Series of processes during extrusion sample preparation (a-e).

Figure 3.13 Shows the series of steps that this study follows for sample preparations. The raw material and extrusion components are prepared first Figure 3.13(a) then billet preparation procced. 40mm dia, 40mm height billets are turned and parted from the long pre-casted AA6063 bar Figure 3.13 (b and c). The extrusion components and raw materials used for this investigation also presented in Figure 3.14.



Figure 3.14 Raw materials and extrusion components.

This calibration is performed using a thermocouple measurement, the thermocouple used in this study was a K-type four channel thermocouple. K-type thermocouple specifications Figure 3.15 shows the thermocouple used for this study:

- Serial number: HT-9815.
- Temperature range: 0-800 °C.
- Power supply: 9V.
- Weight: approx: 250g.



Figure 3.15 Thermocouple

In this study, direct hot extrusion process is used for sample preparation. The extrusion process performed on AA6063 aluminium alloy using a 150-ton Hursan hydraulic press see Figure 3.16, which is accessible at Ethiopian engineering group (formerly known as Hibret manufacturing and machine building industry).

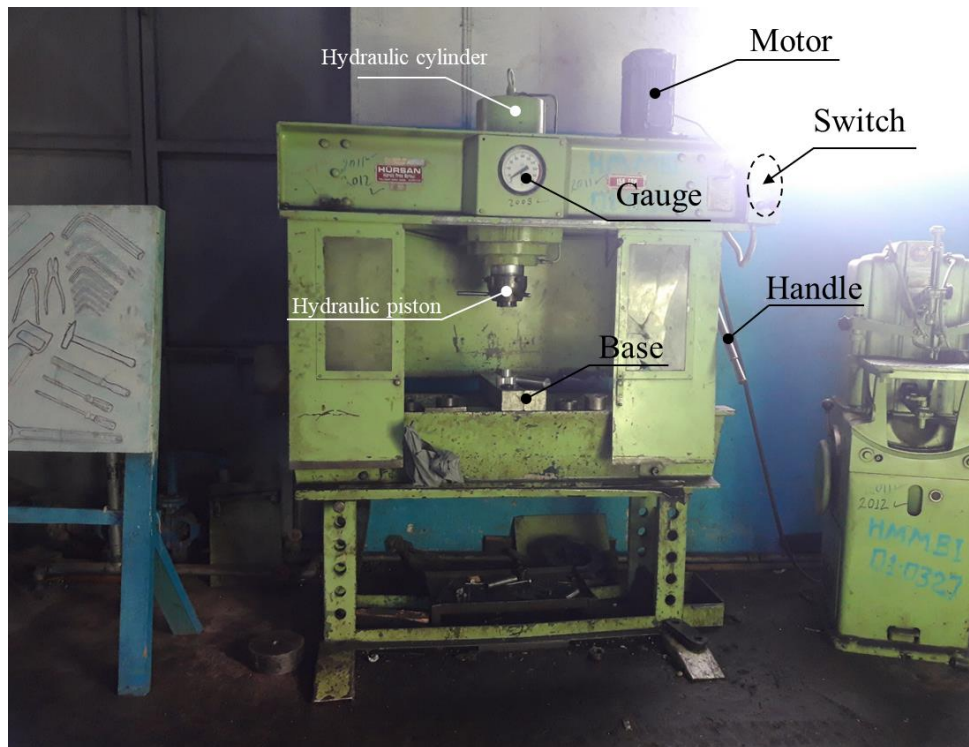


Figure 3.16 HUSAN 150 Ton hydraulic press (EEG bolt and nut workshop).

Figure 3.16 shows Hursan hydraulic press which is ready for extrusion making process. Then by making extrusion arrangements on the Husan hydraulic press heat is given using oxy-Acetylene, until the required temperature is achieved Figure 3.13 (d and e).

The ram speed is arranged according the oil pump to the cylinder of Hursan hydraulic press using the lever of the press illustrated in Figure 3.17, i.e., more oil supply to the cylinder means more speed and vise versa. Then the optimum oil supply for specific speed is known and using the lever of the press the extrusion process is performed.

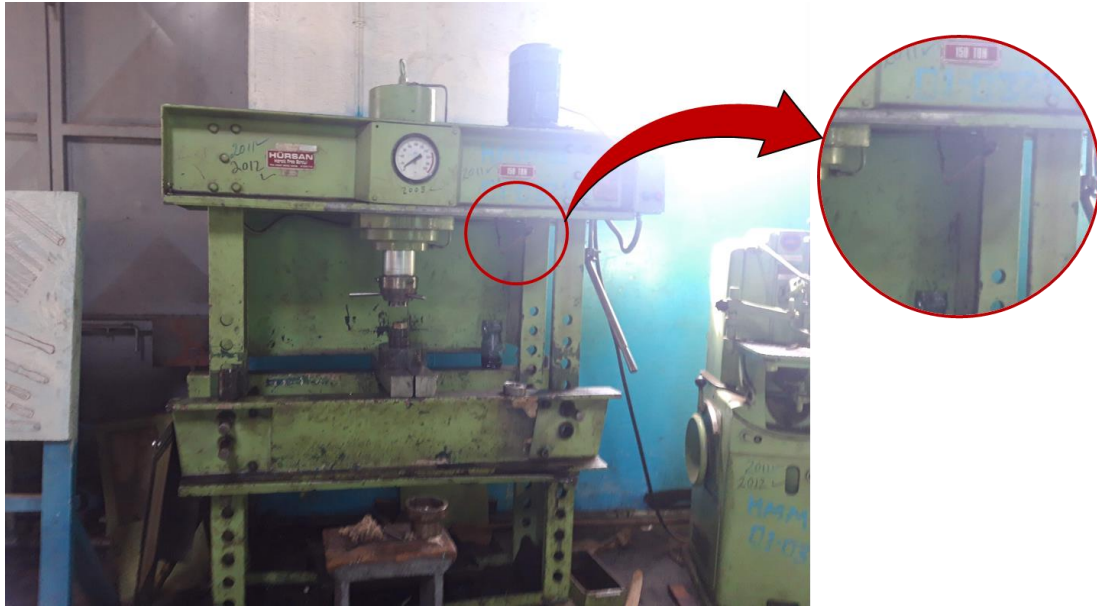


Figure 3.17 Detail of lever in Hursan hydraulic press.

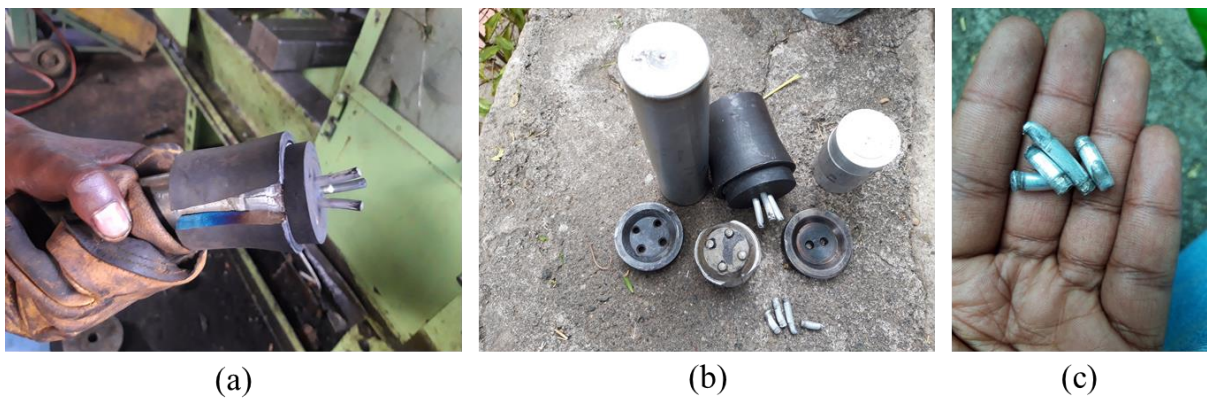


Figure 3.18 Samples and extrusion components after extrusion process (a, b and c).

Finally, the required 4-hole and 3-hole die extrusion is performed as shown in Figure 3.18 (a, b and c). Some of the extrusion components are damaged and deformed due to excess load and temperature effects.

3.7.3. Testing and characterization

The mechanical tests are usually performed on samples taken from the back end of an extrusion, although sometimes samples are collected from three different positions to establish any variation of properties along the length of the extrusion (i.e., front end, middle, and back, or butt end). Generally, with AA6063 architectural and decorative shapes, hardness is the only qualifying test used by most extrusion manufacturers. Since the objective of this study is enhancing the capability of extrusion process, microstructural analysis also performed.

Hardness test

Hardness is the properties of material that allows to resist a plastic deformation, usually measured by penetration. All hardness tests contain the use of a specifically shaped indenter, significantly harder than the test sample. This indenter is pressed into the external surface of the sample using a specific force. Either the size or depth of the indent is measured to determinate a hardness value. Hardness measurements were extensively used for the superiority control of materials because they are rapid and considered to be non-destructive tests when the marks or indentations produced by the test are in low stress areas. There are many methods to determine the hardness, among those Brinell, Vickers and Rockwell hardness tests are frequently used. In this experiment Vickers hardness test was used to measure the sample extrudate qualities. Vickers hardness test was measured to determine the hardness of a material, calculated from the size of an impress produces under load by a pyramid shaped diamond indenter. The diamond was pressed on the surface of material at measuring range up to approximately 50kgf (kilogram force) and the size of the impression was measured with the help of a calibrated microscope. The Vickers hardness number (HV) was calculated using the following formula:

$$HV = Constant * \frac{Test\ force}{Surface\ area\ of\ indentation} \quad (25)$$

$$HV = 0.102 * \frac{F}{A} \quad (26)$$

$$= 0.102 * \left(\frac{F}{\left(\frac{d^2}{2 * \sin \frac{136^\circ}{2}} \right)} \right) \quad (27)$$

$$= 1.8544 * \frac{F}{d^2} \left(\frac{kgf}{mm^2} \right) \quad (28)$$

Where F is in kgf and d is in millimeters.

The corresponding unit of HV is then the kilogram-force per square millimeter (kgf/mm²) or HV number. In the above equation, F could be in N and d in mm, giving HV in the SI unit of MPa. To calculate Vickers hardness number (VHN) using SI units one needs to convert the

force applied from newtons to kilogram-force by dividing by 9.806 65 (standard gravity). This leads to the following equation:

$$HV = 0.1891 * \frac{F}{d^2} \left(\frac{kgf}{mm^2} \right) \quad (29)$$

Where F is in N and d is in millimeters. A common error is that the above formula to calculate the HV number does not result in a number with the unit Newton per square millimeter (N/mm²), but results directly in the Vickers hardness number (usually given without units).

Morphological analysis

Generally, the mechanical properties of a material are closely related to its microstructure, and the material strength increases with decreasing grain size, according to the Hall–Petch relationship (Hall, 1951). For this reason, this study investigates the morphology of samples which are extruded through multi-hole extrusion process and billet materials by using scanning electron microscope (SEM) analysis.

A scanning electron microscope (SEM) is a type of electron microscope that produce images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms that contain information about the surface topology and composition of the sample. SEM with closed sample chamber is shown in Figure 3.19.



Figure 3.19 The SEM setup (ASTU, Collage of natural science)

For conventional imaging in the SEM, specimen must be electrically conductive, at least at the surface, and electrically grounded to prevent the accumulation of electrostatic charge. Metal objects require little special preparation for SEM except for cleaning and conductively mounted to a specimen stub. Magnification ranges from 10 to 3,000,000 times. Figure 3.20 shows AA6063 aluminium alloy at 500x magnification.

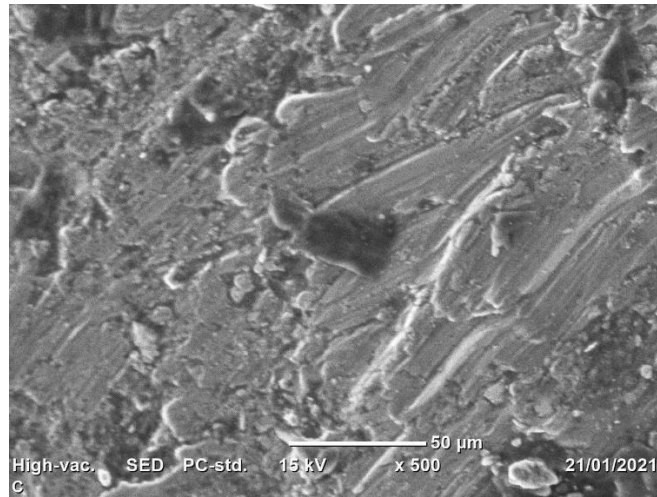


Figure 3.20 Microstructure of AA6063 aluminium alloy at 500x magnification.

Chapter Four

4. Results and Discussion

4.1. Introduction

This chapter presents the results obtained from the numerical and experimental investigation of the multi-hole extrusion process parametric optimization for AA6063 alloy. The first section presents the results of numerical analysis of multi-hole extrusion parameters using finite element-based metal forming software i.e., DEFORM 3D. The next section presents the process parametric optimization of simulation and experimental investigations. Finally, material testing and characterizations have been presented and discussed.

4.2. Numerical investigation

4.3. Numerical analysis of ram damage, displacement and ram force

Simulation was performed as the number of trial experiments (Exp. runs) which were performed using the technique of Taguchi L_{27} OA as shown in Table 4.1. The DOE consisted of 27 combinations of 3 process parameters at three discrete levels, the simulations were procured from DEFORMTM-3D software and their results are disclosed in Table 4.1.

Table 4.1 Simulation results for damage, total displacement, and ram force

Exp.Run	Factorial design			Responses		
	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)	Damage	Displacement (mm)	Ram force (KN)
1	2	6	400	1.42	52.4	1408.9
2	2	6	450	1.33	53.2	1317.2
3	2	6	500	1.15	53.6	1180.8
4	2	7	400	0.8	45.3	1351.5
5	2	7	450	1.08	47	1262
6	2	7	500	1.22	48.9	1220.1
7	2	8	400	1.31	50.8	1325
8	2	8	450	1.5	47.7	1237
9	2	8	500	1.76	53.3	1228.6
10	3	6	400	1.25	50.5	1334.5
11	3	6	450	1.15	40.5	2226.1
12	3	6	500	1.69	51	1230.2

13	3	7	400	1.38	45.9	1323
14	3	7	450	1.47	51	1231.4
15	3	7	500	1.37	49.6	1182.7
16	3	8	400	1.21	46.7	1334.6
17	3	8	450	0.9	45.6	1219.7
18	3	8	500	0.93	50	1165.9
19	4	6	400	0.9	47.3	1236.6
20	4	6	450	0.97	50.7	1172.7
21	4	6	500	1.01	47.2	1142.4
22	4	7	400	0.97	44.4	1226.4
23	4	7	450	1.15	49.2	1162.4
24	4	7	500	0.69	45.3	1082.1
25	4	8	400	0.81	49.6	1188.4
26	4	8	450	0.72	49.7	1143
27	4	8	500	0.77	47.3	1084.8

Material flow

Figure 4.1 (a-e) shows a series of steps that the billet material takes from entering the pocket to emerging from the die, along with ram displacement. It clearly shows how metal flows through the pocket in front of the die orifices (4 number of holes in this investigation). Figure 4.1b shows that the billet is upset in the container and about to flow into the bearing.

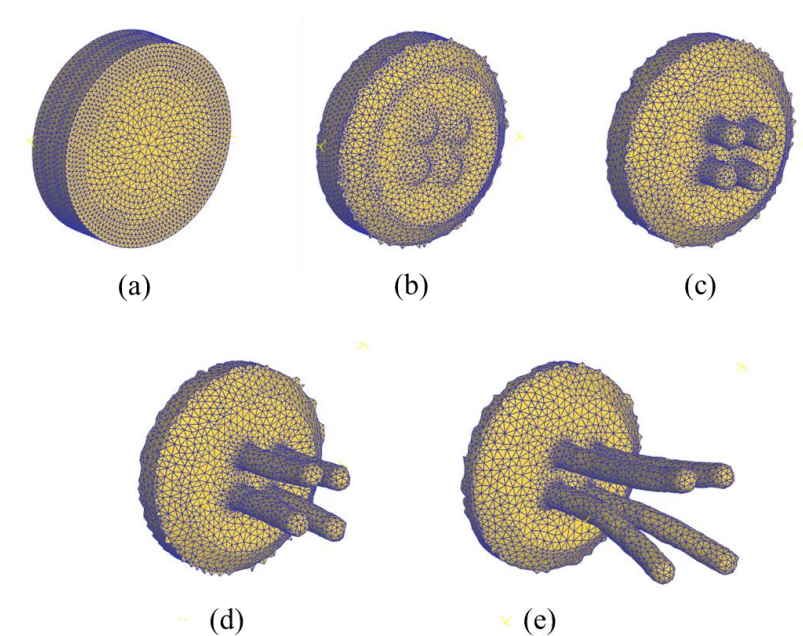


Figure 4.1 Metal flow through 4-hole die (s =ram displacement). (a) $s = 0$ mm; (b) $s = 3.32$ mm; (c) $s = 4.15$ mm; (d) $s = 5.41$ mm; (e) $s = 7.2$ mm.

In Figure 4.1c, the metal is about to exit the die holes and enter die orifices to undergo severe deformation. There is overlapping between the filling of the pocket and the entrance into the die bearing, due to the friction against the pocket wall. Figure 4.1d shows that the extrudate emerges from the die and then the process approaches the steady state. Due to an uneven velocity distribution, there is a little deflection of the extrudates Figure 4.1e.

4.3.1. Selected numerical analysis

From Figure 4.2 to Figure 4.4 shows damage, velocity distribution, contact time, strain distribution, effective stress distributions and load stroke curves during multi-hole extrusion process. The simulation images are taken at the same boundary conditions as mentioned in Table 3.2 and in the same extrusion process parameters except the number of hole difference.

The extrusion process parameters for Figure 4.2, Figure 4.3 and Figure 4.4 is when ram speed is 7mm/s, extrusion temperature is 500°C and 2, 3 and 4 number of holes in extrusion dies is selected for discussions.

Damages

As it is observed from figures (Figure 4.2, Figure 4.3 and Figure 4.4) the damage for each consecutive multi-hole die extrusions, damage is decreased when the number of holes in the die increase. For 2-hole and 3-hole die extrusion the damage values are more than one which is the undesirable effect for extruded products. Whereas for 4-hole die extrusion process the damage value is below one, this shows that the extrudate qualities for 4-hole die extrusion are relatively in safe condition than the 2-hole and 3-hole extrusions. But, if proper optimization taken care of for 2-hole and 3-hole die extrusion the damage of extrudates can be manage as well, Table 4.1 shows that, the damage value for some parametric combinations are below one.

Velocity distributions

The velocity distribution for 2-hole and 3-hole die extrusion is somewhat uniform which helps the extrudate to flow out uniformly. But for 4-hole extrusion die relatively none uniform velocity distribution is observed that why a relative tangled effect of extrudates are observed. As most of the literatures are depicted the velocity distributions of extrudates can be optimized through extrusion die geometry optimizations.

Contact time

If the contact time between billet and extrusion tools is small, there will be a higher chance of reduction to sticking condition of friction between material and tool interfaces. This will

enhance the extrusion speed and improve die tool life. Figure 4.2, Figure 4.3 and Figure 4.4 of figure (c) shows the contact time for 2-hole, 3-hole and 4-hole extrusion dies. The simulation result shows that for 2-holes and 2-holes extrusion die the contact time is higher than that of 4-holes extrusion process, therefore contact time improves at 4 number of holes during multi hole extrusion.

Stress, strain and load distribution

Difference between simulation results, stress and strain distribution for all three simulations doesn't exhibit huge difference. This is due to the fact that the same extrusion process parameters have been implemented for all three simulations. When different extrusion process parameters are used its observed that the effective stress and strain values are fluctuate accordingly. However, the influence of these parameters can be seen in the load stroke distributions of three simulations. As it is observed in Figure 4.2, Figure 4.3 and Figure 4.4 (e) the ram force for each simulation is different. The ram force needed for multi-hole extrusion process is decrease as the number of holes in extrusion die increase, therefore this study agrees to literatures that suggest implementing multi-hole die extrusion for better energy utilizations.

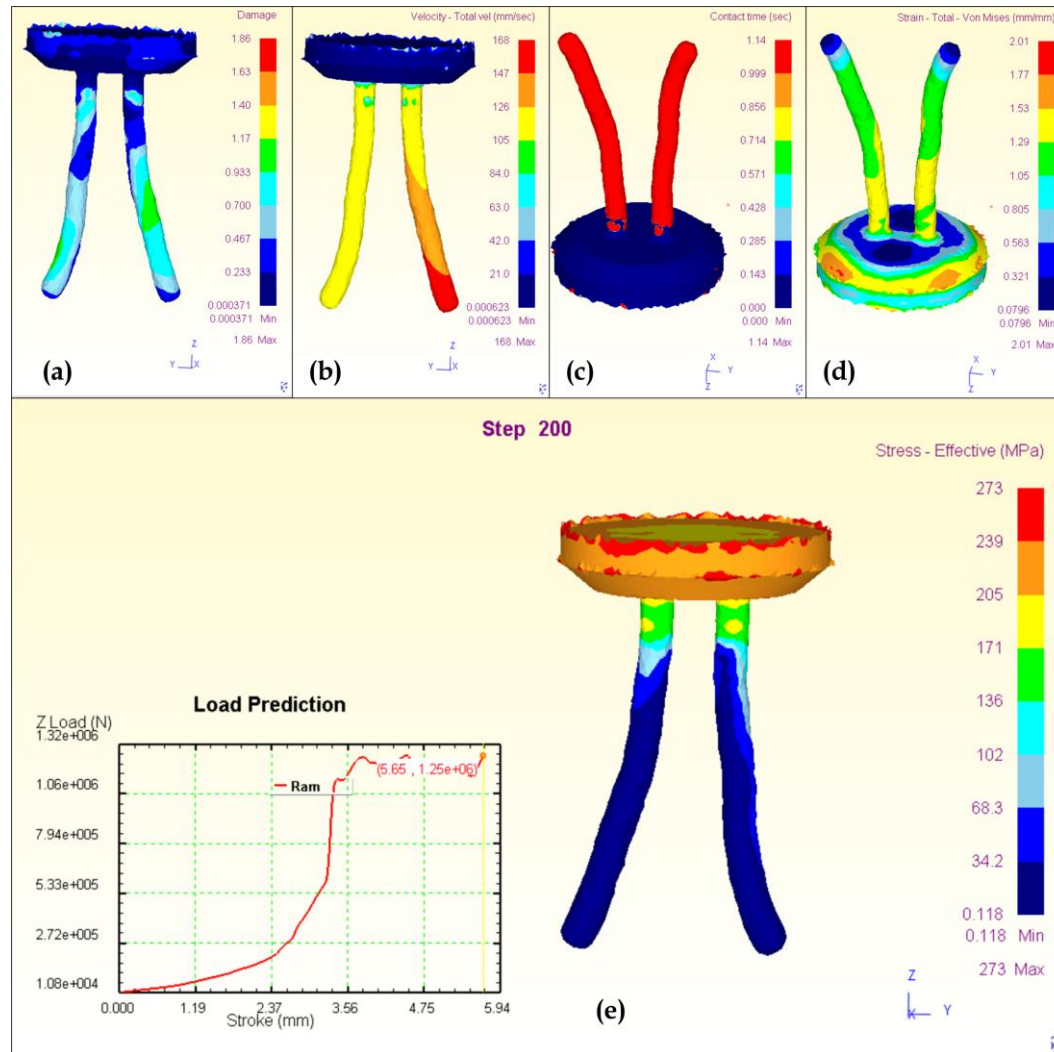


Figure 4.2 Simulation results of (a) Damage, (b) Velocity distribution, (c) Contact time, (d) Strain distribution and (e) Effective stress distribution and Load distribution for 2-hole die extrusion process.

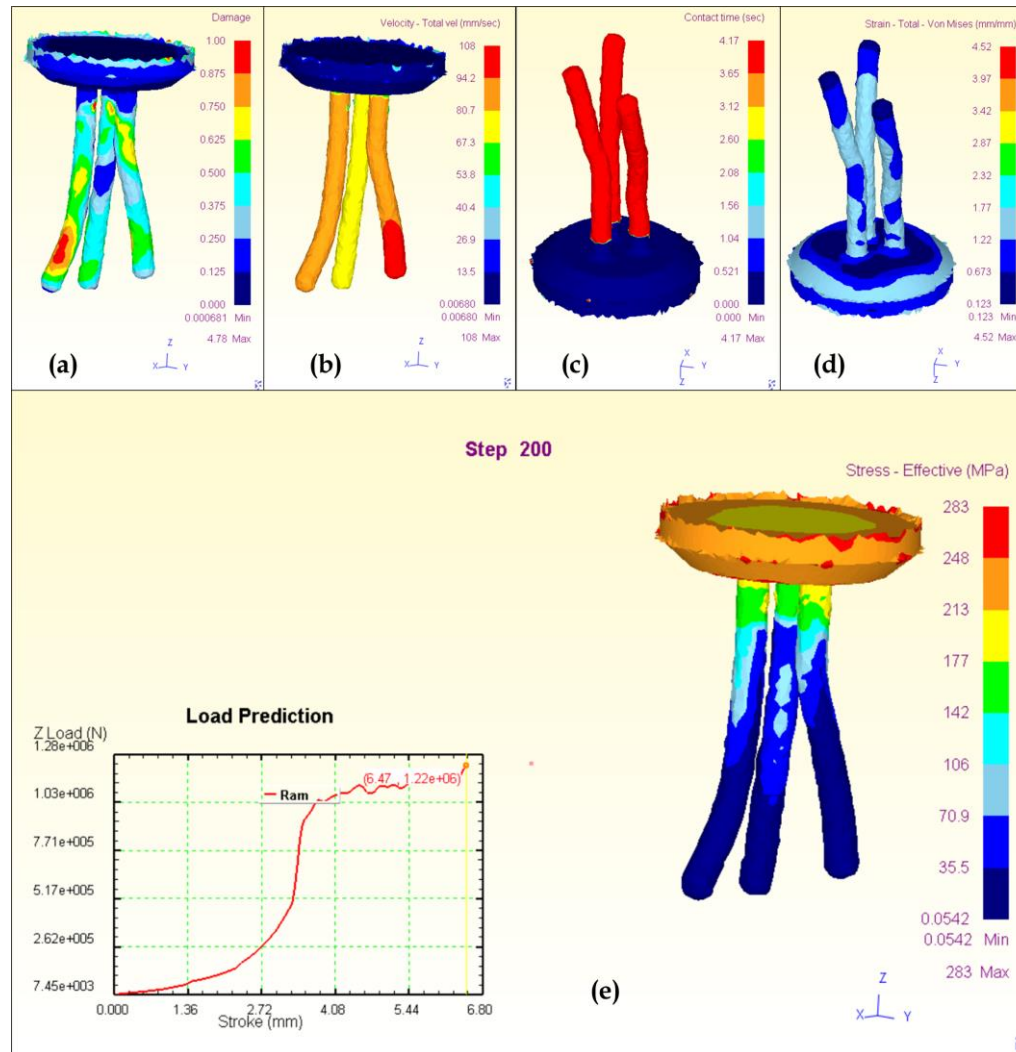


Figure 4.3 Simulation results of (a) Damage, (b) Velocity distribution, (c) Contact time, (d) Strain distribution and (e) Effective stress distribution and Load distribution for 3-hole die extrusion process.

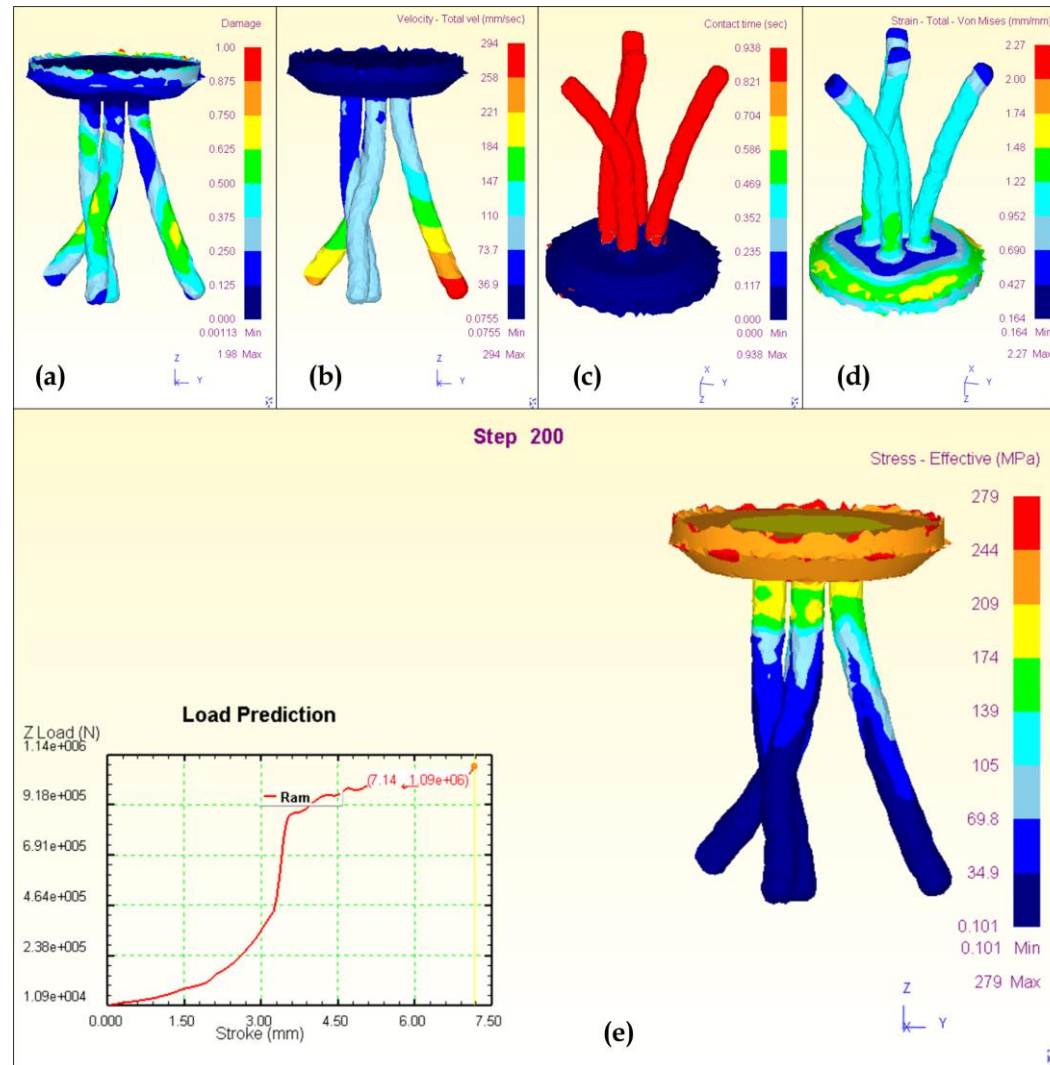


Figure 4.4 Simulation results of (a) Damage, (b) Velocity distribution, (c) Contact time, (d) Strain distribution and (e) Effective stress distribution and Load distribution for 4-hole die extrusion process.

4.4. Optimization of the process parameters

Table 4.2 presents the signal to noise (S/N) ratio of the simulation results of all 27 experiments. The word 'signal' was mentioned as (mean) desirable effect and the word 'noise' was mentioned as (signal disturbance) or undesirable effect of output feature. Least variation as well as optimal design was drawn from S/N ratio, which includes lower-the-better, higher-the-better and nominal-the-better. For this study 'lower-the-better' is taken for extrusion load, damage, and 'high-the-better' is selected for displacement.

Table 4.2 S/N ratio values for damage, displacement and extrusion load.

<i>Damage</i>	<i>S/N</i>	<i>displacement (mm)</i>	<i>S/N</i>	<i>Ram force (KN)</i>	<i>S/N</i>
1.42	-3.05	52.40	34.39	1408.90	-62.98
1.33	-2.48	53.20	34.52	1317.20	-62.39
1.15	-1.21	53.60	34.58	1180.80	-61.44
0.80	1.94	45.30	33.12	1351.50	-62.62
1.08	-0.67	47.00	33.44	1262.00	-62.02
1.22	-1.73	48.90	33.79	1220.10	-61.73
1.31	-2.35	50.80	34.12	1325.00	-62.44
1.50	-3.52	47.70	33.57	1237.00	-61.85
1.76	-4.91	53.30	34.53	1228.60	-61.79
1.25	-1.94	50.50	34.07	1334.50	-62.51
1.15	-1.21	40.50	32.15	2226.10	-66.95
1.69	-4.56	51.00	34.15	1230.20	-61.80
1.38	-2.80	45.90	33.24	1323.00	-62.43
1.47	-3.35	51.00	34.15	1231.40	-61.81
1.37	-2.73	49.60	33.91	1182.70	-61.46
1.21	-1.66	46.70	33.39	1334.60	-62.51
0.90	0.92	45.60	33.18	1219.70	-61.73
0.93	0.63	50.00	33.98	1165.90	-61.33
0.90	0.92	47.30	33.50	1236.60	-61.84
0.97	0.26	50.70	34.10	1172.70	-61.38
1.01	-0.09	47.20	33.48	1142.40	-61.16
0.97	0.26	44.40	32.95	1226.40	-61.77
1.15	-1.21	49.20	33.84	1162.40	-61.31
0.69	3.22	45.30	33.12	1082.10	-60.69
0.81	1.83	49.60	33.91	1188.40	-61.50
0.72	2.85	49.70	33.93	1143.00	-61.16
0.77	2.27	47.30	33.50	1084.80	-60.71

4.5. Multi factor single responses optimizations

shows the signal to noise ratio of each responses (damage, displacement, ram force and exit temperature), therefore the separate effect of parameters on each response can be discussed as follow.

4.5.1. Damage.

Figure 4.5 (a) shows the interaction of extrusion process parameters on damage of extrudates.

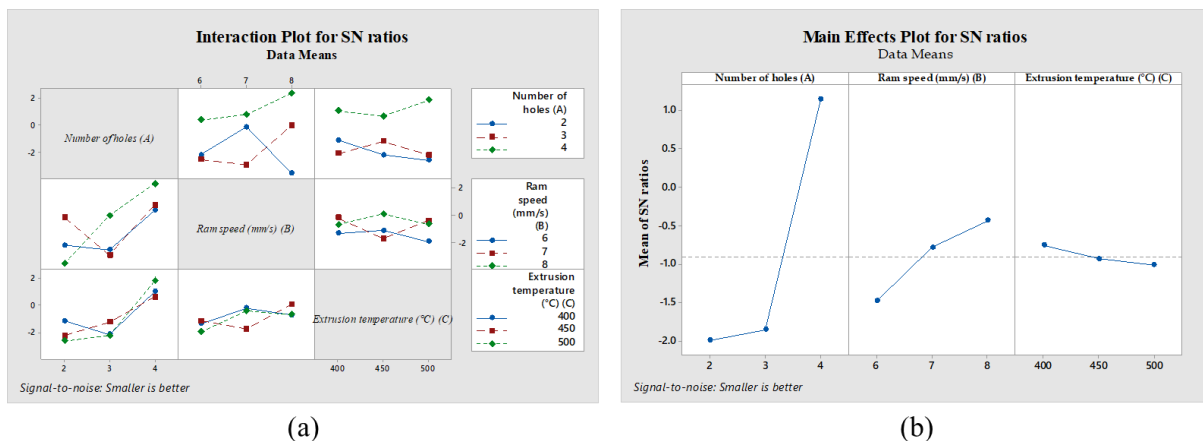


Figure 4.5 (a) Interaction of process parameters on damage of extrudates (b) Main effects plot for S/N ratio for damage.

- Number of holes and ram speed.
 - The damage will increase as ram speed and number holes increases.
 - The list amount of damage is recorded when the number of holes are 2 and ram speed is 8
- Number of holes and Extrusion temperature.
 - For 2-hole extrusion, damage decreases as the extrusion temperature increase.
 - Around 450 °C the damage will increase according to the number of holes increment.
 - The smallest amount is recorded from this interaction is when number of holes are 2 and extrusion temperature is 500 °C.
- Ram speed and Extrusion temperature.
 - As it can be seen in the interaction graph ram speed and extrusion temperature have a balanced effect on the damage of extrudates.
 - The list damage would obtain when the ram speed is 6 and extrusion temperature is 500 °C.

The combined effect of parameters on damage of extrudates also shown in Figure 4.5 (b). As it can be seen in the graph the lowest damage of all combined factors are when 2 number of holes, 6 mm/s ram speed and 500 °C extrusion temperature is used among the 27 runs.

Since p-value of all factors greater than 0.005 except number of holes, number of holes are the significant factor affecting damage of extrudates (Table 4.3).

Table 4.3 ANOVA table for damage

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Number of holes (A)	2	0.89461	0.447304	7.37	0.004
Ram speed (mm/s) (B)	2	0.05621	0.028104	0.46	0.636
Extrusion temperature (°C) (C)	2	0.01639	0.008193	0.14	0.874
Error	20	1.21307	0.060654		
Total	26	2.18027			

4.5.2. Displacement.

Figure 4.6(a) shows the interaction of extrusion process parameters on displacement of extrudates.

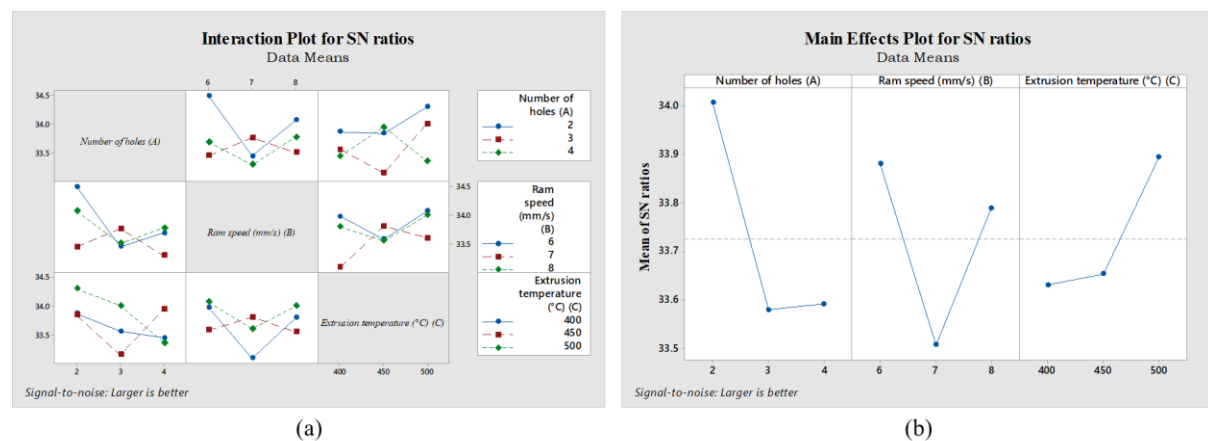


Figure 4.6 (a) Interaction of process parameters on displacement of extrudates. (b) Main effects plot for S/N ratio of displacement

➤ Number of holes and ram speed.

- Since larger is the better at number of holes 2 and ram speed is 6 mm/s the larger extrudate length is recorded.
- The smallest length of extrudate also recorded when ram speed is 7 mm/s and number of holes are 4.

- Number of holes and Extrusion temperature.
 - For 2-hole extrusion, displacement increases as the extrusion temperature increase.
 - When there is 3-hole die extrusion and the extrusion temperature is around 450 °C the length of extrudates will be minimum.
 - The largest extrudate length is when extrusion temperature is 500 °C and number of holes are 2.
- Ram speed and Extrusion temperature.
 - When the ram speed is 6 mm/s and extrusion temperature is 500 °C the largest extrudate length have been recorded.

The combined effect of parameters on displacement of extrudates also shown in Figure 4.6(b). As it can be seen in the graph the highest displacement of all combined factors are when 2 number of holes, 6 mm/s ram speed and 500 °C extrusion temperature is used among the 27 runs.

Since p-value of all factors greater than 0.005 there is no significant factors affecting length of extrudates (Table 4.4).

Table 4.4 ANOVA table for Displacement.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Number of holes (A)	2	34.08	17.041	1.92	0.173
Ram speed (mm/s) (B)	2	23.09	11.543	1.3	0.294
Extrusion temperature (°C) (C)	2	11.64	5.821	0.66	0.53
Error	20	177.44	8.872		
Total	26	246.25			

4.5.3. Ram force

Figure 4.7 (a) shows the interaction of extrusion process parameters on displacement of extrudates.

- Number of holes and ram speed.
 - The relation between number of holes and ram speed is more linear as it can be seen in the graph (Figure 4.7 (a)). For each hole type the ram force increases as the ram speed increase.

- Since the small amount of ram force is intended to optimize in this study the smallest amount of ram force is recorded when the number of holes are 3 and ram speed is 6mm/s.

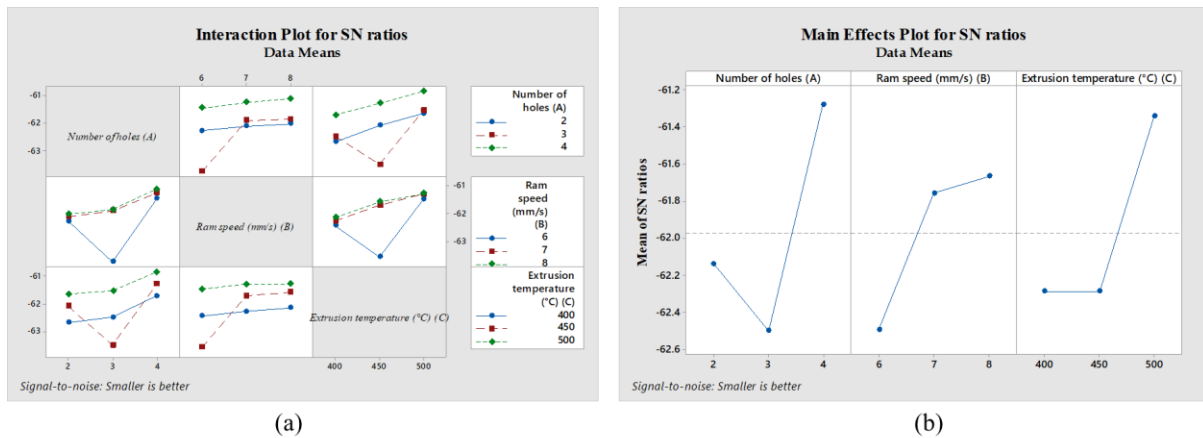


Figure 4.7 (a) Interaction of process parameters on the ram force. (b) Main effects plot for S/N ratio of ram force.

- Number of holes and Extrusion temperature.
 - From the graph Figure 4.7 (a) it is observed that a linear relation exists between these two parameters except if the number of holes are 3.
 - When there is 3-hole die extrusion and the extrusion temperature is around 450 °C the ram force will be small.
- Ram speed and Extrusion temperature.
 - The relation between ram speed and extrusion temperature is more linear as it can be seen in the graph (Figure 4.7 (a)). For each extrusion temperature the ram force increases as the ram speed increase.
 - When the ram speed is 6 mm/s and extrusion temperature is around 450 °C the smaller ram force is recorded.

The combined effect of parameters on ram force of multi-hole extrusion also shown in Figure 4.7 (b). As it can be seen in the graph the lowest ram force of all combined factors is recorded when 3 number of holes, 6 mm/s ram speed and 400-450 °C extrusion temperature is used among the 27 runs.

4.6. Multi-response single response optimizations

Grey relational grade is employed to convert multi objective problem into a single objective. The scope of this study was to identify the optimal combination of process parameters that concurrently minimize damage, ram force, and maximize displacement. In order to accomplish this, grey relational analysis is employed. Table 4.6 shows the normalized, calculated GRC, GRG, and signal to noise ratio of the combined process parameter effects.

4.6.1. Analysis of responses for GRG (ANOVA)

Analysis of variance is the most widely used statistical technique in the field of statistical inference and it is also the appropriate procedure for testing the equality of several means. Analysis of variance confirms the amount of impact of process parameters on the response parameter. ANOVA is used in this study to determine the impact of considered process parameters on the properties of simulated extrudates. The ANOVA table for process parameters is shown in Table 4.5. For this model 95% confidence level is considered to confirm the experimental results.

Table 4.5 ANOVA table of GRG

Source	DF	Adj SS	Adj MS	F-Value	% of contributions
Number of holes (A)	2	0.043328	0.021664	12.84	50
Ram speed (mm/s) (B)	2	0.007648	0.003824	2.27	8.8
Extrusion temperature (°C) (C)	2	0.001859	0.00093	0.55	2.1
Error	20	0.033756	0.001688		39
Total	26	0.086591			100

Using Minitab 18 software the analysis of GRG values was done to find the relative effect of process parameters while extruding the AA6063 alloy can be evaluated by ANOVA. The results of ANOVA in Table 4.5 displayed that number of holes was the major parameter contributing 50 % to extrusion load, displacement, and damage. The contributions from other parameters were ram speed 8.8 % and the extrusion temperature 2.1 %. Since, number of holes are the highest contributor for product quality enhancement and capability of product efficiency the number of holes during multi-hole die extrusion should be selected carefully.

Table 4.6 Normalized S/N ratios and calculated GRCs

Exp.Run	Factorial design			Responses			Normalization			Deviation sequence			Gray rational coefficient (GRC)			GRG	S/N
	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)	Damage	Displacement (mm)	Ram force (KN)	Damage	Displacement (mm)	Ram force (KN)	Damage	Displacement (mm)	Ram force (KN)	Damage	Displacement (mm)	Ram force (KN)		
1	2	6	400	1.42	52.4	1408.9	0.318	0.908	0.714	0.682	0.908	0.286	0.423	0.355	0.636	0.28287	-7.998
2	2	6	450	1.33	53.2	1317.2	0.402	0.969	0.794	0.598	0.969	0.206	0.455	0.340	0.709	0.30086	-8.063
3	2	6	500	1.15	53.6	1180.8	0.570	1.000	0.914	0.430	1.000	0.086	0.538	0.333	0.853	0.34477	-7.531
4	2	7	400	0.8	45.3	1351.5	0.897	0.366	0.765	0.103	0.366	0.235	0.829	0.577	0.680	0.41727	-5.472
5	2	7	450	1.08	47	1262	0.636	0.496	0.843	0.364	0.496	0.157	0.578	0.502	0.761	0.36821	-6.812
6	2	7	500	1.22	48.9	1220.1	0.505	0.641	0.879	0.495	0.641	0.121	0.502	0.438	0.806	0.34922	-7.540
7	2	8	400	1.31	50.8	1325	0.421	0.786	0.788	0.579	0.786	0.212	0.463	0.389	0.702	0.31077	-7.812
8	2	8	450	1.5	47.7	1237	0.243	0.550	0.865	0.757	0.550	0.135	0.398	0.476	0.787	0.33221	-7.688
9	2	8	500	1.76	53.3	1228.6	0.000	0.977	0.872	1.000	0.977	0.128	0.333	0.339	0.796	0.29359	-8.868
10	3	6	400	1.25	50.5	1334.5	0.477	0.763	0.779	0.523	0.763	0.221	0.489	0.396	0.694	0.31564	-6.145
11	3	6	450	1.15	40.5	2226.1	0.570	0.000	0.000	0.430	0.000	1.000	0.538	1.000	0.333	0.37420	-6.091
12	3	6	500	1.69	51	1230.2	0.065	0.802	0.871	0.935	0.802	0.129	0.349	0.384	0.794	0.30541	-8.174
13	3	7	400	1.38	45.9	1323	0.355	0.412	0.789	0.645	0.412	0.211	0.437	0.548	0.704	0.33770	-5.993
14	3	7	450	1.47	51	1231.4	0.271	0.802	0.869	0.729	0.802	0.131	0.407	0.384	0.793	0.31680	-7.405
15	3	7	500	1.37	49.6	1182.7	0.364	0.695	0.912	0.636	0.695	0.088	0.440	0.419	0.850	0.34186	-7.450
16	3	8	400	1.21	46.7	1334.6	0.514	0.473	0.779	0.486	0.473	0.221	0.507	0.514	0.694	0.34292	-6.406
17	3	8	450	0.9	45.6	1219.7	0.804	0.389	0.880	0.196	0.389	0.120	0.718	0.562	0.806	0.41729	-5.748
18	3	8	500	0.93	50	1165.9	0.776	0.725	0.927	0.224	0.725	0.073	0.690	0.408	0.872	0.39413	-6.537
19	4	6	400	0.9	47.3	1236.6	0.804	0.519	0.865	0.196	0.519	0.135	0.718	0.491	0.787	0.39922	-4.448
20	4	6	450	0.97	50.7	1172.7	0.738	0.779	0.921	0.262	0.779	0.079	0.656	0.391	0.863	0.38215	-5.776
21	4	6	500	1.01	47.2	1142.4	0.701	0.511	0.947	0.299	0.511	0.053	0.626	0.494	0.905	0.40494	-6.018
22	4	7	400	0.97	44.4	1226.4	0.738	0.298	0.874	0.262	0.298	0.126	0.656	0.627	0.799	0.41636	-4.572
23	4	7	450	1.15	49.2	1162.4	0.570	0.664	0.930	0.430	0.664	0.070	0.538	0.430	0.877	0.36882	-6.322
24	4	7	500	0.69	45.3	1082.1	1.000	0.366	1.000	0.000	0.366	0.000	1.000	0.577	1.000	0.51542	-4.384
25	4	8	400	0.81	49.6	1188.4	0.888	0.695	0.907	0.112	0.695	0.093	0.817	0.419	0.843	0.41572	-4.910
26	4	8	450	0.72	49.7	1143	0.972	0.702	0.947	0.028	0.702	0.053	0.947	0.416	0.904	0.45331	-5.025
27	4	8	500	0.77	47.3	1084.8	0.925	0.519	0.998	0.075	0.519	0.002	0.870	0.491	0.995	0.47117	-5.177

Table 4.5 shows the parameters such as (MS) mean of square, (SS) sum of squares, (F) ratio of mean square factor to the square of error mean and (DF) degree of freedom.

Table 4.7 Response table of means for GRG

Level	Number of holes (A)	Ram speed (mm/s) (B)	Extrusion temperature (°C) (C)
1	0.3333	0.3456	0.3598
2	0.3495	0.3813	0.3682
3	0.4252	0.3812	0.3801
Delta	0.0919	0.0357	0.0202
Rank	1	2	3

The mean response gives us the significant effect of process parameters on the extrusion process. The mean of response for GRG was disclosed in Table 4.7. The number of holes has most significant effect then remaining parameters as it got first rank followed by extrusion temperature as second and ram speed as third. The response table depicted in Table 4.7 obtained from Minitab software reveal that at 4-number of holes, 7mm/s ram speed and 500°C extrusion temperature (A3 B2 C3) optimum multi-response optimization can be achieved.

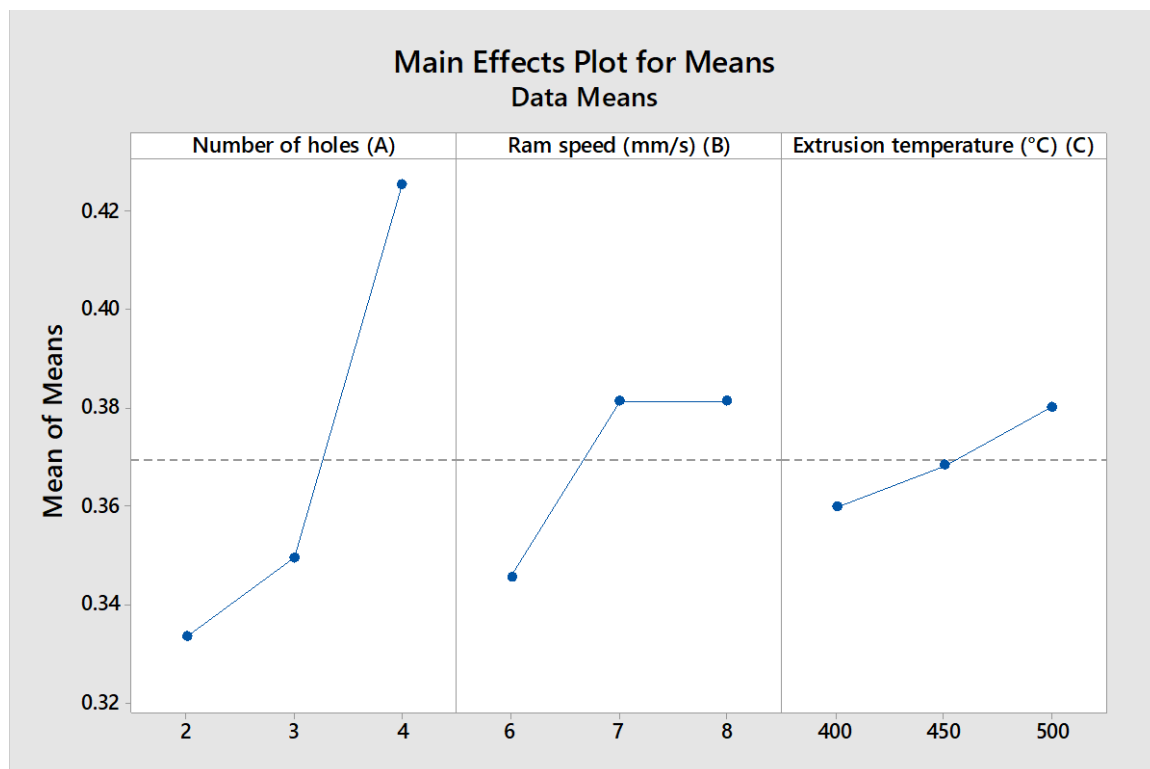


Figure 4.8 Main effects of process parameters for means (GRG)

4.6.1.1. Influence of process parameters on multi-responses.

From previous studies (He et al., 2009; Inamdar & Chahare, 2017; Jajimoggala et al., 2019; Zhang et al., 2012) die temperature, ram speed, billet temperature, billet diameters and container temperature, are the process parameters which influence the extrusion process but they have not measured in case of multi-hole multi response condition. So, in this work apart from single hole single response optimization a case of multi-hole combined (multi response) optimization is performed.

4.6.1.2. Effect of number of holes.

The Table 4.7 and Figure 4.8 which is obtained from the result of variance of analysis show the number of holes with 4 is better than other. While relating the outcomes at optimum factors from the previous observation (Table 4.1) it is clear that with the increase of number of holes, extrusion load and damage is decrease. The exit temperatures were little better for number of holes of 4 than 2 and 3, for total displacement higher extrudate displacement is recorded at 3 number of holes.

4.6.1.3. Effect of ram speed.

The ram speed determines the production efficiency of extrusion has better responses at 7mm/sec as per ANOVA results, the same can be detected while comparing it with Table 4.1 as the ram speed rises extrusion load falls, but while ram speed rises the exit temperature also rises. In general, if an alloy prone to excess speed, overheating of the exit temperature and other surface faults were observed. Concurrently a low speed will increase to greater extrusion load and also reduce the tool life. For displacement, with the increase of ram speed a minor quantity of displacement is getting high compared with low ram speeds.

4.6.1.4. Estimation of optimum conditions.

The optimum design process parameters were supportive for the evaluation and confirmation of the performance of responses improves. The optimum parameters and levels are selected from the graph of main effects of means (Figure 4.8) as A3, B2 and C3, that is, number of holes 4, ram speed=7mm/sec and extrusion temperature=500°C is disclosed in The mean response gives us the significant effect of process parameters on the extrusion process. The mean of response for GRG was disclosed in Table 4.7 The number of holes has most significant effect then remaining parameters as it got first rank followed by extrusion temperature as second and ram speed as third.

Experimental investigation

For sample preparation two experimental runs from simulation and GRG results have been selected. i.e., the list optimum combination which is an experimental run of 12nd simulation, at which number of holes are 3, extrusion speed 6 mm/s, and extrusion temperature 500 °C; and the most optimum combination which is an experimental run of 24th simulation, when number of holes are 4, extrusion speed 7 mm/s, and extrusion temperature 500 °C.

After the arrangement of extrusion components in 150-ton Hursan hydraulic press see Figure 3.16, the sample preparation is performed. And during sample preparation the ram speed was fixed to constant level of 6 mm/sec and 7 mm/sec respectively, therefore the variation of ram force was observed easily. At the time of sample preparation, the hydraulic piston was exceeded up to 60 tons while extrusion performed through 3-hole extrusion die with respect to the process parameter selected for this study. But when the 4-hole extrusion die is used with respect to the process parameters selected for this study the hydraulic ram exceeded 40 tons as it was observed from calibration gauge. This result illustrates that the extrusion ram force for 3-hole die is more than that of 4-hole die. The same agreement is observed in numerical simulation results shown in Table 4.1.

4.7. Material testing and characterizations

In this section the material testing and characterization of multi-hole extruded samples and billets have been performed. The first section presents the result of microstructural analysis, and in second section the hardness test result is presented.

4.7.1. Morphology result

Figure 4.9 shows the morphology image of base material (billet AA6063), 3-hole extrudate sample, and 4-hole extrudate samples.

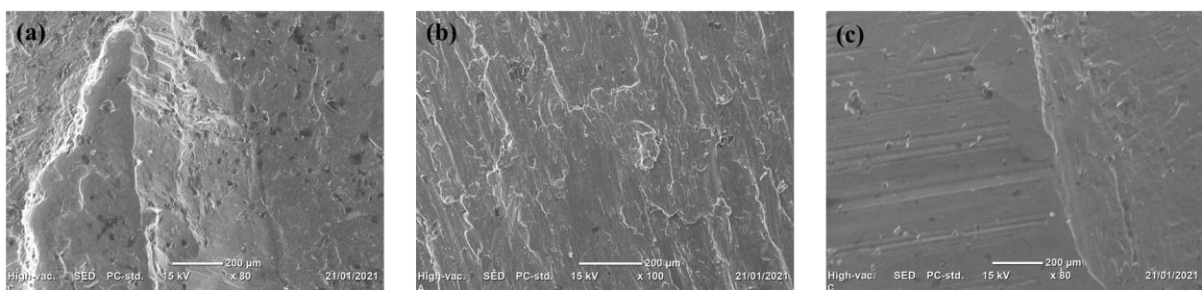


Figure 4.9 SEM microstructure image 80x magnification (a) base material (billet AA6063), (b) 3-hole die extrudate sample, and (c) 4-hole die extrudate sample.

In Figure 4.9 it is clearly observed that, after extrusion the morphology of extrudates becomes smoother. This is due to the plastic deformation of the material change through extrusion process, as a result the grain size becomes smaller than the base material. According to the Hall–Petch relationship (Hall, 1951) the material strength increases with decreasing grain size.

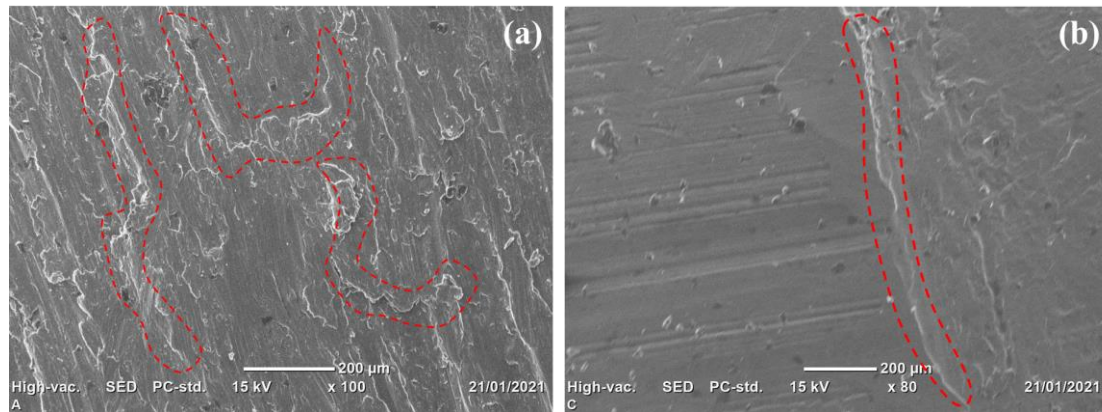


Figure 4.10 SEM microstructure image (a) 3-hole extrudate sample, (b) 4-hole extrudate sample.

The SEM image in Figure 4.10 illustrates the micro cracks and surface damages in 3-hole extrudate sample and 4-hole extrudate sample. The image is taking at 100x and 80x magnification by using SEM. From the figure it's clearly observed that, the surface damage for each sample is different. The reason behind this phenomenon is, as stated in the numerical simulation results the effective strain rate (ram speed) difference between these two processes exhibit that micro structural damages. In 3-hole extrudate sample Figure 4.10(a) more micro cracks are observed, while in 4-hole extrudate sample little micro-cracks are seen through SEM analysis. The numerical simulation results also reveal that the extrudate damage for 12nd run (3-hole die, 6 mm/s ram speed and 500 °C extrusion temperature) is around 1.69 (which is more than 1), and 24th run (4-hole die, 7 mm/s ram speed and 500 °C extrusion temperature) is around 0.69 (less than 1).

4.7.2. Hardness test

The hardness test was performed in Vickers hardness tester and the dwelling period was 12 seconds and done by square-based pyramid diamond indenter with an angle of 136° between the opposite faces at the vertex. Which is pressed into the surface of the test piece using a prescribed force F. The calibration range of this machine is 5-2900 HV and the force ranges 1-50kgf. To this work, two samples and one base material (AA6063 aluminium alloy billet) were tested by three trials and analyzed the average value.

The Vickers hardness result for each sample presented in Table 4.8. The average test results in the table showed that the hardness value for each extrudates is different than the base material i.e., the billet material. And also, it is observed that hardness value between 3-hole die extrusion and 4-hole die extrusion have little difference.

Table 4.8 The mean value and each trial value of hardness tested value

Tests	Billet AA6063 (HV)	3-Hole die extrudate (HV)	4-Hole die extrudate (HV)
Test 1	80.5	91.5	89.1
Test 2	89.2	95.3	91.8
Test 3	87.6	94.6	91.5
Avg.	85.76	93.8	90.8

In this study the 3-hole die extrudate sample have higher hardness value than the two samples. This is due to the higher plastic strain occurrence in extrudates since the extrusion ratio is higher than 4-hole extrusions. 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. 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.

Chapter Five

5. Conclusions and Recommendations

5.1. Conclusions

This study validates the capability of multi-hole extrusion process enhancement for AA6063 aluminium alloy through different process parameters. The effect on process parameters and design of damage, extrusion load, and displacement were accomplished by using DEFORMTM-3D simulation software basis on FEM. Method of Taguchi alongside with GRA (a multi performance response optimization) was employed for the optimization of process parameters for damage, extrusion load, and displacement. The experimental validation also performed from this study and the conclusions is presented as follow

- DEFORMTM-3D was known to be an effectual tool to study the consequences of design and process parameters for variant responses can be efficiently recognized by performing the experiments which are designed help of the OA of Taguchi's method.
- GRA was introduced for translating a multi performance response into a single optimized output denoted as the GRG. This determines the optimum process parameter level setting to optimize all performance characteristics concurrently. The optimum process parameters obtained by method of Grey based-Taguchi to optimize extrusion load, displacement, and damage simultaneously are number of holes 4, ram speed=7mm/sec and extrusion temperature=500°C respectively.
- The ANOVA result for GRG shows that number of holes are the highest contributor for damage, ram force and displacements. Therefore, for product quality enhancement and capability of product efficiency the number of holes and geometrical layout of holes during multi-hole die extrusion should be selected carefully.
- The tests from experimental investigation shows that the effective strain rate (ram speed) increment in extrusion process lead for microscopic damages in extrudates. therefore, an optimum strain rate (ram speed) for multi-hole extrusion process to be found as 7mm/sec through numerical investigations and design of experiment techniques.
- Both experimental and numerical result shows that the ram force for multi-hole extrusion process increases as the extrusion ratio decrease. The micro hardness result also shows that extrusion ratio has influence on the hardness of extruded materials. Therefore, from this study it is found that; energy utilization, product enhancement and capability of fabrication more than one extrusion product at a time can be achieved.

- The optimum process enhancement for this study have observed through multi-hole extrusions process. Therefore, the manufacturing firms or any industries who intend to work in extrusion of aluminium material will enhance their productivity and product quality by using multi-hole extrusion process.

5.2. Recommendations

The aluminium extrusion products have much interested areas where structural members and architectural applications are used in. AA6063 alloy material is one of the engineering materials which used for architectural uses. As the result of this study stated that the extrusion process parameters trough multi-hole die has a significant influence on quality and productivity of extrusion products. Therefore, structural aluminium profile manufacturers in Ethiopia will be benefited if they consider further investigations and implementation of findings for extruded structural aluminium profiles. Some of future scopes and suggestions are;

- Experimental investigation of multi-hole extrusion for hollow profiles.
- Analysis and design of multi-hole extrusion die for aluminium materials can be addressed.
- Multi-hole extrusion process for composite materials and ferrous metals can be conducted.

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APPENDIX-A

Useful tables and charts

Table A1 Extrudability ratings of soft and medium grade alloys (*Saha, 2000. Aluminum extrusion technology*).

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

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

Table A2 Aluminum alloys commonly used for various extruded products Extrusion, (*Saha, 2000. Aluminum extrusion technology*).

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

Source: Ref 6

Table A3 The lowest recrystallization temperature of common metals (Kohser, 2012. *Materials and processes in manufacturing*).

Metal	Temperature [°F(°C)]
Aluminum	300 (150)
Copper	390 (200)
Gold	390 (200)
Iron	840 (450)
Lead	Below room temperature
Magnesium	300 (150)
Nickel	1100 (590)
Silver	390 (200)
Tin	Below room temperature
Zinc	Room temperature

Table A4 Typical values of billet temperatures and extrusion speeds of soft and medium grade alloys.

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

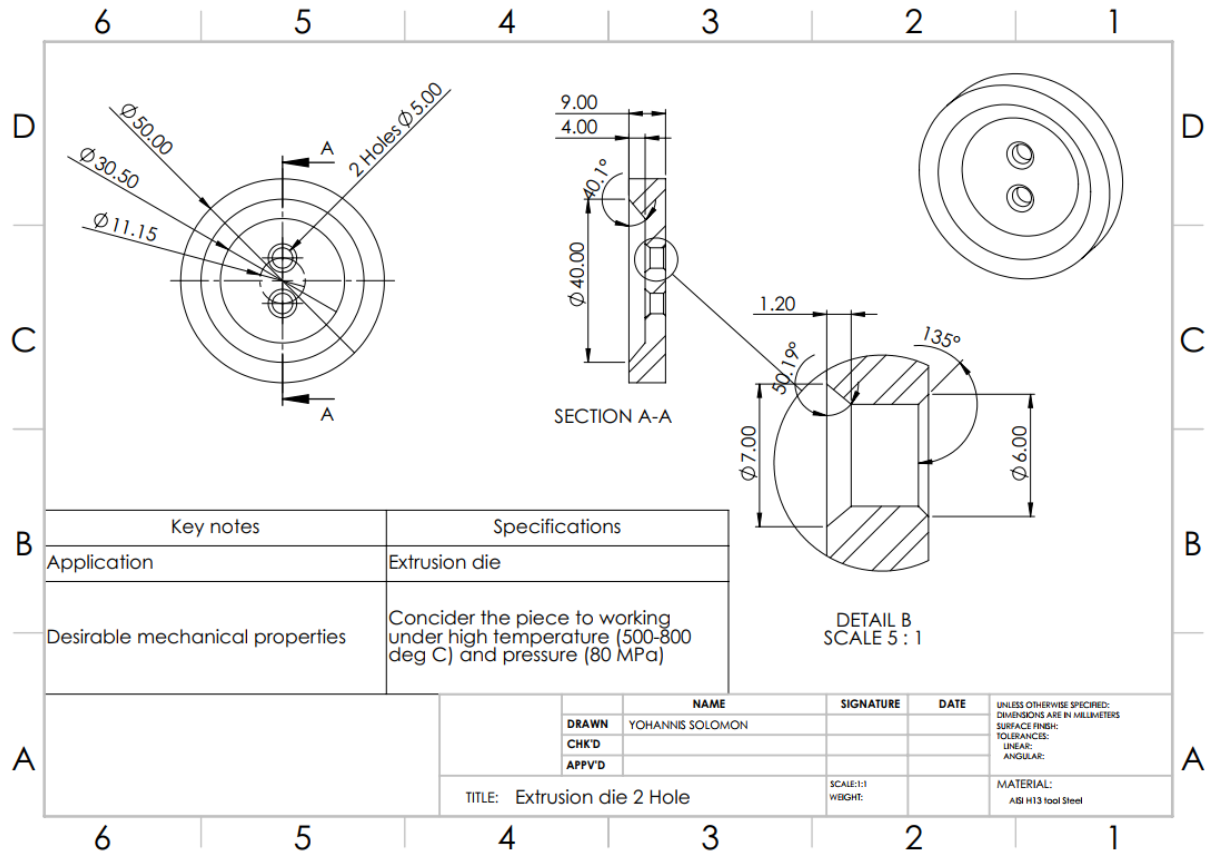
Source: Ref 8

APPENDIX-B

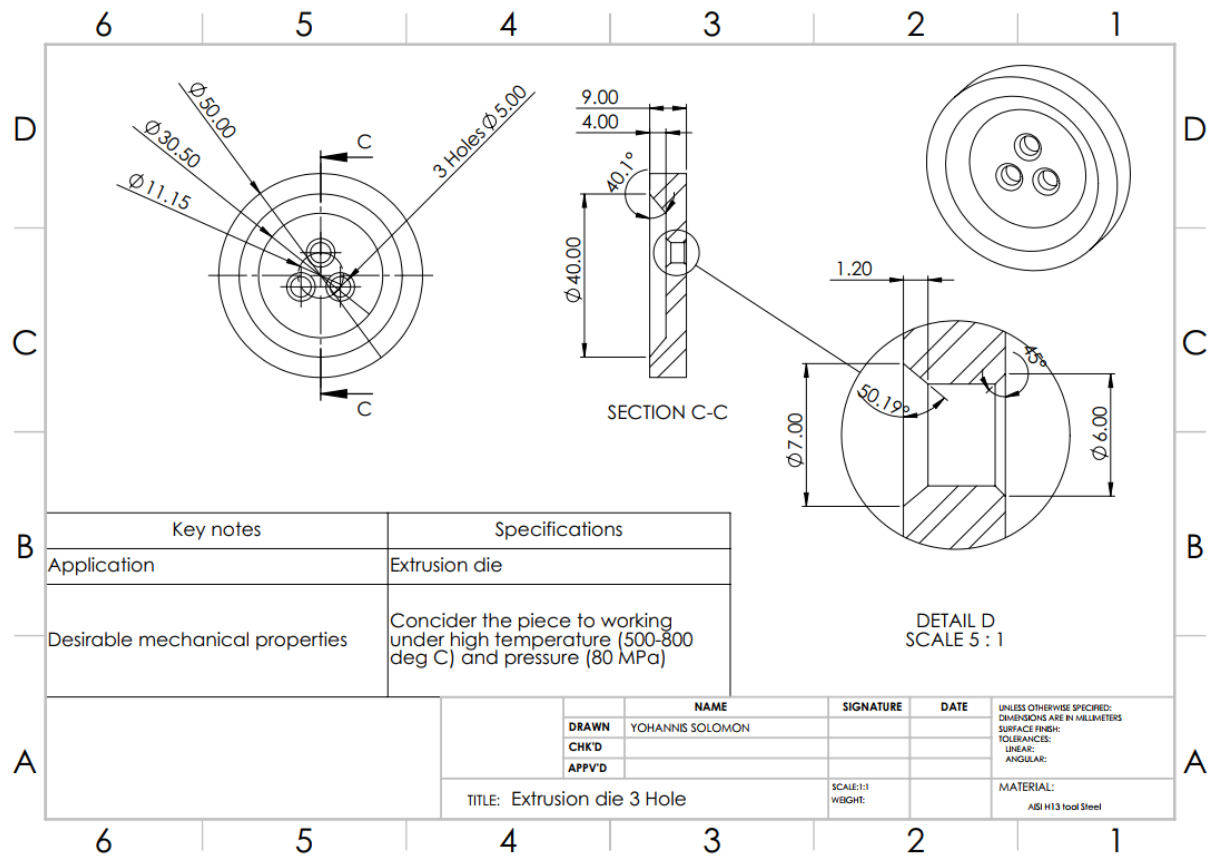
Die designing charts and geometrical descriptions

[A1] Geometrical description and layouts

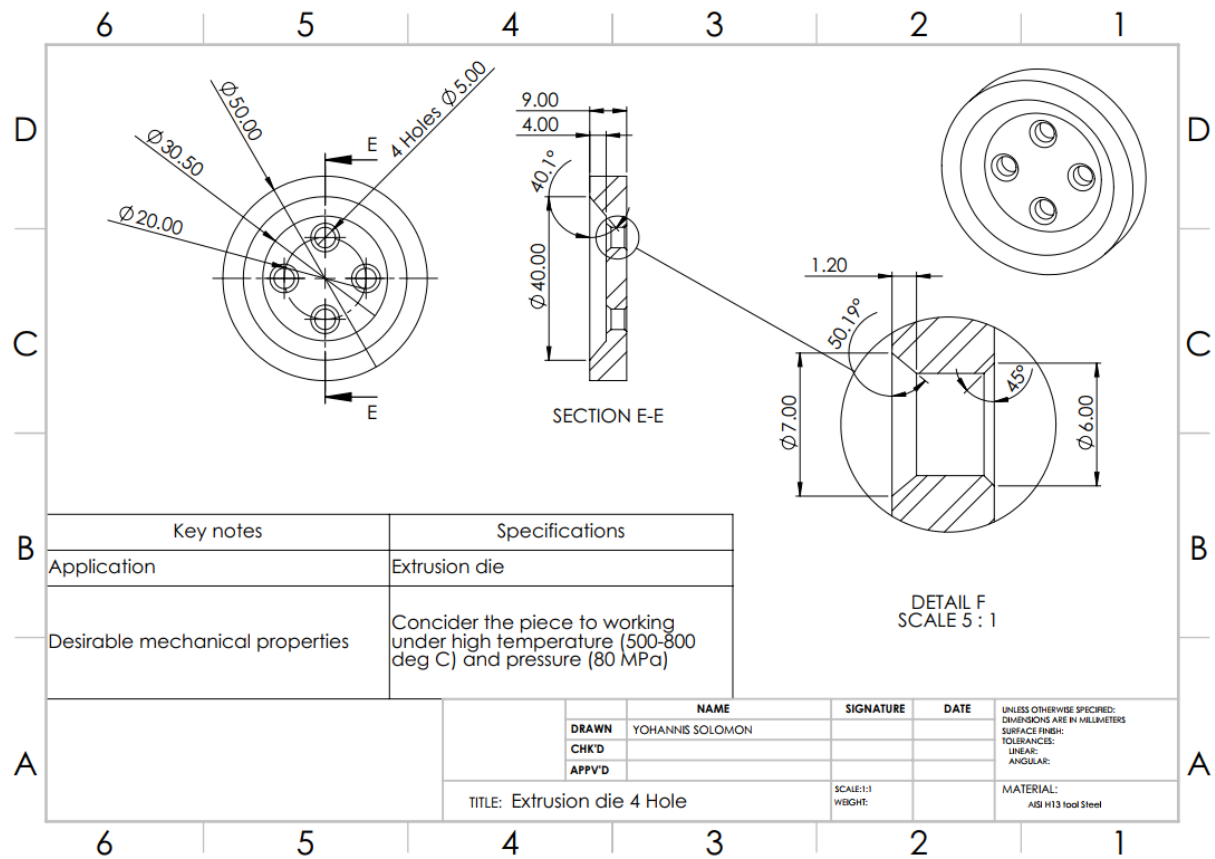
2-Hole die geometry



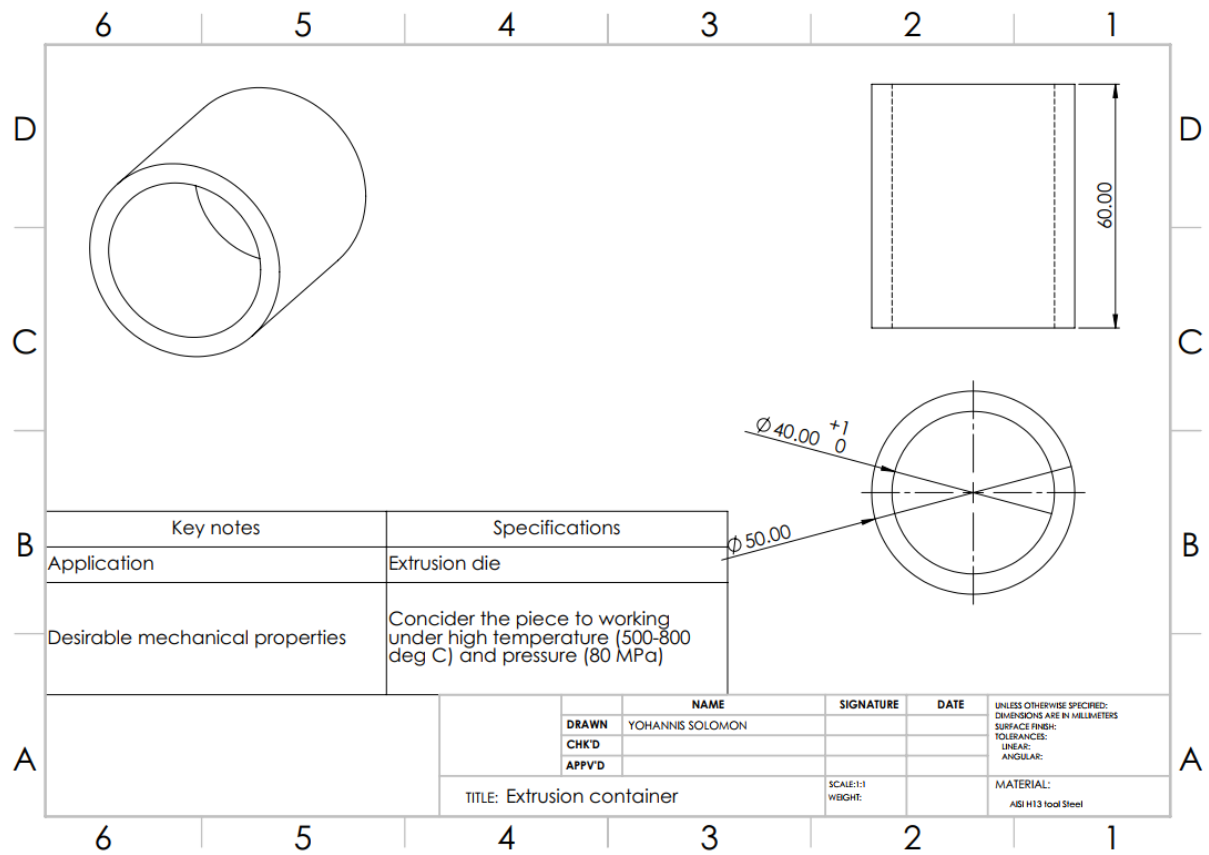
3-Hole die geometry



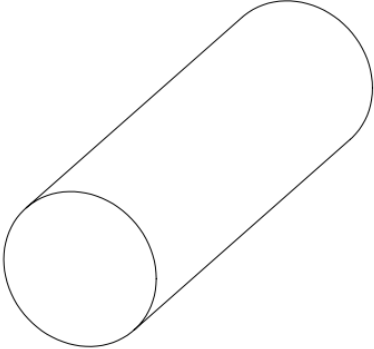
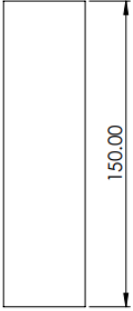
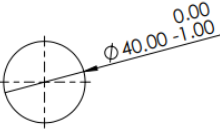
4-Hole die geometry



Extrusion container



Extrusion ram

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Composition and Properties of Some Wrought Aluminum Alloys in Various Conditions

Designation ^a	Composition (%) Aluminum = Balance					Form Tested	Tensile Strength		Yield Strength ^b		Elongation in 2 in. (%)	Brinell Hardness	Uses and Characteristics		
	Cu	Si	Mn	Mg	Others		ksi	MPa	ksi	MPa					
Work-Hardening Alloys—Not Heat-Treatable															
1100-O	0.12				99 Al	$\frac{1}{16}$ -in. sheet	13	90	5	34	35	23	Commercial Al: good forming properties		
1100-H14						$\frac{1}{16}$ -in. sheet	16	110	14	97	9	32	Good corrosion resistance, low yield strength		
110-H18						$\frac{1}{16}$ -in. sheet	24	165	21	145	5	44	Cooking utensils; sheet and tubing		
3003-O	0.12		1.2			$\frac{1}{16}$ -in. sheet	16	110	6	41	30	28	Similar to 1100		
3003-H14						$\frac{1}{16}$ -in. sheet	22	152	21	145	8	40	Slightly stronger and less ductile		
3003-H18						$\frac{1}{16}$ -in. sheet	29	200	27	186	4	55	Cooking utensils; sheet-metal work		
5052-O				2.5	0.25 Cr	$\frac{1}{16}$ -in. sheet	28	193	13	90	25	45	Strongest work-hardening alloy		
5052-H32						$\frac{1}{16}$ -in. sheet	33	228	28	193	12	60	Highly yield strength and fatigue limit		
5052-H36						$\frac{1}{16}$ -in. sheet	40	276	35	241	8	73	Highly stressed sheet-metal products		
Precipitation-Hardening Alloys—Heat-Treatable															
2017-O	4.0	0.5	0.7	0.6		$\frac{1}{16}$ -in. sheet	26	179	10	69	20	45	Duralumin, original strong alloy		
2017-T4								$\frac{1}{16}$ -in. sheet	62	428	40	276	20	105	Hardened by quenching and aging
2024-O						4.4	0.6	1.5	$\frac{1}{16}$ -in. sheet	27	186	11	76	20	42
2024-T4			$\frac{1}{16}$ -in. sheet	64	441				45	290	19	120	Used widely in aircraft construction		
2014-O	4.4	0.8	0.8	0.5	$\frac{1}{2}$ -in. extruded shapes				27	186	14	97	12	45	Strong alloy for extruded shapes
2014-T6							Forgings	65	448	55	379	10	125	Strong forging alloy	
2014-T6							$\frac{1}{16}$ -in. sheet	70	483	60	413	8		Higher yield strength than Alclad 2024	
Alclad															
2014-T6	4.5	1.0	0.8	0.4	$\left\{ \begin{array}{l} 0.3 \text{ Cr} \\ 5.6 \text{ Zn} \end{array} \right.$	$\frac{1}{16}$ -in. sheet	63	434	56	386	7		Clad with heat-treatable alloy ^c		
7075-O	1.6		0.2	2.5		$\frac{1}{16}$ -in. sheet	33	228	15	103	17	60	Alloy of highest strength		
7075-T6						$\frac{1}{16}$ -in. sheet	76	524	67	462	11	150	Lower ductility than 2024		
Alclad															
7075-T6						$\frac{1}{16}$ -in. sheet	76	524	67	462	11		Strongest Alclad product		
7075-T6						$\frac{1}{2}$ -in. extruded shapes	80	552	70	483	6		Strongest alloy for extrusions		
6061-T6	0.28	0.6		1.0	0.20 Cr	$\frac{1}{2}$ -in. extruded shapes	42	290	40	276	12	95	Strong, corrosion resistant		
6063-T6						0.4	0.7	$\frac{1}{2}$ -in. rod extruded	35	241	31	214	12	80	Good forming properties and corrosion resistance
6151-T6						0.9	0.6	0.20 Cr	Forgings	48	331	43	297	17	90
2025-T6	4.5	0.8	0.8			Forgings	55	379	30	207	18	100	Good forgeability, lower cost		
2018-T6	4			0.7	2 Ni	Forgings	55	379	40	276	10	100	Strong at elevated temperatures; forged pistons		
4032-T6	0.9	12.2		1.1	0.9 Ni	Forgings	55	379	46	317	9	115	Forged aircraft pistons		
2011-T3	5.5			(0.5 Bi)	0.5 Pb	$\frac{1}{2}$ -in. rod	55	379	43	297	15	95	Free cutting, screw-machine products		

^a O, annealed; T, quenched and aged; H, cold-rolled to hard temper.

^b Yield strength taken at 0.2% permanent set.

^c Cladding alloy; 1.0 Mg, 0.7 Si, 0.5 Mn.

Standard press capacity and specific pressure chart

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

(a) Maximum billet length $\equiv 4 \times$ billet diameter. (b) Container diameter is generally 0.375 in. (9.53 mm) more than the specified.

[A2] Die designing charts and specifications (Tyrer & Waheed, 2006)

Die shop parameters for solid dies

Press size:				Item:		Type:										Die size:	
Container size:				Die No.:		Die vendor:										Bolster size/No.:	
Design parameters															Die deflection		Comments
Die bearing (as received)				Correction			Trial/production run						Hardness, HRC				
Wall	Bearing length	Squareness	Surface condition	Pocket/feeder plate	Wall	Bearing length (b1, b2, etc.)	Pocket/feeder plate	Date	Shift	Billet size	Runout	Wt/unit length	No. of billets	New	Old		

Standard press capacity and specific pressure chart

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

(a) Maximum billet length $\cong 4 \times$ billet diameter. (b) Container diameter is generally 0.375 in. (9.53 mm) more than the specified.

Minimum bearing lengths for easy-to-extrude aluminum alloys as a function of the wall thickness and circumscribing circle of the cross section of the semifinished product

Wall thickness, mm	Minimum bearing length, mm								
	Diameter of the circumscribing circle, mm								
	30	60	100	150	200	250	300	400	500
To 1.5	2	3	3.8	3.8	4.5	4.5	...	...	...
2	3	3	3.8	4.5	4.5	5	5	...	...
3	3	3.8	4.5	4.5	5	6	6	6.8	...
4	4.5	4.5	4.5	5	6	6	7.5	9	9
5	4.5	6	6	6	7.5	7.5	9	9	10.5
6	6	7.5	7.5	7.5	9	9	10.5	10.5	12
8	7.5	7.5	7.5	9	9	10.5	10.5	12	12
10	9	9	9	10.5	10.5	10.5	12	12	12
13	9	10.5	10.5	12	12	12	12	12	13.5
16	10.5	10.5	12	12	12	13.5	13.5	13.5	15
Over 16	10.5	12	12	13.5	13.5	13.5	15	15	18

Source: Ames

Preheat temperature and pre-heat times for aluminum extrusion tooling

Tool size diameter, mm		Solid section		Hollow section		Support tool	
		Extrusion die and backer with die holder		Porthole die Bridge die with die holder		Bolster Pressure ring	
		Time, h	Temperature, °C	Time, h	Temperature, °C	Time, h	Temperature, °C
...	300	2.5–3	420–450	3–4	440–460	~3	350
300	500	3–4	420–450	4–5	440–460	~3	350
500	700	4–5	420–450	5–6	440–460	~3	350
Over	700	5–6	420–450	6–8	440–460	~3	350

Source: Ames

Hot working steels for extrusion tools for the direct and indirect extrusion of aluminum and copper alloys

Material No.	Abbreviation	Nominal composition, wt%							
		C	Co	Cr	Mo	Ni	V	W	Ti
1.2311	40CrMnMo7	0.40	...	2.00	0.20	...	...	...	...
1.2323	48CrMoV51	0.45	...	1.45	0.75	...	0.30	...	...
1.2713	55NiCrMoV6	0.55	...	0.70	0.30	1.65	0.10	...	...
1.2714	56NiCrMoV7	0.55	...	1.10	0.50	1.65	0.10	...	...
1.2343	X38CrMoV51	0.38	...	5.20	1.25	...	0.40	...	...
1.2344	X40CrMoV51	0.40	...	5.20	1.35	...	1.00	...	...
1.2365	X32CrMoV33	0.32	...	3.00	2.80	...	0.55	...	...
1.2367	X40CrMoV53	0.38	...	5.00	3.00	...	0.55	...	...
1.2567	X30WCrV53	0.30	...	2.35	0.60	...	...	4.25	...
1.2581	X30WCrV93	0.30	...	2.65	0.35	...	...	8.50	...
1.2678	X45CoCrWV555	0.45	4.50	4.50	0.50	...	2.00	4.50	...
1.2885	X32CrMoCoV333	0.32	2.80	3.00	2.80	...	0.60	...	...
1.2889	X45CoCrMoV553	0.45	4.50	4.50	3.00	...	2.00	...	...
1.2731	X50NiCrWV1313	0.50	...	13.00	...	13.0	1.30	1.30	...
1.2758	X50WNiCrVCo1212	0.50	1.70	4.00	0.70	11.5	1.10	12.50	...
1.2779	X60NiCrTi2615	0.05	...	15.00	1.30	25.5	0.30	...	2.10 + B

Source: [Kor 95]

Hot working materials for direct deformation extrusion tooling

Extrusion tools	Extruded material					
	Lead-zinc and tin alloys	Magnesium and aluminum alloys		Copper alloys		Iron alloys
	Tool material	Tool material	Initial strength, N/mm ²	Tool material	Initial strength, N/mm ²	Tool material
Extrusion dies	1.2343 Stellite 3/stellite 6 (for solder wires)	1.2343/1.2367	1500–1800	1.2365/1.2888/1.2889 1.2731 2.4668	1450–1550 ~1050 1300–1400	1.2343/1.2731 (forged or cast)
Feeder chambers	1.2323/1.2343	1.2343	1500–1700	Not suitable	...	Not suitable
Die inserts	Not common	In general, not common	...	Cermotherm (brass wire) MHC/ZrO ₂ (German silver) 2.4668/2.4973/2.4979 Stellite 3/stellite 6 1.2343/1.2367/1.2889 1.2731	1200–1500	TZM
Die body	Not common	In general, not common	...	1.2343/1.2367/1.2889 1.2731	1450–1550 ~1200	1.2343
Mandrel	1.2343	<60 mm diameter, 1.2367 >60 mm diameter, 1.2343	<60 mm diameter, 1600–1800 >60 mm diameter, 1500–1600	<60 mm diameter, 1.2367 >60 mm diameter, 1.2343/1.2367	<60 mm diameter, 1600–1700 <60 mm diameter, 1500–1600	1.2344/1.2367
Mandrel tips	Not common	1.2343/1.2367	1600–1800	1.2889 2.4973/2.4979	1400–1500 1200–1500	Not common
Porthole dies	1.2343	1.2343/1.2367 1.2885	1500–1800	Not suitable	...	Not suitable
Bridge dies	1.2343	1.2343/1.2367 1.2885	1500–1800	2.4668/2.4973	1200–1500	Not suitable

Dimensions of extrusion stems for indirect extrusion for specific press pressures

Stem dimensions and stem loads								
Specific extrusion pressure, N/mm ²		Press capacity, MN						
		12.5–14	16–18	20–22.5	25–28	31.5–36	40–45	50–56
		Shank length, mm						
		1000	1120	1250	1400	1600	1800	2000
315	Outside diameter, mm	230	259	293	328	373	417	467
	Inside diameter, mm	175	195	220	245	280	310	350
	Compressive stress, N/mm ²	800	789	765	750	744	737	746
400	Outside diameter, mm	206	230	259	293	328	373	415
	Inside diameter, mm	145	160	180	205	230	265	290
	Compressive stress, N/mm ²	836	840	826	814	827	801	809
500	Outside diameter, mm	185	206	230	259	293	328	373
	Inside diameter, mm	115	125	140	160	180	200	225
	Compressive stress, N/mm ²	849	855	860	859	846	848	806
630	Outside diameter, mm	165	185	206	230	259	293	328
	Inside diameter, mm	85	95	105	115	130	150	165
	Compressive stress, N/mm ²	891	901	912	899	901	904	887
710	Outside diameter, mm	155	175	195	219	244	274	308
	Inside diameter, mm	65	70	80	90	100	110	125
	Compressive stress, N/mm ²	900	890	906	895	913	910	900

Source: Groos

Hot working materials for extrusion containers

Extruded metal(a)		Characteristic data for current hot working materials(b)		
For the application:		Maximum working temperature, °C	Material No.	Strength heat treated to, N/mm ²
IB = Liner				
ZB = Liner holder				Permitted load at operating temperature(c), N/mm ²
M = Mantle				
IB Easily extruded aluminum alloys	500	1.2367	1300–1500	850
IB Moderately difficult aluminum alloys	500	1.2367	1300–1500	850
IB Moderately difficult aluminum alloys, indirect	450	1.2344	1300–1500	850
IB Difficult-to-extrude aluminum alloys	500	1.2367	1300–1500	850
IB Difficult-to-extrude aluminum alloys, indirect	450	1.2344	1300–1500	850
IB Easily extruded copper alloys	600	1.2779	1000–1100	550(d)
IB Easily extruded copper alloys, indirect	600	1.2779	1000–1100	550(d)
IB Moderately difficult copper alloys	650	1.2779	1000–1100	500(d)
IB Difficult-to-extrude copper alloys	700	1.2779	1000–1100	425(d)
IB Easily extruded iron alloys	550	1.2343	1300–1500	700
IB Difficult-to-extrude iron alloys	600	1.2367	1300–1500	800
IB Nickel alloys	650	1.2779	1000–1100	500(d)
ZB Moderately difficult aluminum alloys	500	1.2343	1100–1300	800
ZB Difficult-to-extrude aluminum alloys	500	1.2343	1100–1300	800
ZB Difficult-to-extrude aluminum alloys, indirect	450	1.2343	1100–1300	800
ZB Moderately difficult copper alloys	550	1.2367	1100–1300	800
ZB Difficult-to-extrude copper alloys	600	1.2367	1100–1300	750
ZB Easily extruded iron alloys	500	1.2343	1100–1300	800
ZB Difficult-to-extrude iron alloys	500	1.2367	1100–1300	850
ZB Nickel alloys	550	1.2367	1100–1300	800
M Easily extruded aluminum alloys	500	1.2343/1.2323(d)	1000–1200	750/600
M Moderately difficult aluminum alloys	500	1.2343	1000–1200	750
M Moderately difficult aluminum alloys, indirect	450	1.2343/1.2323(e)	1000–1200	750/700
M Difficult-to-extrude aluminum alloys	500	1.2343	1000–1200	750
M Difficult-to-extrude aluminum alloys, indirect	450	1.2343	1000–1200	750
M Easily extruded copper alloys	450	1.2343/1.2323(e)	1000–1200	750/700
M Easily extruded copper alloys, indirect	450	1.2343/1.2323(e)	1000–1200	750/700
M Moderately difficult copper alloys	500	1.2343	1000–1200	750
M Difficult copper alloys	550	1.2367	1000–1200	750
M Easily extruded iron alloys	450	1.2343/1.2323(de)	1000–1200	750/700
M Difficult-to-extrude iron alloys	450	1.2343	1000–1200	750
M Nickel alloys	500	1.2367	1000–1200	800

(a) Table 7.10 gives data on the contributing factors, including billet temperature, specific extrusion pressure, extrusion time, as well as the friction and shear forces.
(b) Only a limited range of materials are listed. (c) 85% of the 0.2% hot proof stress, with the exception of the austenitic steel 1.2779. (d) Data taken from the steel application lists 201 and 202 (VDE h). (e) Alternative for less severe thermal stresses. Source: Groos

Working conditions for containers operating with cooling Material-specific

Material-specific method	Temperature(a), °C	Extrusion pressure, N/mm ²	Friction/shearing	Evaluation(b)	Comments(c)
Easily extruded aluminum alloys	500	0–630	Moderate	Possible	Favorable
Moderately difficult aluminum alloys	500	630–800	Moderate to high	Possible	Favorable
Moderately difficult aluminum alloys, indirect	450	400–630	Not present	High possibility	Increases difficulty
Difficult-to-extrude aluminum alloys	500	800–1000	High	Possible	Favorable
Difficult-to-extrude aluminum alloys indirect	450	630–710	Not present	High possibility	Increases difficulty
Easily extruded copper alloys	500	630	Low	Possible	Favorable
Easily extruded copper alloys, indirect	500	400–630	Not present	Possible	Favorable
Moderately difficult copper alloys	550	630–800	Low	Limited	Increases difficulty
Difficult-to-extrude copper alloys	600	800–1000	Low to moderate	Limited	Difficult
Easily extruded iron alloys	500	630–800	Minimum(d)	Possible	Difficult
Difficult-to-extrude iron alloys	500	800–1250	Minimum(d)	Possible	Very difficult
Nickel alloys	600	800–1250	Low(d)	Limited	Very difficult

(a) Maximum container temperature in the liner in direct and indirect extrusion. Temperature control using a combined heating and cooling system. (b) Estimation on the possibility of design using classical elasticity. (c) Comments on the operating conditions. (d) Dependent on lubrication. Source: Groos

Factors that affect the material-dependent design of containers

Extruded material	Temperature(a), °C	Specific extrusion pressure, $p_{St} = F_{St}/A_0$, N/mm ²	Extrusion time as a percentage of cycle time(b)	Friction and shearing at the liner wall(c)
Easily extruded aluminum alloys	<550	<630	80	Moderate
Moderately difficult aluminum alloys	<550	630–800	85	Moderate to high
Moderately difficult aluminum alloys, indirect	<450	400–630	80	Not present
Difficult-to-extrude aluminum alloys	<550	800–1000	95	High
Difficult-to-extrude aluminum alloys, indirect	<450	630–710	85	Not present
Easily extruded copper alloys	<800	<630	65	Low
Easily extruded copper alloys, indirect	<750	400–630	60	Not present
Moderately difficult copper alloys	<900	630–800	50	Low
Difficult-to-extrude copper alloys	<1000	800–1000	20	Low to moderate
Easily extruded iron alloys	<1200	630–800	10	Negligible(d)
Difficult-to-extrude iron alloys	<1200	800–1250	10	Negligible(e)
Nickel alloys	<1200	800–1250	20	Low to moderate

(a) Maximum billet temperature. (b) Average values. (c) Does not apply to indirect extrusion. (d) For carbon steels using oil-graphite-salt lubrication. (e) For carbon steels with glass lubrication. Source: Groos

Working conditions for containers operating without cooling

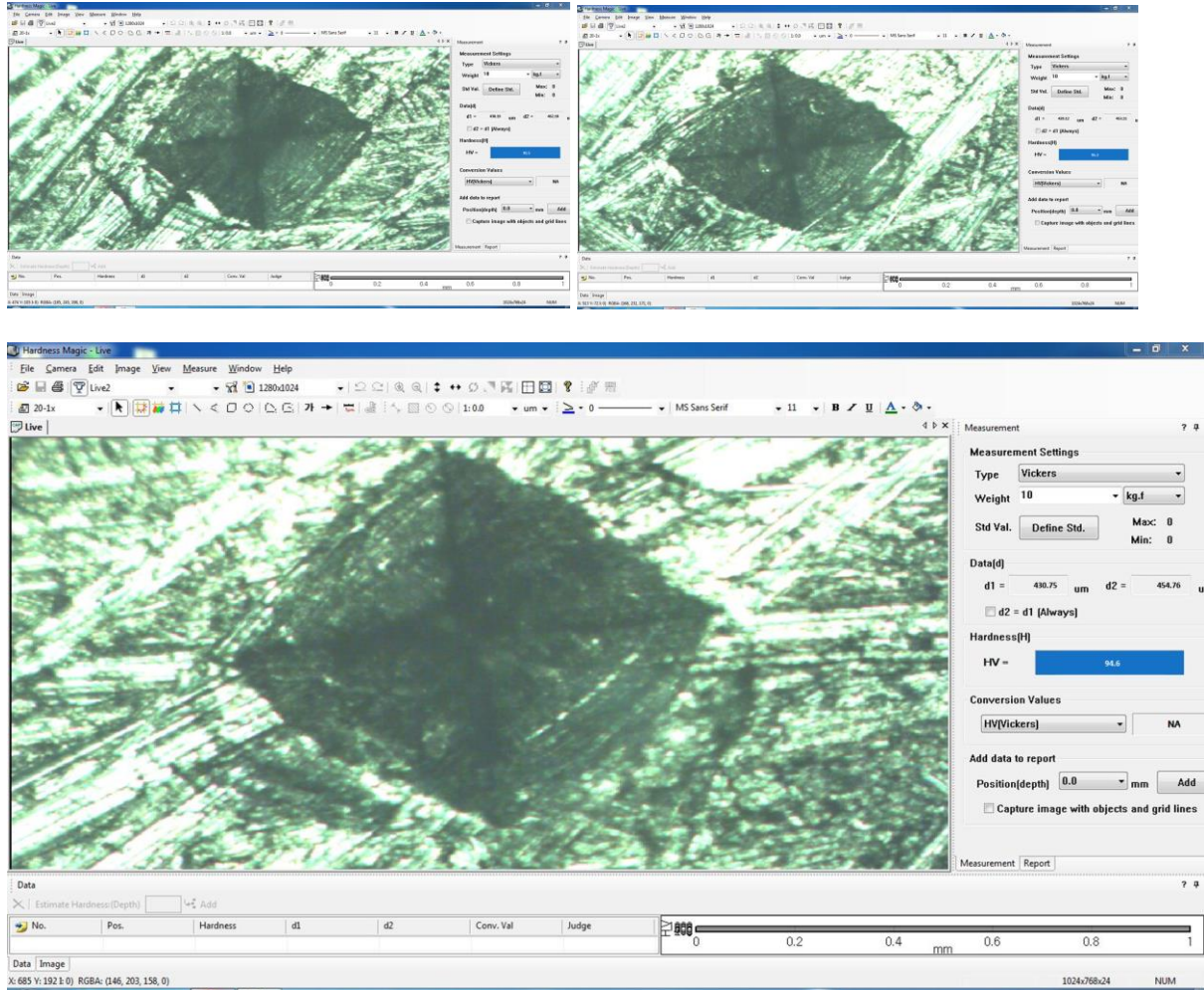
Material and specific method	Temperature(a), °C	Extrusion pressure, N/mm ²	Friction/shearing	Evaluation(b)	Comments(c)
Easily extruded aluminum alloys	500	0–630	Moderate	High possibility	Favorable
Moderately difficult aluminum alloys	500	630–800	Moderate to high	High possibility	Favorable
Moderately difficult aluminum alloys, indirect	450	400–630	Not present	High possibility	Increases difficulty
Difficult-to-extrude aluminum alloys	500	800–1000	High	Possible	Favorable
Difficult-to-extrude aluminum alloys, indirect	450	630–710	Not present	High possibility	Increases difficulty
Easily extruded copper alloys	600	630	Low	Limited	Favorable
Easily extruded copper alloys, indirect	600	400–630	Not present	Limited	Favorable
Moderately difficult copper alloys	650	630–800	Low	Questionable	Increases difficulty
Difficult-to-extrude copper alloys	700	800–1000	Low to moderate	Questionable	Difficult
Easily extruded iron alloys	550(d)	630–800	Minimum(e)	Possible	Difficult
Difficult-to-extrude iron alloys	600(d)	800–1250	Minimum(e)	Limited	Very difficult
Nickel alloys	650(d)	800–1250	Low(e)	Questionable	Very difficult

(a) Maximum container temperature in the liner in direct extrusion. With temperature monitoring. (b) Estimation of the possibility of design using classical elasticity theory. (c) Comments on the operating conditions. (d) Short extrusion times and glass lubrication largely prevent overheating. (e) Dependent on the lubrication. Source: Groos

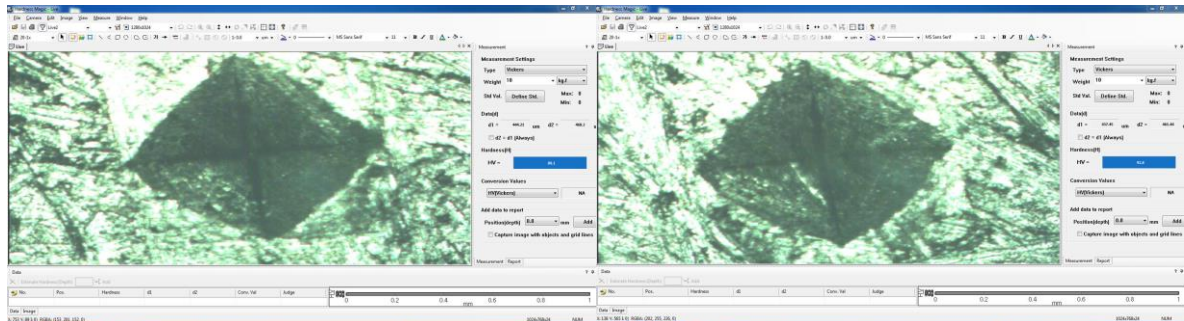
APPENDIX-C

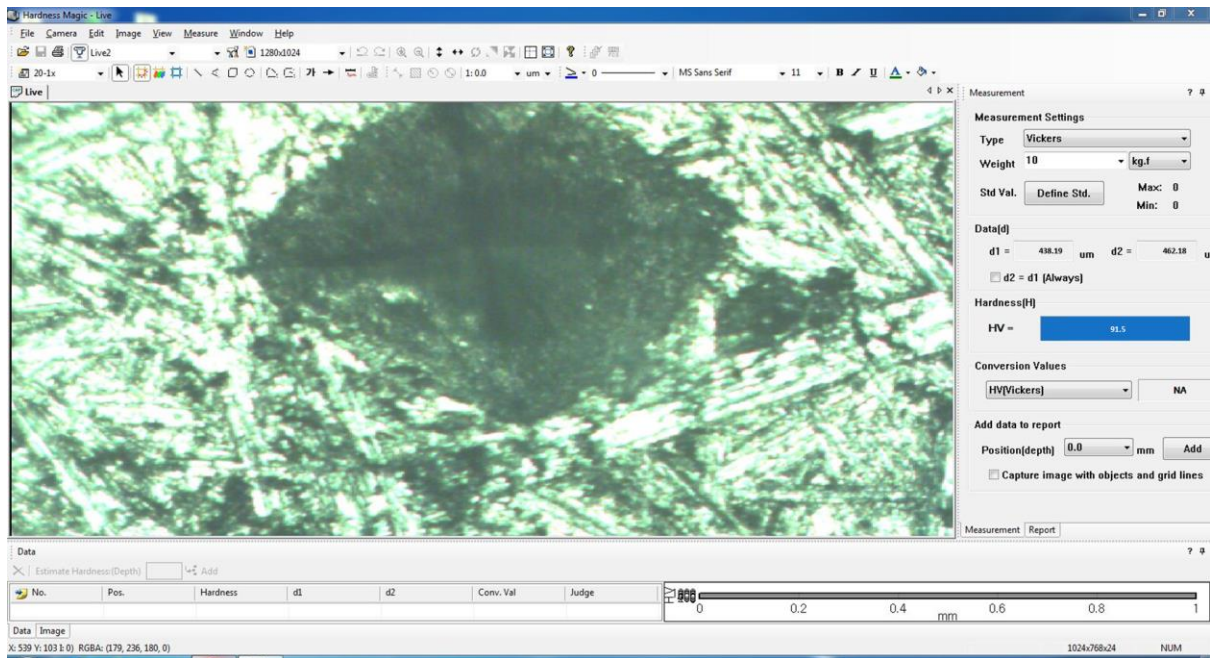
Characterized and tested results

3-Hole die extrusion Vickers hardness images.

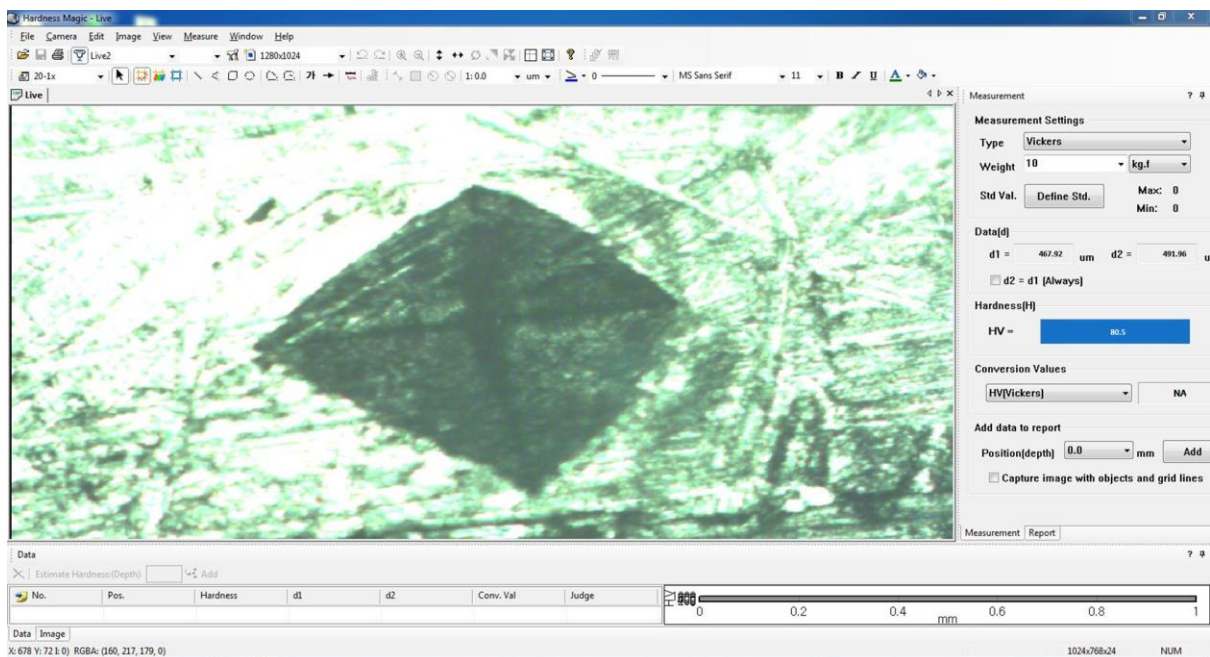
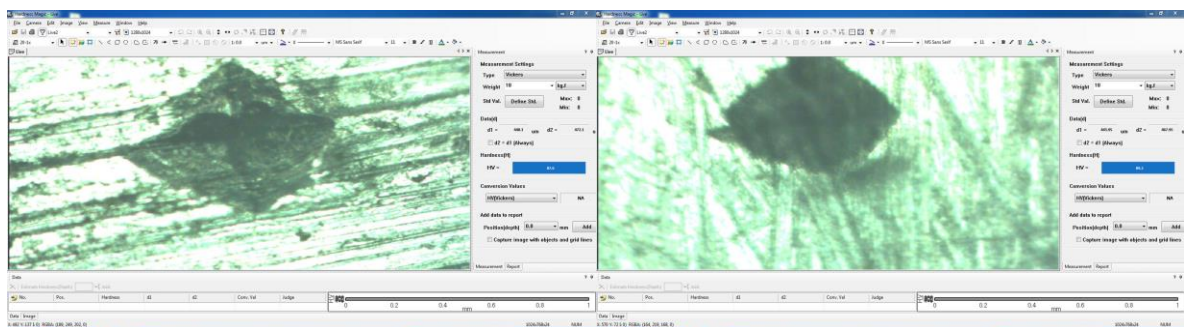


4-Hole die extrusion Vickers hardness images.



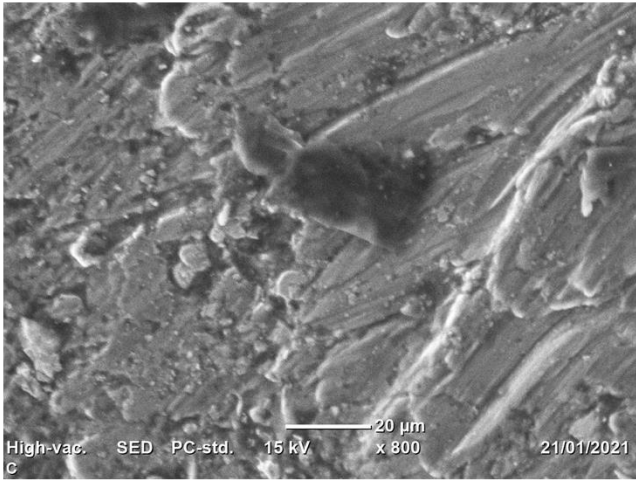
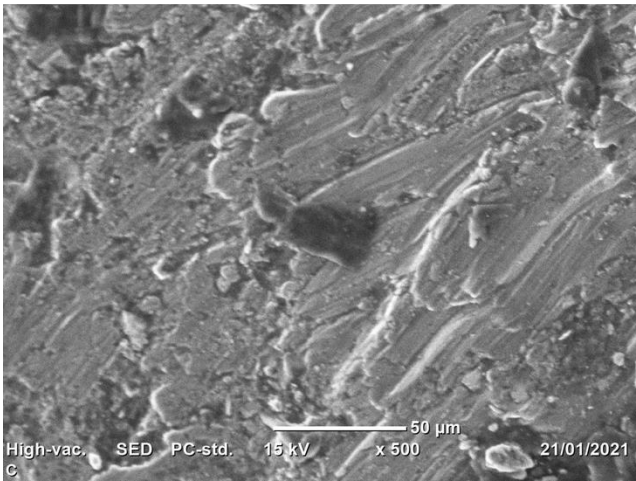
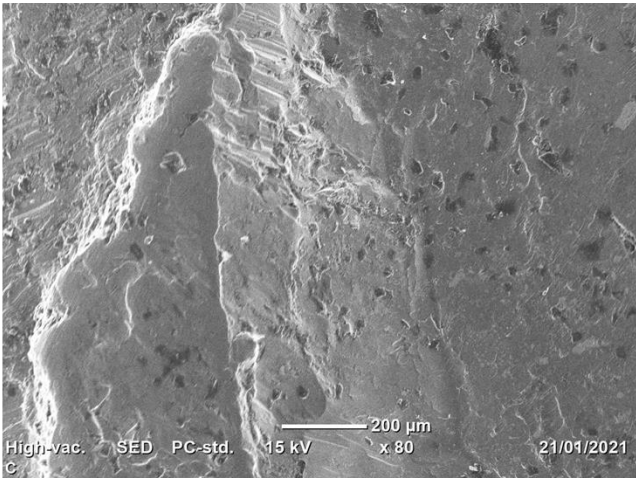
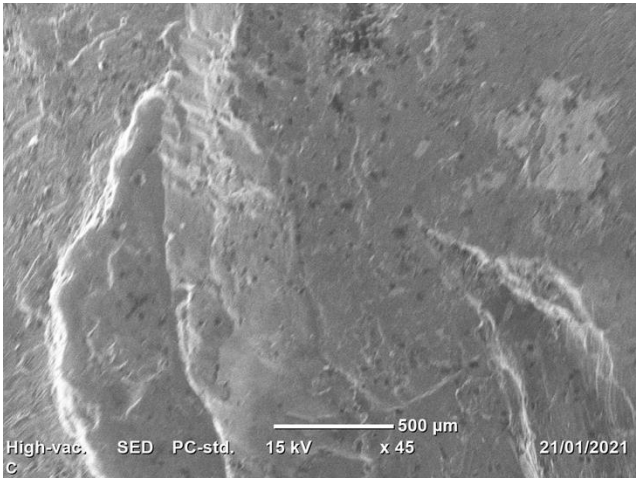


Billet Vickers hardness images.

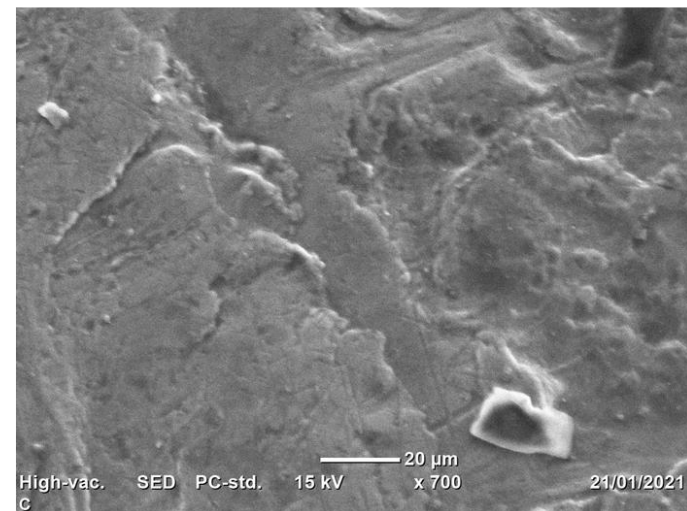
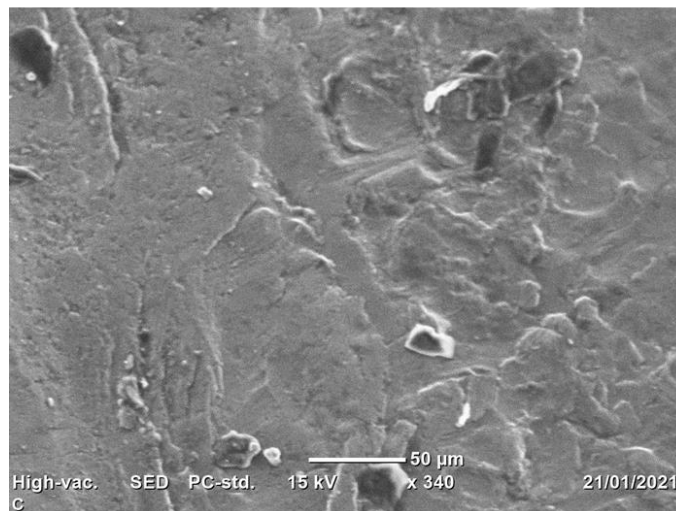
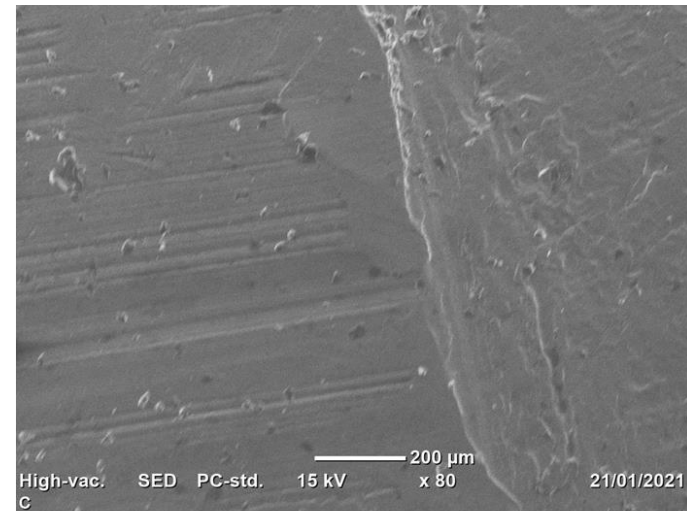
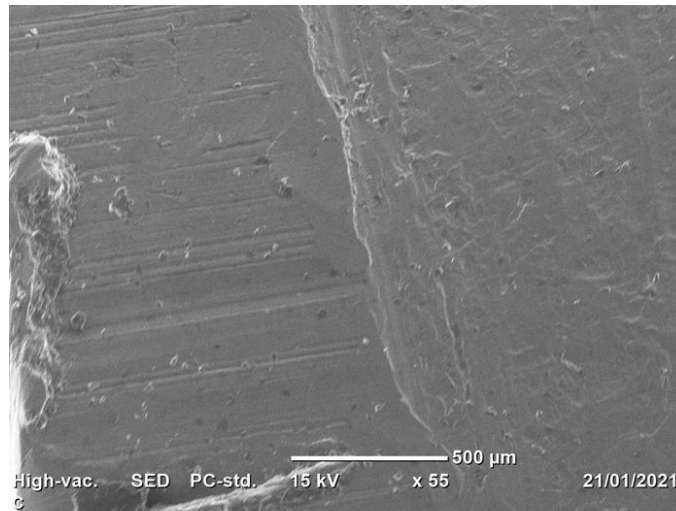


Scanning electron microscope images

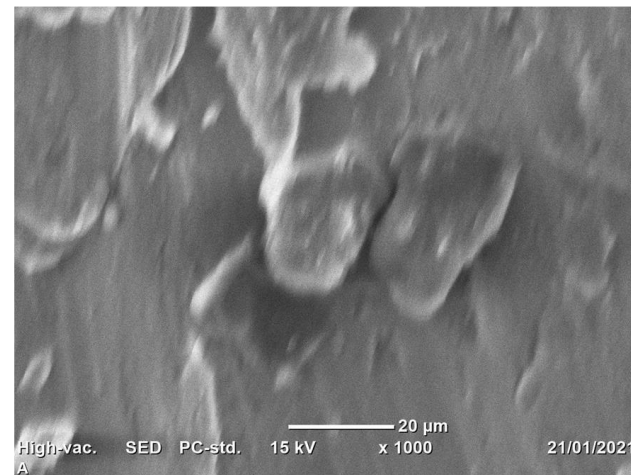
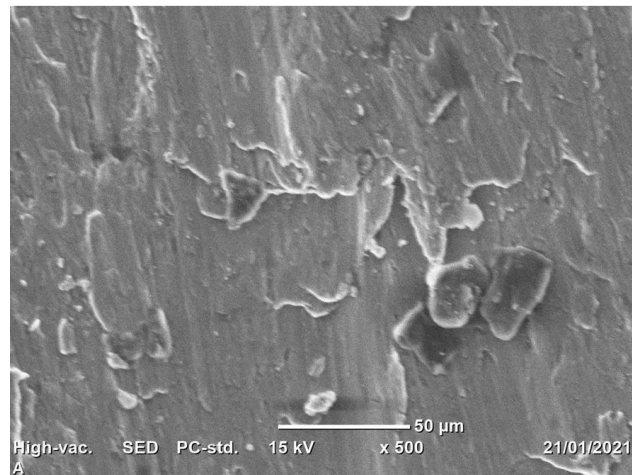
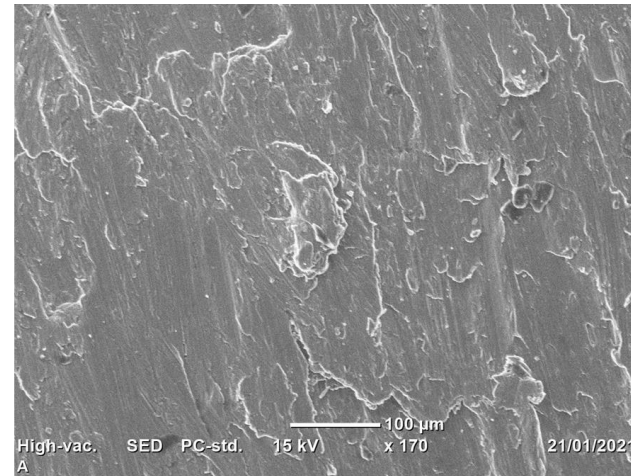
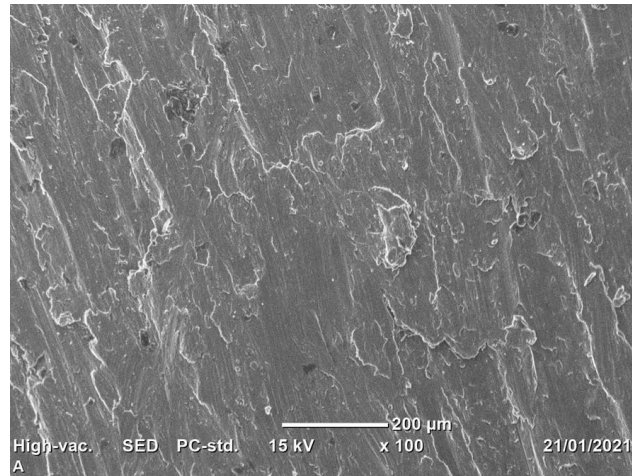
Billet



4- Hole extruded sample

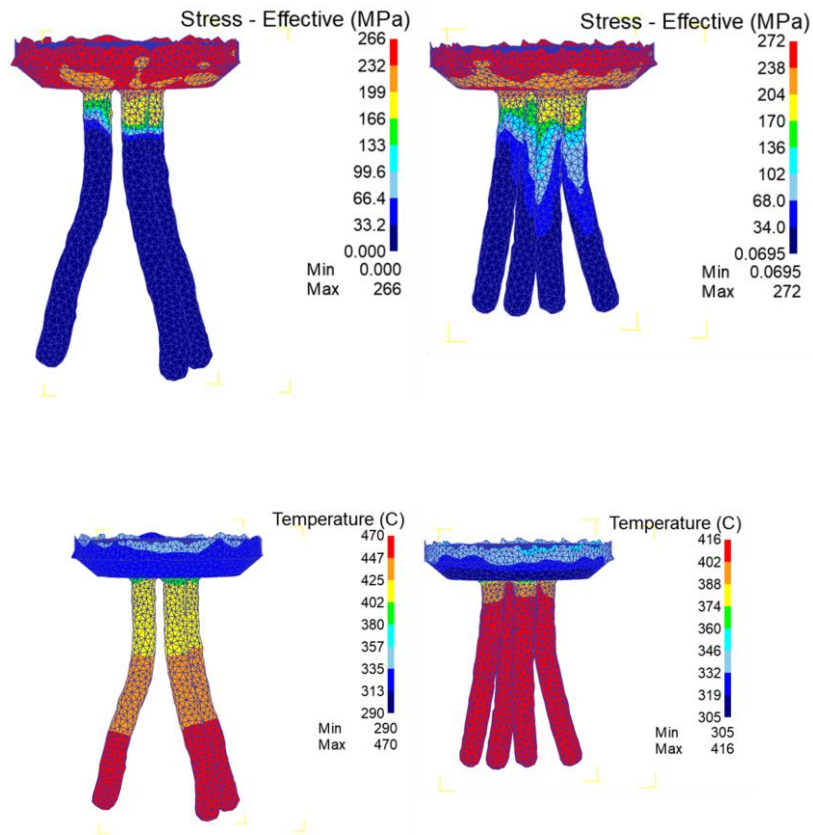


3- Hole extruded sample

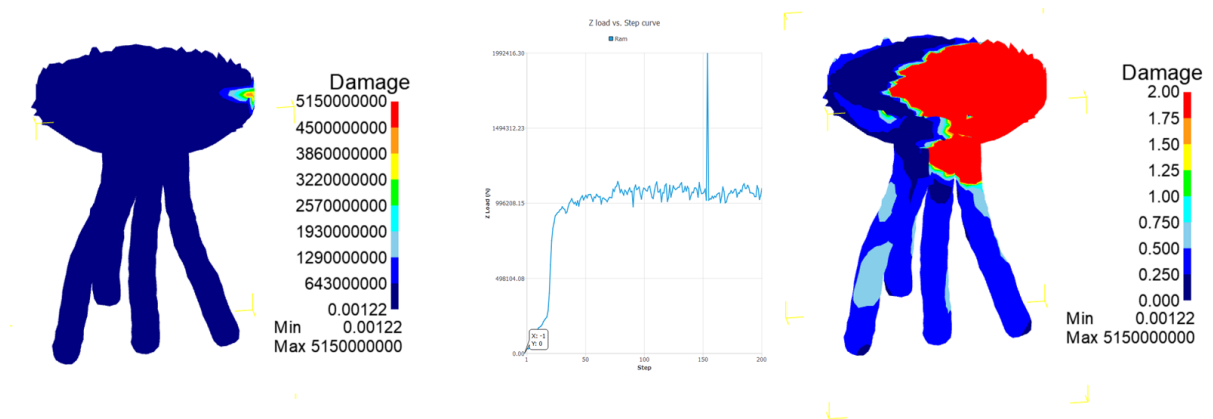


APPENDIX-D

Simulation images



Simulation failures due to bad meshing



APPENDIX-E

Experimental work images

Experimental findings failure and achievements

