INVESTIGATION OF EXTRUDABILITY OF DIFFERENT ALUMINUM ALLOYS BY USING THE METHOD OF HOT EXTRUSION

by

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ABSTRACT

INVESTIGATION OF EXTRUDABILITY OF DIFFERENT ALUMINUM ALLOYS BY USING THE METHOD OF HOT EXTRUSION

Aluminum extrusion is a very important forming process in metal industries. By using different dies and technologies, high variety of products can be produced by using the method extrusion. Extrudability is an important parameter for extrusion processes. For evaluating extrudability of a material not only force and energy requirements must be investigated but also surface quality and mechanical properties of product must be considered properly.

In this study, by using the method hot extrusion, extrudabilities of AA 6063 and AA 7075 aluminum alloys are investigated. Furthermore, by using die-bearing angled dies with relief and choke systems, effect of die-bearing angle on the extrudability of these alloys is tried to be evaluated. Three different choke dies with die- bearing angle of 1.5^{o} choke , 1^{o} choke , 0.5^{o} angle, one type of relief die with die-bearing angle of 0.3^{o} relief adding to all these a standard extrusion die, with no angle system is used for experiments. During experiments, AA 6063 and AA 7075 alloys are used as billets with 30 mm diameter and 80 mm length. A special designed hydraulic hot extrusion press with 350 bars of maximum extrusion pressure is used for extruding the billets. In order to discuss results of experiments properly, SEM images of samples are obtained, for detecting surface qualities of samples roughness test is conducted and for evaluating mechanical properties of samples, tensile test and hardness test are made. Also for investigating flow behaviours of samples during extrusion a special microstructural study is made.

ÖZET

SICAK EKSTRÜZYON YÖNTEMİ KULLANILARAK DEĞİŞİK ALUMİNYUM ALAŞIMLARININ EKSTRÜZYON EDİLEBİLMESİNİN ARAŞTIRILMASI

Aluminyum ekstrüzyon, metal endüstrilerinde kullanılan çok önemli bir şekillendirme yöntemidir. Değişik kalıp ve teknolojiler kullanılarak, geniş yelpazeli ürün çeşitlerini ekstrüzyon yöntemiyle üretmek mümkündür. Ekstrüzyon edilebilme kabiliyeti ekstrüzyon işlemlerinde önemli bir unsurdur. Bir malzemeyi ekstrüzyon edilebilme açısından değerlendirmek için sadece enerji ve kuvvet gereksinimleri değil aynı zamanda ürünün yüzey kalitesi ve mekanik özellikleri de dikkatlice incelenmelidir.

Bu çalışmada, AA 6063 ve AA 7075 aluminyum alaşımlarının, sıcak ekstrüzyon yöntemi kullanılarak ekstrüzyon edilebilmesi araştırılmıştır. Bunun yanı sıra, açılı fren ve hız kalıbı sistemlerinin kullanılmasının, söz konusu alaşımların ekstrüzyon edilebilmesini nasıl etkilediği konusu üzerinde durulmuştur. Deneyler sırasında 1.5^o fren, 1^o fren, 0.5^o fren, 0.3^o hız ve açısız standart kalıplar kullanılmıştır. Bu deneylerin gerçekleştirilebilmesi için AA 6063 ve AA 7075 alaşımları 30 mm çapında ve 80 mm uzunluğunda biyetler haline getirilmiştir. Aynı zamanda, deneyler için özel tasarlanan edilen, maksimum 350 bara kadar çıkabilen bir hidrolik pres bu biyetlerin ekstrüzyonu için kullanılmıştır. Deney sonuçlarının daha iyi irdelenebilmesi amacıyla, örneklerin taramalı elektron mikroskobu görüntüleri alınmış, yüzey kalitelerini belirlemek için yüzey pürüzlüğü ölçümü yapılmış bunun yanı sıra mekanik özelliklerinin saptanması amacıyla sertlik testi ve çekme deneyi uygulanmıştır. Ayrıca ekstrüzyon sırasındaki akışın görüntülenmesi için özel bir mikroyapı çalışması yapılmıştır.

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a	The thermal diffusivity
A	The final area
A_A	The apparent area of contact
A_B	Cross sectional area of billet
A_C	The area of the container bore
A_E	The final area of the extruded rod
A_i	Instantaneous cross section of the specimen
A_0	The original area of the container
A_R	The real area of contact
A_1	Sticking zone area
A_2	Sliding zone area
c	The specific heat
D_C	The inside diameter of the container
D_E	The equivalent diameter of the extruded rod
D_B	Billet diameter
D_0	Container bore
ER	The extrusion ratio
ER_1	The extrusion ratio for the bigger opening die
ER_2	The extrusion ratio of the smaller opening die
F	The tensile load
F_F	Frictional forces
F_{id}	Ideal deformation load
F_T	Total load
J	The mechanical equivalent of heat
k	The material shear strength

k_f	The flow stress
l	The final length
l_i	Instantaneous billet length
l_0	Initial billet length
l_1	Length of the extruded product
L	Length of deformation zone
dL	An element of volume by a change in length
m	The friction factor between billet and container interface
m'	The friction factor between flowing metal and die-bearing interface
m_1	Sticking friction factor
m_2	Sliding friction factor
N	The normal force
p_l	The ram pressure
p_e	Extrusion pressure
q_f	Frictional heat flux
R_m	The radius of billet at any nodal point (m,j)
T	Temperature of the billet
U	Circumference
U'''	Strain rate
V	Deforming volume
v_R	The average ram speed
$v_{material}$	The speed of material in billet – container interface
$v_{m,j}$	The speed of the following material at the interface nodal points
v_z	The speed of material along the Z-axis with respect to stationary co-ordinates
W_F	Work to overcome friction
W_{id}	The ideal work of deformation
W_S	Shearing work

W_T	Total deformation work
α	The dead-metal zone semi angle
α_1	The semi dead-metal zone angle corresponding to ER_1
α_2	The semi dead-metal zone angle corresponding to ER_2
$\dot{\varepsilon}$	Mean effective strain rate
$\bar{\varepsilon}$	The natural or effective strain
η_f	Deformation efficiency factor
μ	Coefficient of friction
μ_f	Coefficient of friction between billet surface and container wall
ρ	The specific weight
σ	Stress
$\sigma_1, \sigma_2, \sigma_3$	Normal principal stresses
τ	The shear stress
τ_i	Shear strength of the interface
τ_f	Frictional stress
τ_F	Measured shear stress
φ	Logarithmic strain

1. INTRODUCTION

The importance of metals in modern technology is due, in large part, to the ease with which they may be formed into useful shapes such as tubes, rods and sheets. Useful shapes may be generated in two basic ways:

- By plastic deformation processes in which the volume and mass of metal are conserved and the metal is displaced from one location to another.
- By metal removal or machining processes in which material is removed in order to give it the required shape [1].

A metal forming process is characterized by various process parameters including the shape of the work piece and product, forming sequence, shapes of the tools or dies, friction, temperature, forming speed, and material property of the work piece and those of the tools. Apparently, making proper selections regarding controllable process parameters is the main problem that a process designer is ultimately faced with [2].

Various metal forming processes such as extrusion, drawing, and rolling may be characterized by the steady state thermo-mechanical behavior in which the values of the state variables measured at any point in the analysis domain do not vary with time [2].

Hundreds of processes have been developed for specific metalworking applications. However, these processes may be classified into only a few categories on the basis of the type of forces applied to the work piece as it is formed into shape. These categories are:

- Direct-compression-type processes
- Indirect-compression processes
- Tension type processes
- Bending processes
- Shearing processes

In direct-compression processes the force is applied to the surface of the workpiece, and the metal flows at right angles to the direction of the compression. The chief examples of this type of process are forging and rolling. Indirect-compression processes include wiredrawing and tube drawing, extrusion, and the deep drawing of a cup. The primary applied forces are frequently tensile, but the indirect compressive forces developed by the reaction of the work piece with the die reach high values. Therefore, the metal flows under the action of a combined stress state which includes high compressive forces in at least one of the principal directions. The best example of a tension-type forming process is stretch forming. Bending involves the application of bending moments to the sheet, while shearing involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear [1].

Hot metal forming (rolling, forging, extrusion, wire drawing) constitutes a very large proportion of manufacturing activity. All of the equipment and tooling involved in a hot forming process, the most critical component is usually considered to be the die due to its superior precision and reliability requirement and the associated high cost. Dies and ancillary tooling are exposed to high pressures/forces, elevated temperatures, mechanical and thermal fatigue. Cost and engineering difficulty are then obviously high because of factors such as special material and processing, very fine tolerances, and high demands on repeated thermo-mechanical performance. Critical to any study involving efficiency, productivity, or overall economy of any hot forming operation is thus an analysis of tooling performance in terms of die life and reliability assessment and prediction [3]. A very important factor contributing to the performance and economics (efficiency and quality) of any hot metal-forming process is the service life of tooling. Product rework and rejects can be traced back to various defects spread over the die life-cycle: die design, die manufacture, heat treatment and die service [4].

Extrusion is a plastic deformation process in which a block of metal (billet) is forced to flow by compression through the die opening of a smaller cross-sectional area than that of the original billet as shown in Figure 1.1 [5].

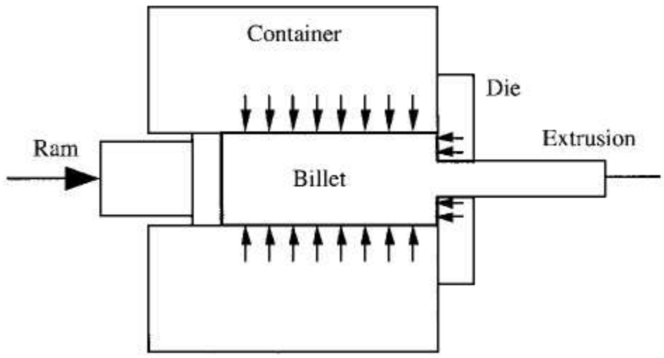


Figure 1.1. Definition and principle of extrusion [5]

Extrusion is an indirect-compression process. Indirect-compressive forces are developed by the reaction of the work piece (billet) with the container and die; these forces reach high values. The reaction of the billet with the container and die results in high compressive stresses that is 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 [5].

The aluminum extrusion process is a thermoforming operation using a combination of heat and pressure to transform aluminum billets into functional products. Historically, processes have been operated manually at conservative levels using intermittent measuring techniques and accepting product variability and waste. The operator’s experience was the key. Now new technology allows one to fully characterize the thermoforming parameters of the process, learn more about what is happening in real time, and take the extrusion process to the next level of managed automation. Second tier benefits include microstructure analysis, physical properties of the profile, and surface and dimensional characteristics [6].

The purpose of this thesis is to investigate the extrudabilities of AA 6063 and AA 7075 alloys by using a hot metal forming method of hot extrusion. Die bearing angle effect on extrudabilities of these alloys is the main investigation topic in this thesis. The effect of other parameters like temperature of extrusion, speed of extrusion, extrusion ratio, friction between material-container and material die interfaces are also discussed.

2. EXTRUSION PROCESS; CLASSIFICATION AND DEFINITION

2.1. Hot Extrusion and Extrudability

Extrusion is commonly classified as a hot-working process. Hot working is defined as deformation under different temperature and strain-rate so that recovery processes take place simultaneously within deformation. With aluminum dynamic recovery is usually the only such process that can be observed. The critical characteristics of the extrusion process is that the work should be carried out in a range of temperatures, in which the metal has adequate plasticity to allow for the desired shape change, usually severe, to be carried out and also to reduce the forces required for extrusion [7].

The principal variables which influence the force required to cause extrusion are:

- the type of extrusion (direct vs. indirect)
- the extrusion ratio
- the working temperature
- the speed of deformation
- the frictional condition at the die and container wall [1].

In Figure 2.1 the extrusion pressure is plotted against ram travel for direct and indirect extrusion. Extrusion pressure is the extrusion force divided by the cross-sectional area of the billet. The rapid rise in pressure during the initial ram travel is due tot the initial compression of the billet to fill the extrusion container. For direct extrusion the metal begins to flow through the die at the maximum value of pressure, the breakthrough pressure. As the billet extrudes through the die the pressure required to maintain flow progressively decreases with decreasing length of the billet in the container. For indirect extrusion there is no relative motion between the billet and the container wall. Therefore, the extrusion pressure is approximately constant with increasing ram travel and represents the stress required to deform the metal through the die. While this appears to be an attractive process, in practice it is limited by the need to use a hollow ram which creates limitations on the size of the extrusion and the extrusion pressures which can be achieved. Therefore, most hot extrusion is done by the direct process [1].

The term hot extrusion is used to describe processes in which a billet, enclosed in a container, is pushed through a shaped opening (die, orifice) at an elevated temperature. As a result of the forming operation, the initial cross-sectional area of the workpiece is reduced and a bar of solid or hollow cross section is produced. Hot extrusion is used primarily to manufacture semifinished products such as bars, tubes or profile sections. The main advantage over other processes, such as rolling or bar drawing, is that practically any desired cross-sectional shape can be produced, that is, not only solid sections but also hollow sections with differently shaped inner and outer contours where required. In contrast to cold extrusion, which is also a member of compressive-forming group of processes, hot extrusion is, for the majority of metals, performed above the recrystallization temperature [8].

For solid forward hot extrusion, dies with an opening angle of $2\alpha = 180^0$ (flat dies) or $2\alpha < 180^0$ (conical dies) are used. Light alloys like aluminum are worked with $2\alpha = 180^0$, often without lubrication, with or without leaving a shell. For other metals the die-opening angle is $2\alpha < 180^0$ when lubrication is used and $2\alpha = 180^0$ when extruding with shell [8].

When hollow sections are to be produced by means of direct extrusion, either a (fixed or moving) mandrel or specially designed dies may be used. Such dies (bridge dies and prothole dies among others) are often used when tubes and especially hollow sections of complicated cross-sectional shapes mostly made of aluminum are to be produced. As a rule, the billet is first split into several streams by applying a high pressure to the end face. The streams then flow over a short, exactly centered fixed mandrel and, behind this, weld together to form a hollow profile of the desired cross-section [8].

Hot extrusion is a very cost efficient method of aluminium forming. One limitation for further improvement of cost reduction is wear of the bearing surface on the die which deteriorates the dimensional tolerance and surface quality of the profile. Nitrided hot work tool steels are commonly used as die material but new surface treatments are being introduced [9].

Most metals are extruded hot so as to take advantage of the decrease in flow stress or deformation resistance with increasing temperature. Since hot-working introduces the problems of oxidation of the billet and the extrusion tools and softening of die and tools, as well as making it more difficult to provide adequate lubrication, it is advantageous to use the minimum temperature which will provide the metal with suitable plasticity. The upper hot-working temperature is the temperature at which hot shortness occurs, or, for pure metals, the melting point. Because of the extensive deformation produced in extrusion, considerable internal heating of the metal also results. Therefore, the top working temperature should be safely below the melting point or hot-shortness range [1].

Hot extrusion is usually performed using converging dies, in which the cross-section of the die orifice changes gradually from the initial billet shape to the final product shape over the length of the die. The strain and strain rate variations that the material experience as it flows through the die depends on the die profile. The dies commonly used during hot extrusion are conical, cubic streamline, and have a constant true strain rate. The various die shapes impose considerably different strain rate conditions on the deforming billet and thus, influence the product microstructure in various ways. Dynamic recrystallisation is commonly observed in hot extrusion processes which involve very large strains (typically greater than one). Metals and alloys characterized by relatively low stacking fault energy (e.g. copper, nickel, and austenitic steels) have a high propensity for undergoing restoration via dynamic recrystallisation and recovery. Under practical hot working conditions, these materials exhibit flow curves containing single maxima [10].

Altıntaş [11] had investigated the effect of extrusion parameters on the mechanical properties of AlMgSi0.5 alloy. In this study, extrusion experiments were conducted at different temperatures and with different ram speeds, results of these investigations showed that these parameters do not have an serious influence on the mechanical properties of extruded products but strength values differs in the front and end zones of the product. It was also reported that strength differences in the front and end zones of the products was seen mostly in the heat-treated products. It was concluded that the billets, used during the experiments were unhomogenized and these unhomogenized billets were the reason for the differences of the strength in the front and end parts of the products.

All aluminum alloys can be extruded but some are less suitable than others, requiring higher pressures, allowing only low extrusion speeds and/or having less than acceptable surface finish and section complexity. “Extrudability” is the ability to be extruded at high speed with optimum force and energy. The term "extrudability" is used to embrace all of these issues with pure aluminum at one end of the scale and the strong aluminum/zinc/magnesium/copper alloys or other (Table 2.1). Because of the mentioned complex interaction of process factors this rating can be seen to be arbitrary [12].

Knowledge of optimal extrusion speed, billet temperature, and billet length help increase productivity and reduce scrap. Demand for high-speed production rates, increased product safety standards, and lower energy consumption have prompted plants to use various methods to determine optimum process conditions. One such method is use of control systems that adjust extrusion speeds using the exit temperature. These systems, objective is to reach the isothermal extrusion. Such control systems are capable of dynamically updating the process conditions from billet-to-billet, and recommend near optimal press speed and billet preheat. This approach, however, still required the extrusion engineer to guess process conditions for the first billet. Another approach is through the use of analytical methods to compute extrusion speed. One of the drawbacks of using analytical methods is that they cannot be generalized, and usually produce incorrect results for complex profiles [13].

The limitation of analytical expressions can be overcome by including higher order terms in the analytical models. The expressions for pressure and temperature derived from upper bound theory are modified using results from press data and finite element analysis. The model uses press capacity, container diameter, temperature and strain rate dependent alloy properties, die shape, and profile geometry to compute the extrusion limit diagram. This extrusion limit diagram is then used to determine the optimal extrusion speed, billet preheat and taper. The main advantage of the approach is that it is general enough to be applied to many different alloys. The method also helps remove the guesswork from estimation of extrusion speeds. Extrusion limit diagrams are very useful for determining extrudability of different alloys in the extrusion processes [13].

Both solid and hollow sections can be supplied by any extrusion plant, but there are differences in the philosophy of design and manufacture of the dies for the latter which affect both cost and quality of the product; also some structural features of the product may require modification for better extrudability [12]. In Table 2.1 relative extrudabilities of some 6xxx and 7xxx series commercial aluminum alloys are given.

Table 2.1. Relative Extrudability of Aluminum Alloys [12]

ALLOY	**RATING**
6063	100
6066	40
6101	100
6151	70
6253	80
6351	60
6463	100
6663	100
7001	7
7075	10
7079	10
7178	7

Hjung-Ho Jo *et al.* studied on the effect of Magnesium alloys in 7003 alloy. They have used different A7003 alloy billets with 72 mm diameter and 200 mm length. In the experiments extrusion dies with an angle $2\alpha = 180^0$ are used. They made different experiments and finally stated that increasing the Mg alloy content in 7003 alloy will decrease the extrudability [14].

2.2. Classification of Extrusion Processes

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

- Solid sections, bars, and rods extruded from solid billets by direct extrusion
- Tubes and hollow sections extruded from solid billets through port hole or bridge-type dies (for certain alloys) by direct extrusion
- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in the press via floating mandrel) by direct extrusion.
- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in the press via stationary mandrel) by direct extrusion
- Critical solid sections, bars, and rods extruded from solid billets with sealed container through the die mounted on the stem by indirect extrusion.
- Tubes and hollow sections extruded from hollow or solid billets (latter pierced in press) via stationary mandrel through the die mounted on the stem by the indirect extrusion process [5].

2.2.1 Conventional direct extrusion

The most important and common method used in aluminum extrusion is the direct process. Figure 2.1 shows the principle of direct extrusion where the billet is placed in the container and pushed through the die by the ram pressure. Direct extrusion finds application in the manufacture of solid rods, bars, hollow tubes, and hollow and solid sections according to the design and shape of the die. In direct extrusion, the direction of metal flow will be in the same direction as ram travel. During this process, the billet slides relative to the walls of the container. The resulting frictional force increases the ram pressure considerably. During direct extrusion, the load or pressure-displacement curve most commonly has the form shown in Figure 2.2. Traditionally; the process has been described as having three distinct regions:

- The billet is upset, and pressure rises rapidly to its peak value.

- The pressure decreases, and what is termed “steady state” extrusion proceeds.
- The pressure reaches its minimum value followed by a sharp rise as the “discard” is compacted.

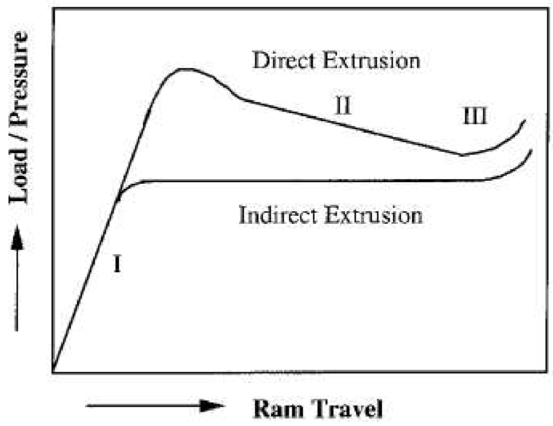


Figure 2.1. Variation of load or pressure with ram travel for both direct and indirect extrusion process [5]

2.2.2. Billet–On–Billet Extrusion

Billet-on-billet extrusion is a special method for aluminum alloys that are easily welded together at the extrusion temperature and pressure. Using this process, continuous lengths of a given geometry (shape) can be produced by different methods. Billet-on-billet extrusion is also a viable process in the production of coiled semi finished products for further processing, such as rod and tube drawing production. Perfect welding of the billet in the container with the following billet must take place as the joint passes through the deformation zone. The following requirements have to be fullfilled:

- Good weldability at the temperature of deformation.
- Accurate temperature control
- Cleaned billet surface
- Sawn, clean billet ends free from grease
- Bleeding of air from the container at the start of the extrusion using taper-heated billet as shown in Figure 2.3 to avoid blisters and other defects [5].

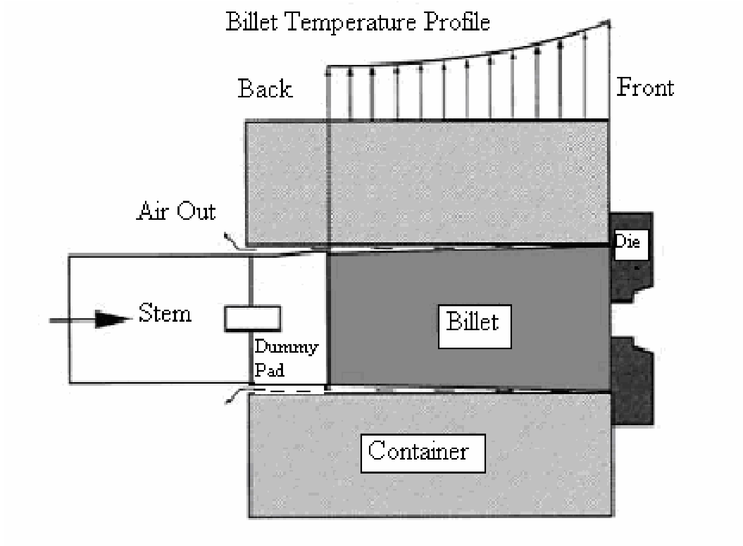


Figure 2.2. Bleeding out air during upsetting [5]

Two methods of billet-on-billet extrusion have been developed. In the first method, the discard is removed, and the following billet is welded to the one remaining in the welding or feeder plate, as can be seen in Figure 2.4.

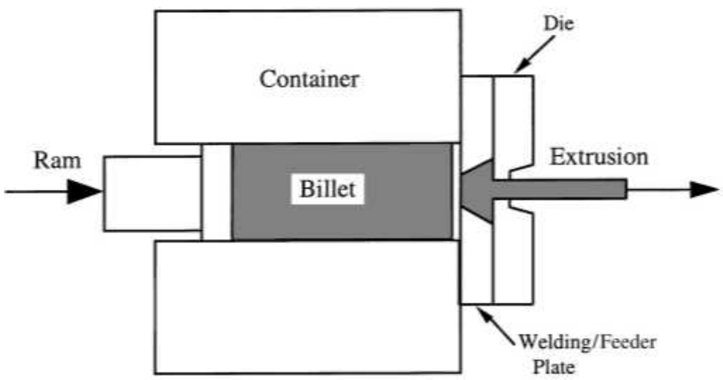


Figure 2.3. Continuous-type extrusion using welding plate in front of the die

(Method one)[5]

The second method does not need a discard; the subsequent billet is pressed directly onto the billet still in the container as shown in Figure 2.4. The dummy block attached with the stem shears an aluminum ring from the container during each return stroke, and has to be removed from the stem.

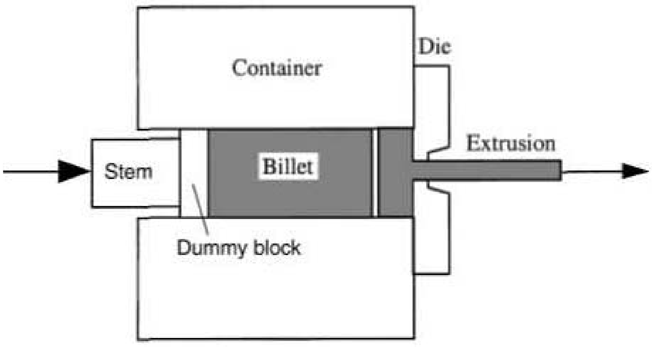


Figure 2.4. Billet-on-billet extrusion (method two) [5]

2.2.3. Indirect Extrusion

In indirect extrusion, the die at the front end of the hollow stem moves relative to the container, but there is no relative displacement between the billet and the container as shown in Figure 2.5. Therefore, this process is characterized by the absence of friction between the billet surface and the container, and there is no displacement of the billet center relative to the peripheral regions. The variation of load or pressure with the ram travel during both direct and indirect extrusion processes is shown in Figure 2.2 [5].

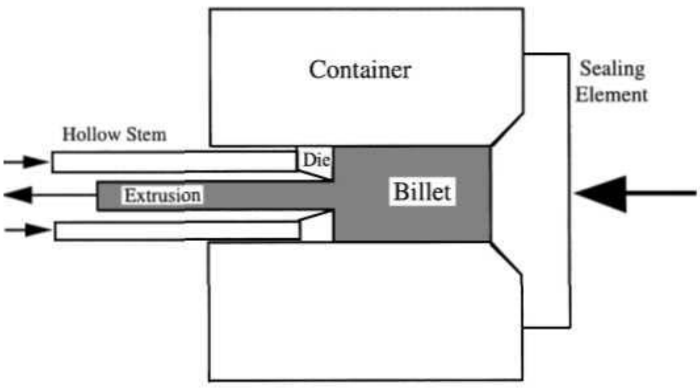


Figure 2.5. Indirect extrusion process [5]

2.3. Mechanics of Extrusion

2.3.1. Plastic Deformation and Metal Flow

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

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

The mechanics of plastic deformation provide the means for determining how the metal flows in different forming operations, the means of obtaining desired geometry through plastic deformation, and the means for determining the expected mechanical and physical properties of the metal produced. Different mathematical equations can be obtained through a different approach for different forming operations, including extrusion [5].

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

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

A fairly large numbers of investigations of the flow characteristics of metal, such as lead, tin, and aluminum, have been made by using split-billet technique. Typical flow patterns observed in extrusion are shown in Figure 2.6 [5].

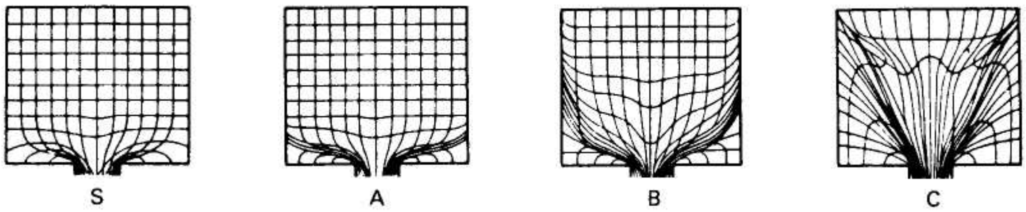


Figure 2.6. Four different types of flow in extrusion [5]

Flow pattern A is obtained in extrusion of homogeneous materials in the presence of friction at the die interface, not at the container-billet interface. This flow pattern is good for indirect extrusion. The metal at the center of the billet moves faster than the metal at the periphery. In the corner of the leading en of the billet, a separate metal zone is formed between the die face and the container wall, known as a dead-metal zone. The material near the surface undergoes shear deformation compared with the pure deformation at the center, and it flows diagonally into the die opening to form the outer shell of extrusion [5].

Flow pattern B is obtained in homogeneous materials when there is friction in both container and die interfaces. This flow pattern is good for direct extrusion processes. An extended dead-metal zone is formed. In this case, there is more shear deformation compared with that in flow pattern A. The extrusion has nonuniform properties compared with that in flow pattern A [5].

Flow pattern C is obtained with billets having inhomogeneous material properties or with a nonuniform temperature distribution in the billet. Materials undergo more severe shear deformation at the container wall and also form a more extended dead-metal zone [5].

Figure 2.7 shows metal flow of billet in direct extrusion. In direct extrusion, billet goes forward in the standstill container. Shear friction generates at the outer billet surface. Metal flow in the center of billet is faster than that in the outer part of the billet. Therefore, shear deformation zone appears between the dead metal zone and the flow zone. Oxide layer and segregation on the surface of cast billets accumulate in the back end of the billet with the progression of extrusion. At the end of extrusion, billet skin begins to flow from the back end of the billet to the extrudate. Therefore, butt thickness has to be set at the proper value to prevent billet skin from entering extrudates. Otherwise, defects in the extrudates will ruin product quality [15].

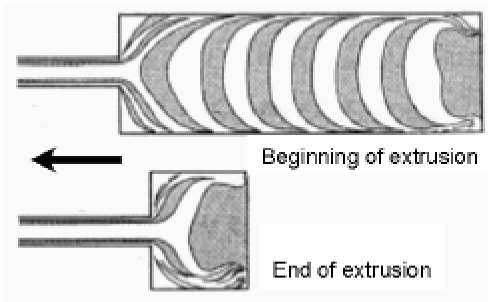


Figure 2.7. Metal flow of billet in direct extrusion [15]

Extrusion methods can be classified by relative movement between billet and container. Figure 2.8 shows metal flow of billet in indirect extrusion. In indirect extrusion, the container goes forward along with the billet, and there is no shear friction between them. Extrusion load in indirect extrusion is stable during one run, and lower than that in direct extrusion. Therefore, hard alloys can be extruded easily in indirect extrusion. As billet metal flow is relatively uniform, structure and properties of extrudates are uniform in the cross section and during extrusion. Billet skin enters extrudate during the run in indirect extrusion. If oxides and segregation at the cast billet surface enter extrudates, they must be defects, which ruin product quality. For that reason, billet has to be scalped to eliminate oxides and segregation [15].

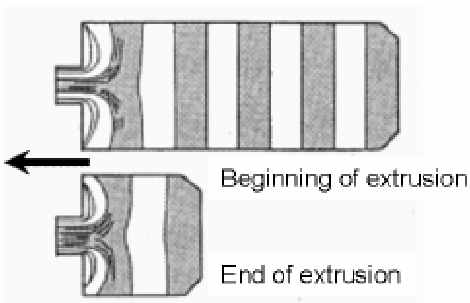


Figure 2.8. Metal flow of billet in indirect extrusion [15]

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

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

Type, layout and design of the die might change the mechanical working of the billet material during extrusion. Hollow dies perform much more mechanical work on the material than simple-shape solid dies do [5].

A dead-metal zone builds up in the corners of the die, and the material shears along this face. The material may continue to extrude over this generated zone, which acts like a conical die surface. The surface and subsurface defects are likely to occur on the extruded product if the sufficient amount of butt is not kept. Typical etched cross section of a 7075 alloy butt remaining after extrusion is shown in Figure 2.9(a) and Figure 2.9(b) shows schematically two clear zones. Zone one shows the flowing metal through the rigid conical zone two, which is defined to be a dead-metal zone. The darker patches carry oxides and other inclusions into the extruded section, leading to extrusion defects [5].

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

$$\alpha = f(ER, k_f, m, m') \qquad (2.1)$$

where ER is the extrusion ratio, which is defined by the ratio of container bore area and the total cross-sectional area of extrusion, k_f is the flow stress, m is the friction factor between billet and container interface, and m' is the friction factor between flowing metal and die-bearing interface [5].

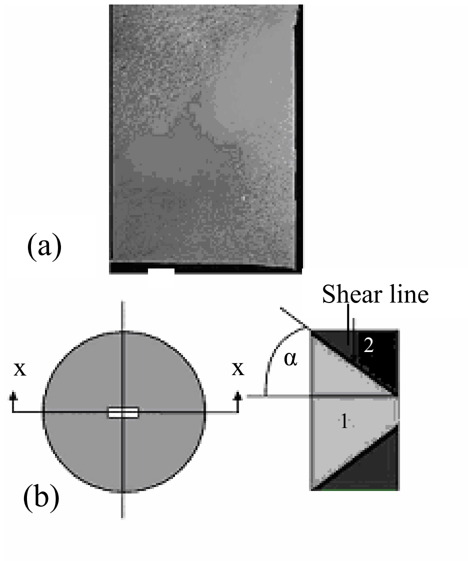


Figure 2.9. Longitudinal cross section of butt after extrusion. (a) Typical etched cross section of a 7075 butt (b) Schematic diagram of butt cross section showing dead zone [5]

Under the same friction condition at the billet-container interface for the same alloy billet, the dead-metal zone semi angle (α) varies with the extrusion ratio, ER, as shown in Figure 2.10. As the extrusion ratio increases, α increases, the length of shear line decreases. In Figure 2.10, ER_1 is the extrusion ratio for the bigger opening die, whereas ER_2 is the extrusion ratio of the smaller opening die, and α_2 is the semi dead-metal zone angle corresponding to ER_2 [5].

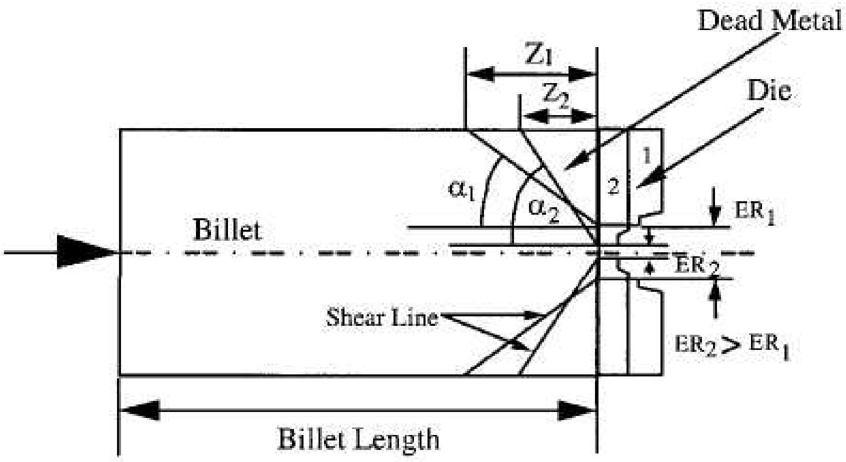


Figure 2.10. Relationship between extrusion ratio and semi dead-metal zone angle [5]

<u>2.3.1.1. Flow Stress</u>. The flow stress k_f is a material constant for homogeneous deformation. It varies with temperature, strain (in cold working) and strain rate (especially in hot working), and is measured experimentally as a function of these factors. The method used is usually selected to give uniaxial stressing because this simplifies the analysis [16].

In uniaxial tension (i.e., up to the onset of necking in a normal tensile test):

$$\sigma_2 = \sigma_3 \tag{2.2}$$

$$k_f = \sigma_1 = \frac{F}{A} \tag{2.3}$$

where $\sigma_1, \sigma_2, \sigma_3$ = normal principal stresses

F = the tensile load

A = the corresponding cross-sectional area

k_f = the flow stress

In compression tests (where uniaxial pressure is obtained if friction at the ends of the specimen is eliminated):

$$\sigma_1 = \sigma_2 \tag{2.4}$$

$$k_f = -\sigma_3 = \frac{F}{A} \tag{2.5}$$

where F = the compressive load

A_i = the corresponding cross-sectional area

k_f = the flow stress

In torsion tests (pure shearing):

$$k_f = 2\tau_F \tag{2.6}$$

where k_f = the flow stress

τ_F = measured shear stress

The flow stress increases with increasing strain in cold working by an amount depending on the alloy (work hardening), whereas in hot working the stress is almost independent of the strain because no work hardening takes place. Only a low uniform strain can be attained in tensile tests, and so the flow stress is measured by a compression or a torsion test [16].

The latter gives constant stress conditions up to failure and, consequently, k_f can be measured up to high strains together with the strain to fracture, which can be used as a measure of workability. However, because the high temperature flow stress depends on the strain rate, it is important to keep the strain rate constant during the test. The constant speed of rotation used in torsion tests fullfills this need. In compression tests the rate of compression has to be varied as a function of the height of the specimen [16].

2.3.2. Butt Thickness

According to industry practice, standard butt thickness for direct extrusion is kept to ten to fifteen percent of the billet length. Butt thickness may be a function of the dead-metal zone, which is also a function of the extrusion ratio, type of die, billet temperature, billet-container friction condition, and flow stress of the billet material. Figure 2.11 shows the relationship between butt thickness and the dead-metal zone conical surface. Stopping extrusion at the safe margin zone prevents oxide and other metallic or nonmetallic inclusions from flowing into the extrusion. It is always recommended to continue research on macro etching of the longitudinal section of the butt to gain a better understanding of the following aspects [5]:

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

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

This is more important for harder alloy extrusion, especially in aircraft industry. The press should be stopped within the safe margin zone as shown in Figure 2.11 [5].

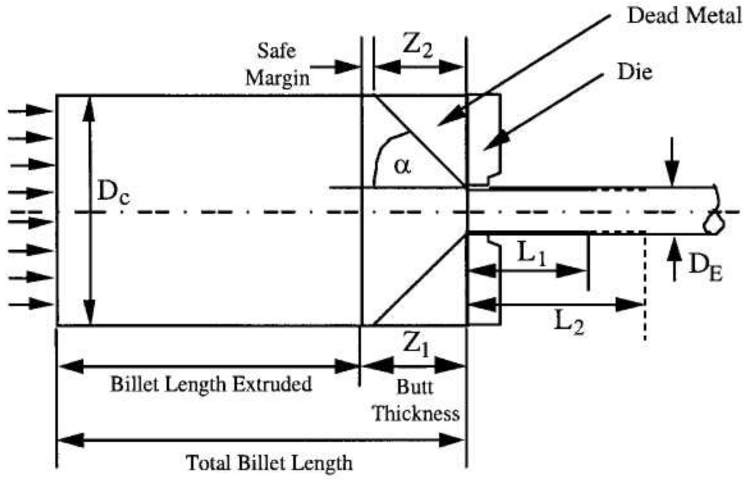


Figure 2.11. Relationship between dead zone and butt thickness [5]

2.3.3. Plastic Strain and Strain Rate

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

$$d\bar{\varepsilon} = \frac{dl}{l} \qquad \bar{\varepsilon} = \int_{l_0}^{l} \frac{dl}{l} = \ln\frac{l}{l_0} \tag{2.7}$$

where $\bar{\varepsilon}$ = the natural or effective strain

l_0 = the initial length

l = the final length

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

$$A.l = A_0.l_0 \tag{2.8}$$

where A = the final area

A_0 = the original area

Now, the natural strain is given by :

$$\bar{\varepsilon} = \ln\frac{l}{l_0} = \ln\frac{A}{A_0} \tag{2.9}$$

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

$$\bar{\varepsilon} = 2\ln\frac{D_C}{D_E} = 2\ln\sqrt{ER} \tag{2.10}$$

where D_C = the inside diameter of the container

D_E = the equivalent diameter of the extruded rod

ER = the extrusion ratio

In determining the strain rate, the complex flow pattern in the deformation zone creates a problem. The material undergoes a rapid acceleration as its passes through the deformation zone, and therefore, a mean strain rate has to be estimated for determining flow stress. The deformation zone is assumed to be conical for simplicity as shown in Figure 2.12 [5].

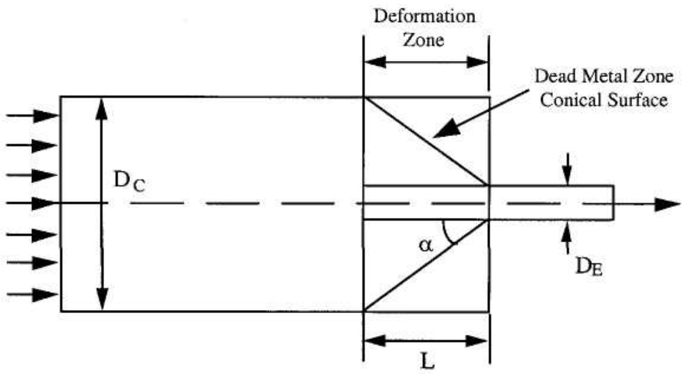


Figure 2.12. Billet geometry inside the container [5]

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

$$L = \frac{(D_C - D_E)}{2\tan\alpha} \tag{2.11}$$

where D_C = the inside diameter of the container

D_E = the equivalent diameter of the extruded rod

α = the dead-metal zone semiangle

L = length of deformation zone

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

$$ER = \frac{A_C}{A_E} \tag{2.12}$$

where A_C = the area of the container bore

A_E = the final area of the extruded rod

Therefore, the equivalent diameter of the extruded rod is given by:

$$D_E = \frac{D_C}{\sqrt{ER}} \tag{2.13}$$

The mean effective strain rate is given by :

$$\dot{\varepsilon} = \frac{6 v_R D_C^2 \tan\alpha}{(D_C^3 - D_E^3)} 2 \ln \frac{D_C}{D_E} \qquad (2.14)$$

where v_R = the average ram speed

D_C = the inside diameter of the container

D_E = the equivalent diameter of the extruded rod

α = the dead-metal zone semiangle [5]

2.3.4. Load and Energy Requirements In Extrusion

Several methods for calculating the deformation load have been developed since the start of systematic extrusion research. They differ from each other in the assumptions made, the method and complexity of analysis, the theoretical basis and the degree of approximation of the solution. The solution obtained by elementary analysis has proved to be the most useful in practice, because of its simplicity. Therefore, this method is given priority but the basic principles of the most important other methods are also compared [16].

2.3.4.1. Elementary Analysis. The starting point of this approach is the influence of material, extrusion ratio, temperature and friction between billet and the container on the magnitude of the work of deformation [16].

A considerable amount of calculation would be required to obtain the total work of deformation from the nonuniform distribution of strain and deformation energy in the deformation zone. Therefore, the billet is assumed to deform homogeneously with plane sections remaining plane. Tresca's yield criterion is used for the three-dimensional state of stress – with principal stress of $\sigma_1 > \sigma_2 > \sigma_3$ that develops in each element of volume under the applied ram load. Frictionless deformation of an element of volume by a change in length of dL requires the ideal deformation load F_{id}. The ideal work of deformation is:

$$dW_{id} = FdL_i \tag{2.15}$$

where F = Load

W_{id} = the ideal work of deformation

For uniaxial loading:

$$F = A_i.k_f \tag{2.16}$$

where F = load

A_i = instantaneous cross section of the specimen

k_f = the flow stress

which can be extended to:

$$F = \frac{V}{l_i}.k_f \tag{2.17}$$

where V = deforming volume

l_i = instantaneous billet length

giving:

$$dW_{id} = V.k_f.\frac{dL_i}{L_i} \tag{2.18}$$

Therefore:

$$W_{id} = V.k_f \int_{l_1}^{l_0} \frac{dL_i}{L_i} \tag{2.19}$$

$$\int_{l_1}^{l_0} \frac{dL_i}{L_i} = \ln \frac{l_1}{l_0} = \varphi \tag{2.20}$$

where φ = logarithmic strain

l_1 = length of the extruded product

l_0 = initial billet length

The volume remains constant. Therefore:

$$A_B.l_0 = A_E.l_1 \tag{2.21}$$

$$\ln\frac{l_1}{l_0} = \varphi = \ln\frac{A_B}{A_E} \tag{2.22}$$

where A_B = cross sectional area of billet

A_E = cross sectional area of the extruded product [16]

Hence;

$$W_{id} = V.k_f.\varphi \tag{2.23}$$

$$F_{id} = \frac{W_{id}}{l_i} = A_B.k_f.\varphi \tag{2.24}$$

where F_{id} = ideal extrusion load [16]

2.3.4.2. Calculation of the Work of Deformation and the Extrusion Load. In practice, problems are usually solved by elementary analysis because it is easy to understand and simple to use. For frictionless extrusion the ideal extrusion load F_{id} is obtained in the previous section. However, additional work W_S is required, over and above the homogeneous work of deformation, to overcome the shearing deformation – redundant work – in the deformation zone (and friction in the die), as well as the work W_F needed to overcome the friction between the billet and the container, or to shear the material close to the billet surface if sticking friction occurs:

$$W_T = W_{id} + W_S + W_F \tag{2.25}$$

where W_T = total deformation work

W_{id} = ideal deformation work

W_S = shearing work

W_F = work to overcome friction

W_S is difficult to determine theoretically, and so it is combined with W_{id}, and the efficiency of the deformation is defined as:

$$\eta_f = \frac{W_{id}}{W_{id} + W_S} \tag{2.26}$$

where η_f is the deformation efficiency factor which can be measured and which enables the redundant work to be allowed for empirically.

The following expression is then obtained:

$$W_{id} + W_S = \frac{W_{id}}{\eta_f} = V.\varphi.\frac{k_f}{\eta_f} \tag{2.27}$$

where φ = logarithmic strain

V = deforming volume

k_f = the flow stress

The term k_f / η_f is known as the deformation resistance k_w. It differs from the flow stress k_f, which is a material constant, in as much as it includes the internal shearing losses that depend on the geometry of deformation and the die friction. The additional work that has to be expended to overcome the friction between the billet surface and container is:

$$W_F = F_F.l_i = U.l_i^2.\mu_f.k_f = \pi.D_0.l_i^2.\mu_f.k_f \tag{2.28}$$

where F_F = frictional load

U = circumference

D_0 = container bore

l_i = instantaneous billet length

μ_f = coefficient of friction between billet surface and container wall

The expression for the total work then becomes:

$$W_T = V.\varphi.k_w + \pi.D_0.l_i^2.\mu_f.k_f \tag{2.29}$$

and the total load is given by:

$$F_T = A_0.\varphi.k_w + \pi.D_0.l_i.\mu_f.k_f \tag{2.30}$$

where A_0 = cross sectional area of the container

Some other workers have used a different approach for determining total load and work, especially for the friction at the container wall – for example using an exponential function or, when sticking friction occurs, replacing $\mu_f.k_f$ by τ, the shear stress [16].

3. TRIBOLOGY AND THERMODYNAMICS OF EXTRUSION

Tribology (science of friction, lubrication and wear) has long been of both technical and practical interest to those who study improvements in aluminum extrusion quality. The functioning of aluminum extrusion technology depends mostly on friction at the extrusion die-bearing interface affecting die wear and accuracy of the extrusion shape. High quality extrusion processing would be impossible without this science and technology, which analyzes the interaction between metal flow and the die-bearing surface in the extrusion process [17].

The word "tribology" is still new to many people in the industry. Before discussing the prevalence and types of tribological problems in the aluminum extrusion industry, it is important to give an overview of the phenomena. The resistance between the relative motions is defined by the friction coefficient. The energy dissipation in friction results in heat generation at the contact area. The heat generation could be small or significant depending on the geometry surface condition and the contact materials. In relative motion, the mating surfaces could change their basic characteristics to some extent. The surfaces could become smoother or rougher, have physical properties altered, and some loss of material (wear) could also happen [17].

In aluminum extrusion processing, a hot billet is forced to flow by compression through die orifice of smaller cross-sectional area than that of the original billet. The force required for the most common direct extrusion method depend principally on the flow stress of the billet material, the extrusion ratio, the friction condition at the billet container interface, the friction condition at the die material interface, and the other process variables. The principal variables that influence the successful extrusion process and the quality of material exiting from the die are extrusion ratio or strain, initial billet temperature, speed of deformation or strain rate and alloy flow stress. The effect of principal variables on the extrusion process and their interrelationships works like a closed loop chain [18].

Thermodynamics in the direct extrusion process is very complex. Heat is generated by both the frictional and deformation work. This heat is transported with the extruded material and conduction takes place simultaneously. Some of the generated heat remains in the extruded metal, some is transmitted to the container and die, and some even increases the temperature of the part of the billet that is not yet extruded. The exit extrusion temperatures have two distinct effects on both product quality and die life. Regarding product quality, exit temperature mainly affects the dimensional stability, extrusion defects, and heat treatment for certain alloys that get the press quench. Die life and performance also depend on exit temperature, which in turn causes a temperature rise to the die bearing. The exit temperature is directly influenced by the extrusion parameters including billet temperature, die design, extrusion speed, and friction conditions at the billet -container, and die bearing and flowing material interfaces [17].

The thermodynamic and tribological relationships during hot extrusion concerns frictional behaviors at billet-container, dead metal zone-flowing material and finally die bearing-material interfaces during direct aluminum extrusion process. All these iterations including the friction models will be discussed below.

3.1 Friction Models

During the hot extrusion of aluminum, the tribology of the die/material interface has a considerable influence on the accuracy of the shape and surface quality of the extrusion, in this section, friction modeling of the extrusion process is discussed. Figure 3.1 shows the friction force components in direct extrusion. Friction is the resistance to relative motion which is experienced whenever two solids are in contact with one another. The force to overcome the resistance, which is directed in the direction opposite to the relative motion, is the friction force. The Amontons-Coulomb model gives the friction force as;

$$F_F = \mu N \tag{3.1}$$

where F_F = frictional force

μ = the coefficient of friction

N = the normal force [17]

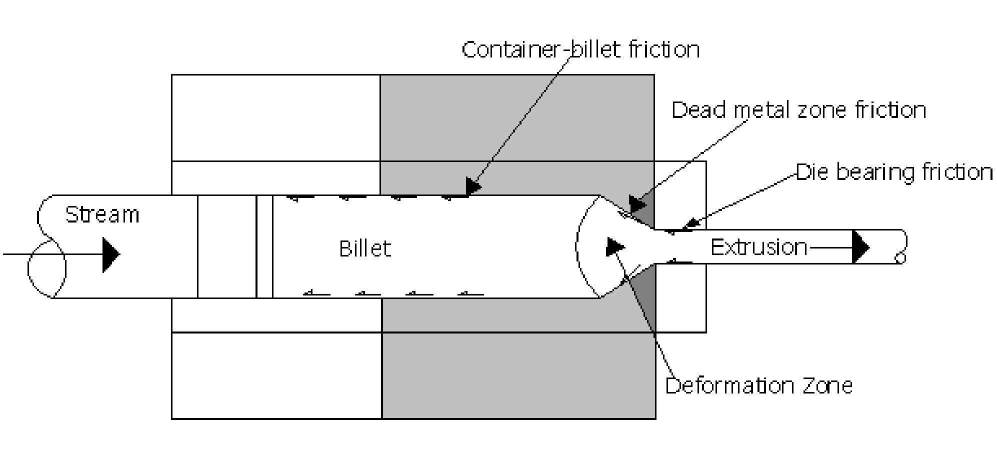


Figure 3.1. Friction-assisted direct extrusion mechanism [18]

The model holds fairly well where contacts are relatively lightly loaded and the surfaces contact only at occasional asperity peaks. This model is of questionable value in bulk deformation processes like extrusion where the contact is more intimate and the pressures are significantly higher [18].

3.1.1. Billet-Container Interface

In direct extrusion the billet is pushed forward against the frictional resistance developed on the container wall. Correspondingly, the extrusion pressure is higher at the beginning of the stroke when a long length rubs against the container wall. At high extrusion ratios interface pressures can be very high and use of a coefficient of friction could be misleading. Therefore, it is better to estimate the shear strength of the interface τ_i and the corresponding pressure to the basic extrusion pressure so as to obtain the ram pressure p_l at any point in the stroke [19].

$$p_l = p_e + 4\frac{\tau_i l_0}{D_B} \tag{3.2}$$

where p_l = ram pressure

p_e = extrusion pressure

τ_i = shear strength of the interface

D_B = billet diameter

l_0 = initial billet length

Data for τ_i are scarce but an upper limit is given by sticking when $\tau_i = \tau_f$ [19].

The real area of contact increases with the increase of contact pressure as shown in Figure 3.2. In the case of direct extrusion (where contact pressures are very high), the real area of contact A_R gradually becomes equal to the apparent area of contact A_A as the billet upsets in the container [18].

Important considerations in the direct extrusion process are the friction forces developed between the billet and the container and interface friction between the flowing metal and the dead metal zone conical interface [18].

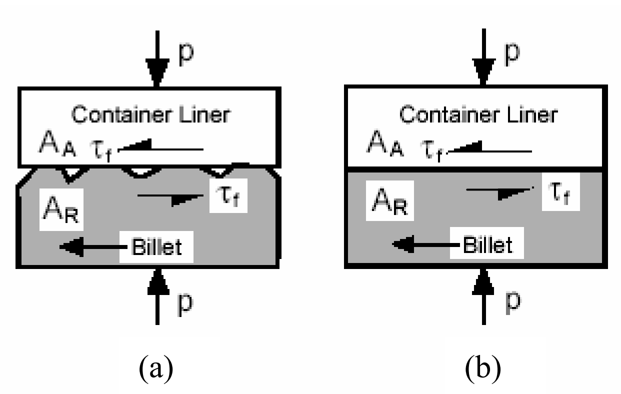


Figure 3.2. Friction model at billet-container interface a) $A_R < A_A$, b) $A_R = A_A$, $p = \overline{\sigma}$ [18]

In the direct extrusion process, the large pressure developed demands that the billet be supported by the container wall. From a practical point of view there are two types of friction conditions:

- Billet-container friction is arrested (sticking friction)
- Lubricated interface flow is ensured (sliding friction) [18].

For container friction, from the practical point of view there are only two possibilities as mentioned above: either the interface is arrested (sticking friction), or sliding of the interface is ensured (lubricated flow). No intermediate condition can be allowed, because partial sticking and partial sliding invariably lead to unsteady material flow and a defective extruded product [20].

In aluminum extrusion, the friction condition at the billet-container interface is considered to be sticking friction as the skin of the billet is being separated in the container wall. Schey [20] gives a useful review of using the friction factor m in metal forming operations where the contact pressure is very high. The friction factor model sometimes referred to as a sticktion model:

$$F_F = m\tau_F A_R \tag{3.3}$$

where F_F = the frictional force

m = the friction factor

k = the material shear strength

A_R = the real area of contact

For this model real area of contact equals to the total area of contact. In the case of sticking friction, $m=1$, while for thick film lubrication conditions m approaches to zero. Therefore, the frictional stress is given by;

$$\tau_f = k = \frac{k_f}{\sqrt{3}} \tag{3.4}$$

where k_f = the flow stress of the material [18]

3.1.2. Dead Metal Zone – Flowing Metal Interface

The dead metal zone shown in Figure 3.1 occurs when a material is extruded through square dies (i.e., the bearing surface is perpendicular to the face of the die). In such geometries, the material in the corners no longer takes part in the flow, but adheres to the die face, forming a conical die-like channel through which the billet passes in a still converging kind of flow. Friction between the dead metal zone and the flowing material is no more than the shear stress of the material. The friction stress is as given by Equation (3.4) with friction factor equal to unity [18].

3.1.3. Die – Material Interface

Based on the observation of the die surface after several extrusion cycles, it is understood that friction in the die may vary in a complicated way when metal is flowing through the die opening. It is observed that an adhesive layer on the die is developed due to strong adhesion of materials such as aluminum with the dies, typically constructed from tool steels. It is also understood that surface treatments which result in harder die surfaces (such as nitriding or thin hard coatings) can reduce the amount of adhered material. Research is continuing on surface treatments for wear resistance [18].

3.1.4. Proposed Model

Figure 3.3 is a schematic diagram of the bearing surface based on the morphology of aluminum build-up on the die bearing surface, which is normal to the extrusion direction. Figure 3.3 also shows the sticking and slipping zones of the die which are used to develop a friction model at the die-material interface. Figure 3.3 (a) shows partial sticking and slipping zones and Figure 3.3 (b) shows a completely adhered surface. After several press cycles, a completely adhered surface is developed on the die face [18].

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

$$F_F = m_1' k A_1 + m_2' k A_2 \tag{3.5}$$

where one denotes sticking, two denotes sliding zone [18].

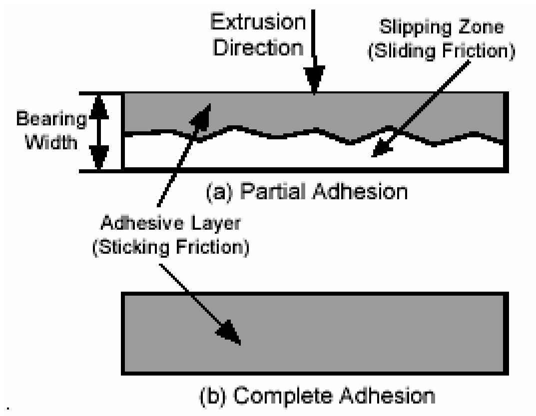


Figure 3.3. Friction model at extrusion die bearing [18]

The friction stress is given by;

$$\tau_f = k\frac{A_1}{A_A} + m_2 'k\frac{A_2}{A_A} \tag{3.6}$$

$m_1 '$ has set been set to unity to reflect sticking friction [17].

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

$$\tau_f = k\frac{(A_1 + A_2)}{A_A} = \frac{k_f}{\sqrt{3}} \tag{3.7}$$

3.2. Lubrication of Aluminum Alloys

Basically, there are two options for extruding aluminum and its alloys.

3.2.1. Unlubricated Extrusion

By far the largest quantity of aluminum alloys is hot extruded without any lubricant whatsoever. A breakthrough pressure of up to 20% is sometimes found and is related to the thermal activation of the flow process. As long as the billet is of good, uniform quality, the die is free of major pickup and no lubricant or contaminant finds it way into the container, the quality of the extrusion will be excellent [20].

For best surface quality, a follower block of small diameter is used to leave a skull, which is removed by specially designed follower blocks or in a separate stroke. The skull entraps imperfections of the billet surface. When extrusion is done without a skull, the billet is scalped for highest quality. Shearing along the container wall contributes to heat generation; in direct extrusion it may reach 50% of the total force and thus greatly adds to the temperature rise. Because the heat rise is proportional to flow stress, k_f, the permissible exit speed is found to be inversely proportional to the square of k_f, and drops to 1.5 mm/s for 2024 and 7075 alloys. In these alloys localized severe deformation may also lead to an undesirable, recrystallized coarse grain structure of inferior properties on the periphery of the extrusion [20].

In unlubricated extrusion with flat dies, extruding without a lubricant not only removes the possibility of lubricant inclusions but also increases the friction between the billet and the container. This restricts the movement of the billet surface along the container wall to such an extent that it cannot flow into the extrusion. The material, therefore, flows beneath the surface of the billet by shearing and the residual surface layer containing the impurities collects in front of the dummy block [16].

The main problem in extrusion with sticking friction is the die. The die is designed and made so that optimum material flow is ensured and an extrusion free of defects is produced. The die usually has a flat face, which is protected by the dead metal zone. However, the high adhesions of aluminum to steel soon results in the build up of a coating on the die and die land. Local lubrication of the die land or of the billet face with a graphitic lubricant is sometimes practiced, even though the lubricant is lost soon after the extrusion emerges and extrusion proceeds over the bare die [20].

Lubricant applied to the tool or billet leading face may be helpful in preventing oxidation of the tool until the billet face passes through. Still, most of the time, uniform die pick up is accepted as a side effect of extruding with sticking friction, and emphasis is placed on the die cleaning and maintenance with the aid of wire brushing and caustic soda etching [20].

3.2.2. Lubricated Extrusion

Lubrication in normal hot extrusion is, however, often impractical, because other defects, including scale or blister formation, developed from the trapped lubricant, particularly on the surface of the product [16]. Lubricated hot extrusion of aluminum alloys has found only limited application. It is not easy to identify an obviously best lubricant. Graphite cannot maintain sliding friction over the entire course of extrusion of a long billet, although both graphite and MoS_2 have been used for mandrel lubrication in tube extrusion. PTFE has been found to be useful in cable extrusion and in experimental hot extrusion of alloy 2024. Despite repeated investigations of lubricated hot extrusion, especially for strong alloys, the unlubricated process remains dominant. In extrusion of high magnesium alloys, a short cylinder of soft aluminum helps to initiate more homogeneous flow [20].

The low cold flow stress of pure aluminum and its low alloys permits their extrusion at room temperature using fats and waxes, such as lanolin, as a lubricant. Even though the temperature increase at high extrusion speeds is sufficient to cause annealing and other desirable metallurgical changes, the lubricant provides effective mixed-film lubrication, and surface quality is good. Hydrostatic extrusion was once also thought of as a competitive process, especially for electrical conductor wire, but the resulting surface quality is inferior because of surface roughening and defects related to the starting material [20].

3.3. Thermodynamics of Extrusion

The sources of heat energy to the direct extrusion process are container-billet friction, die-bearing friction and dead metal zone friction. Most of the work of deformation is transformed into heat. This temperature rise due to plastic deformation can be several hundred degrees. In plastic deformation at high strain-rates the temperature rise can be significant, especially when conduction of heat from the deformation zone is poor. Friction affects the temperature rise in two ways. Under condition of sliding friction, the work required to overcome the frictional force is transformed into heat at the interface. In aluminum extrusion, sticking friction occurs in the billet-container interface. The changes in interface temperature are no greater than changes in bulk temperature but, because deformation now proceeds by shear in the workpiece itself, localization of deformation can also lead to localization of heating [18].

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 of the specific alloy. The temperature changes during extrusion depend on many factors such as:

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

The critical temperature in extrusion is the exit temperature of the metal leaving the die, which depends on all the above factors. It increases if the heat produced by deformation and friction exceeds the heat losses, and decreases if the reverse is true. The higher the ram speed, the less time available for heat conduction, so there will be more localized heat generation due to increase in ram speed [18].

3.3.1. Thermodynamics Model

This modified model for the temperature rise in an aluminum billet during extrusion with friction is presented by Saha [17]. The model uses realistic input parameters typical industry practice in the extrusion of AA 6063 aluminum. Temperature and strain-rate sensitivity has been incorporated into the flow stress. The thermodynamics model predicts the influence of plastic strain and strain-rate on temperature rise extrusion. In this section, the thermodynamic model has been discussed in brief to give an overview of the model. The differential equation of unsteady heat conduction to determine the temperature distribution in the billet during extrusion is given by;

$$a\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{R_m}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial Z^2}\right]+\frac{U'''}{\rho c}=\frac{\partial T}{\partial t}+v_z\frac{\partial T}{\partial Z} \tag{3.8}$$

where a = the thermal diffusivity

R_m = the radius of billet at any nodal point (m,j)

U''' = deformation energy/unit volume/unit time, is the average flow stress, is the strain rate

ρ = the specific weight

c = the specific heat

v_z = the speed of material along the Z-axis with respect to stationary co-ordinates [18].

The average value of flow stress and thermal properties are assumed. Figure 3.4 shows the grinded meridian plane of the billet for numerical computation of the temperature distribution during extrusion.

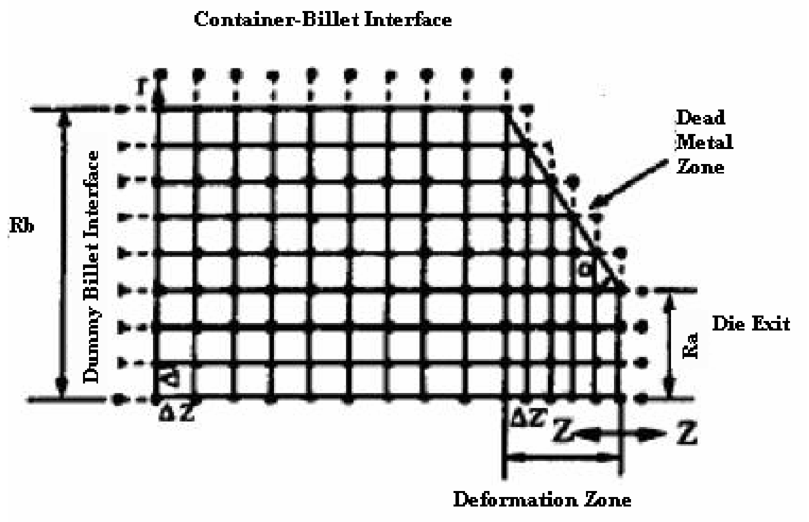


Figure 3.4. Gridded meridian plane of the billet (all extended dotted points are fictitious points) [18]

<u>3.3.3.1. Finite Difference Approximation.</u> The equations can be written in the finite difference form as per the scheme shown in Figure 3.5a and Figure 3.5b for equal and unequal spacing as

$$\frac{\partial^2 T}{\partial r^2} = \frac{T_{m,j+1} + T_{m,j-1} - 2T_{m,j}}{(\Delta r)^2} \tag{3.9}$$

$$\frac{\partial^2 T}{\partial Z^2} = \frac{T_{m+1,j} + T_{m-1,j} - 2T_{m,j}}{(\Delta Z)^2} \tag{3.10}$$

$$\frac{\partial^2 T}{\partial Z^2} = \frac{2T_{m+1,j} + 2\varphi T_{m-1,j} - 2(1+\varphi)T_{m,j}}{(\Delta Z)^2(\varphi + \varphi^2)} \tag{3.11}$$

$$\frac{\partial T}{\partial r} = \frac{T_{m,j+1} - T_{m,j-1}}{2\Delta r} \tag{3.12}$$

$$\frac{\partial T}{\partial Z} = \frac{T_{m+1,j} - T_{m-1,j}}{2\Delta Z} \tag{3.13}$$

$$\frac{\partial T}{\partial Z} = \frac{T_{m+1,j} - \varphi^2 T_{m-1,j} - (1-\varphi^2)T_{m,j}}{(\Delta Z)(\varphi + \varphi^2)} \tag{3.14}$$

where $\varphi = (\Delta Z')/(\Delta Z)$. When $\Delta Z = \Delta Z'$, φ=1. The semi dead metal zone angle α is assumed 45°, or that $\varphi = 1$ in the analysis.

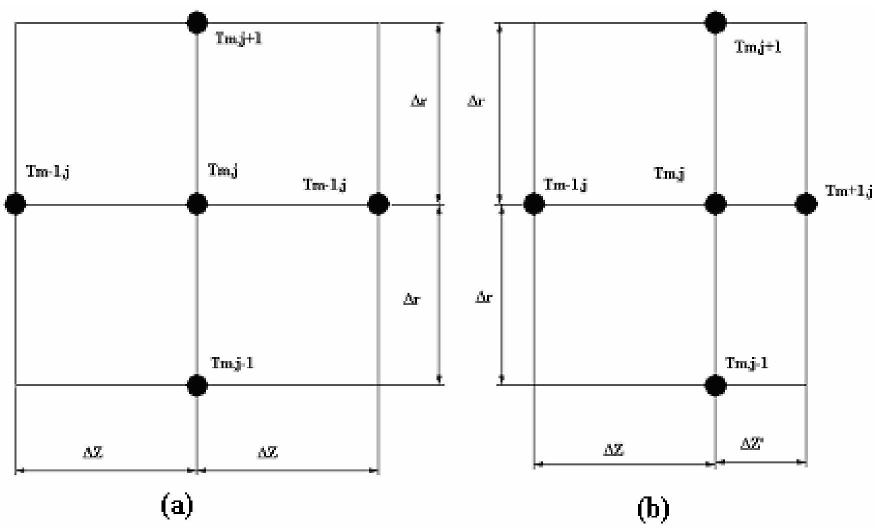


Figure 3.5. Two different configurations of five adjacent points used in numerical calculation [18].

Substituting these finite difference approximations in the differential Equation (3.8) of heat conduction, the temperature at any nodal point (m, j) after time increment Δt can be calculated. By the same method, the temperature rise on the nodal points on the billet-container interface, the dead metal zone surface can be calculated [18].

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

$$q_f = \frac{\overline{\sigma} v_{material}}{\sqrt{3} J} \tag{3.15}$$

where $v_{material}$ = the speed of material in billet – container interface

J = the mechanical equivalent of heat (42.7 kg cm/cal) [18]

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

$$q_f = \frac{\overline{\sigma}(v_{m,j})}{\sqrt{3} J} \tag{3.16}$$

where $v_{m,j}$ = the speed of the following material at the interface nodal points

$v_{m,j}$ is calculated from the following relationship:

$$v_{m,j} = \frac{v_R}{\cos \alpha} \tag{3.17}$$

where v_R = the ram speed

3.3.3.4. Heat Generation Due to Die Bearing – Material Interface Friction. In the case of sliding friction the frictional heat flux/unit area/unit time is given by

$$q_f = \frac{\tau_f v_E}{J} \tag{3.18}$$

τ_f will be calculated using Equation (3.6). The friction factor m_2 in Equation (3.7) may vary according to the surface conditions at the die bearing [18].

4. PROPERTIES AND DESIGN OF EXTRUSION DIES

Die design for aluminum extrusion is up to now to a large extend empirically based. This is among others caused by the complexity of the extrusion process, the difficulty to qualify and quantify the pressures and temperatures found in the extrusion process and a lack of knowledge on the exact role of the different design- and process-characteristics used in the manufacturing of aluminum products. With the powerful growth of the development of 3D CAD and FE-modeling software in the last decades, a new approach to die design, as an alternative for empirical based die design, is looked for. To this extent a new die design support system is being developed. The results of finite element calculations are translated into design rules. In combination with empirically based design guidelines, they are used to lead the die designer through all the steps of the design process. Due to this new approach improvements are expected in of the consistency of the design and manufacturing of extrusion dies, the level of insight in the extrusion process and the time between the start of the design process and the manufacturing of the die [21].

In hot extrusion of aluminum alloys, flat face dies are generally used. Extrusion dies and tooling determine the performance and economics of the aluminum extrusion processes. The functions of the individual tools are shown in Table 4.1 [5].

Solid shaped dies for softer alloy extrusions have feeder plate with diverging cavity in front of the flat-face die for solid-shaped extrusion and also these dies have straight cavity (welding pocket) in front of the die opening. For hard alloy extrusion (2000-series, 7000-series and some 5000-series alloys) with solid shaped dies, some properties of these dies are different. In this condition a solid die is used without using a feeder plate and loose dummy. Adding to all these in hard–alloy extrusion with solid shape dies, solid flat-face die with higher thicknesses and larger die-bearing and pocket die are used. The schematic of a solid flat-face die configuration is shown in Figure 4.1 [5].

Hollow shape dies for softer alloy extrusions are porthole, bridge and spider dies. For hard alloys extrusion, a solid die is used for giving the outer hollow shape also a piercing or a fixed mandrel is used through a hollow stem to produce the inside shape of extrusion [5].

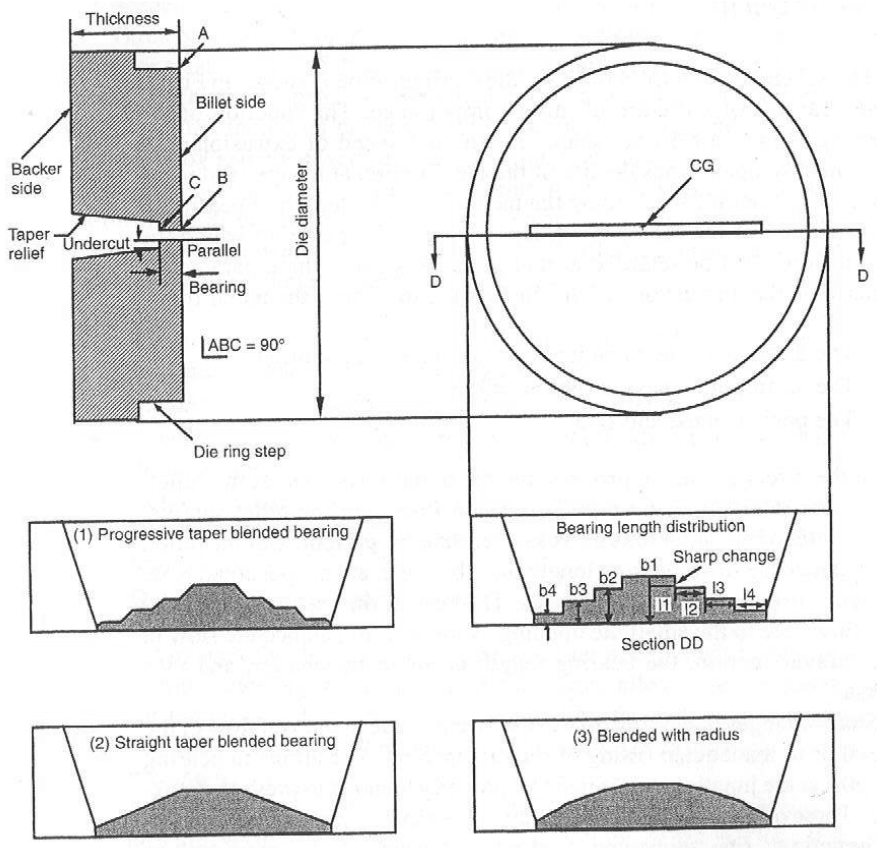


Figure 4.1. Solid flat-face die configuration [5]

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

- The distance of the opening from the center of the billet
- The section thickness at that location
- The pocket shape and size [5]

Table 4.1. Functions of the individual tools used for extrusion of soft and medium grade alloys [5]

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

A die for an aluminum section has to fulfill the following requirements:

- Accurate dimensions and product shape, to avoid the need for any corrective work.
- Maximum possible working life.
- Maximum length of the extruded section.
- A good-quality surface finish maintained over many extrusions – i.e. infrequent die cleaning.
- High extrusion speeds.
- Low manufacturing costs.

These requirements are usually fulfilled with rod and simple shapes. However, as the complexity of the die increases, it becomes increasingly more difficult to comply with all six requirements. Many factors have to be considered in the design and construction of die, including flow pattern, maximum specific pressure, geometrical shape of the section, wall thickness and tongue sizes, shape of the bearing surfaces (die lands), and the tolerances of the section. Incorrect metal flow can give rise to areas of critical deformation, which form visible streaks on the surface of the finished product [16].

Much skill and experience are required to obtain uniform metal flow through all parts of the die, especially with unsymmetrical shapes and different wall thicknesses. The resistance to flow is greatest in the narrow parts of the die, and the bearing lengths in these regions have to be reduced. If insufficient attention is paid to these preventative measures, the extruded product will be twisted and warped [16].

To be able to design a die according to the predefined design demands, the designer should have a thorough understanding of the different design features, their interactions and the influence of the process parameters on their functionality. In the extrusion die design as seen in general practice today, this is not the case. The new die is generally based on an existing die design. An experienced designer adds the necessary changes and the performance of the new die will be tested by trail and error. This may lead to many testing cycles before the die extrudes satisfactory [21].

4.1. Design of Extrusion Dies

One of the most important things in aluminum extrusion is structural die design. Conventional die design, however, relies mostly on experience, which is especially challenging when the product has a difficult form, to achieve the required form in the first extrusion. In such a case, we repair and perfect the die so that it becomes capable of producing the required form. This repairing/perfection process is time and labor consuming [22].

In order to carry out three-dimensional analysis in extrusion design simulation, three-dimensional modeling with 3-D-CAD is required. As shown in Figure 4.2, a die is separated to a mandrel and a die, and three-dimensional models are prepared for them individually. In addition to the die, three-dimensional models of the container, in which the billet is filled, and the ram, which gives the thrust, are prepared. As for a symmetrical model, planes of symmetry are also prepared, so that they will have a boundary aspect. Then, these three-dimensional models are laid out, as in actual extruding [22].

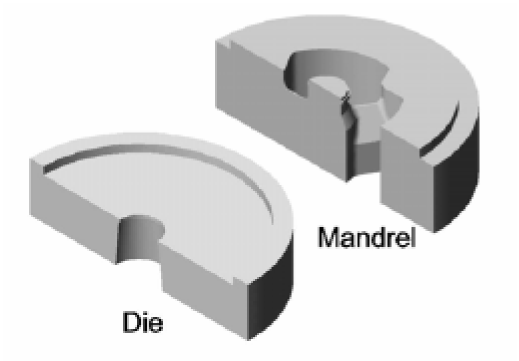


Figure 4.2. 3-D Modeling of a die [22]

Figure 4.3 shows the structure of extrusion area and the layout of the solid models in a simulation. The three-dimensional model of the billet, which is filled inside the die, has to be prepared as well [22].

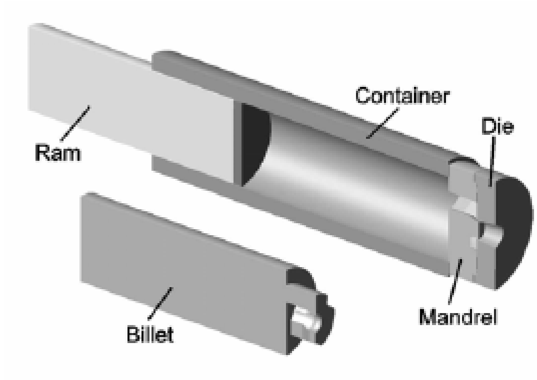


Figure 4.3. The structure of extrusion area [22]

As shown in Figure 4.4, the aluminum filled inside the die is meshed, with tetrahedral elements with four nodes. The mesh should be finer near the bearing. After setting boundary conditions, the simulation starts and the plastic flow of the billet in extruding is simulated. By using results of this simulation, the extrusion die can be redesigned or can be used for bulk production.

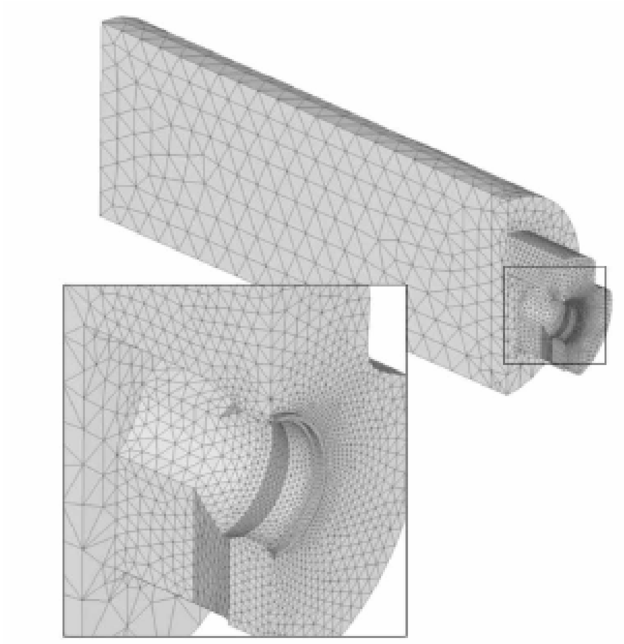


Figure 4.4. FEM mesh of billet [22]

Extrusion dies can be divided into simple ones used for solid and open shapes and those with welding chambers (porthole, spider and bridge dies) for semi hollow and hollow shapes. The normal type of die for solid and open semi hollow shapes can, in principle, be used for all metals that are extruded. Hollow sections in variety of shapes and sizes are reserved for aluminum alloys apart from the simple hollow sections that can be produced in the heavy metals or steel with a mandrel (independent mandrel movement) [16].

The general principal of the design of solid and porthole dies has not changed much over the last decades. As a result of the tendency to sell the profiles no longer by kilogram but to selling them by meter, profile designers want to reduce the wall thickness of the profile to be extruded. Because of this and in combination with the improved quality standards, demanding higher mechanical properties and the tendency of integrating more functions in a single design, leading to more complex profiles, the extrusion process becomes more critical with respect to the design and process parameters. For the die designer this resulted in an increased importance of balancing the different features (legs, sink in, portholes, bearing etc.) of the design. This to ensure the production of the correct profiles at the desired extrusion speed while trying to ensure a long die life, low production costs and meet the increased quality demands [21].

In the extrusion of 6xxx aluminum alloys, the type of die and its design play a significant role in the amount of heat generated in the bulk metal, as well as locally at the aluminum/die bearing interface. When the temperature at the die bearing approaches the solid for the given alloy, tearing, pick-up, and other surface defects start to occur. Therefore, the limiting component of the extrusion process, as it relates to surface defects, is the temperature at this interface [23].

Examining three approaches to extrusion tooling, how a wide range of approaches to flow control can affect productivity can be seen. The three approaches to tooling are represented by three die types or configurations, and these are flat dies, recess pocket dies, and flat dies with ring feeders. A die designer or die corrector has two basic tools for controlling flow through a die:

- Use bearing lengths, and angles of choke or relief, as a means to increase or decrease friction in the die.
- Use pocket geometry to constrict or feed areas of the profile [23].

Flat dies represent an approach where bearing lengths are used to control flow. It is well understood that metal flow in a die is nonuniform, and even if the flow were consistent, an asymmetrical profile would require manipulation in order to make the flow uniform. Therefore, a die can be corrected to allow a nonuniform shape to flow uniformly from the die exit. This approach can be very efficient on simple shapes, even though bearing changes can lead to variations on the extrusion surface [23].

In the direct extrusion process, the frictional resistance at the billet-container interface slows down the metal flow near the billet surface. The center of the billet thus moves faster than the periphery of the billet. To balance the flow, bearing length must be inversely proportional to its distance from the center of the billet. The thinner the section the slower the flow due to the small die opening. Similarly, to balance the flow in the thinner section, the bearing length needs to be smaller, and vice versa [5].

Sharp changes in bearing may cause streaks, due to uneven flow of the metal or inadequate filling of the die opening. Variations in bearing lengths at the junction points must be properly blended to prevent streaking. Three blending processes are shown in Figure 4.1 [5].

Sometimes fine adjustment to the die is necessary for correcting or changing the rate of metal flow by controlling the bearing width (b1-b4) and length (l1-l4) seen in Figure 4.1. The treatment of bearing surfaces at the front and back of the die aperture is known as choke or relief, respectively as shown in Figure 4.5. For extrusion of hard (2000-series and 7000-series) alloys, the front of the bearing is generally choked as can be seen in Figure 4.5a at an angle up to 3°. This slows the metal flow and consequently fills out the die aperture to give better dimensional stability. Increasing the relief angle at the back or exit side of the bearing to as high as 7° increases the speed of metal flow by decreasing the original bearing length (Figure 4.5b). Choke and relief are normally produced using electrical discharge machining (EDM) to quantify [5].

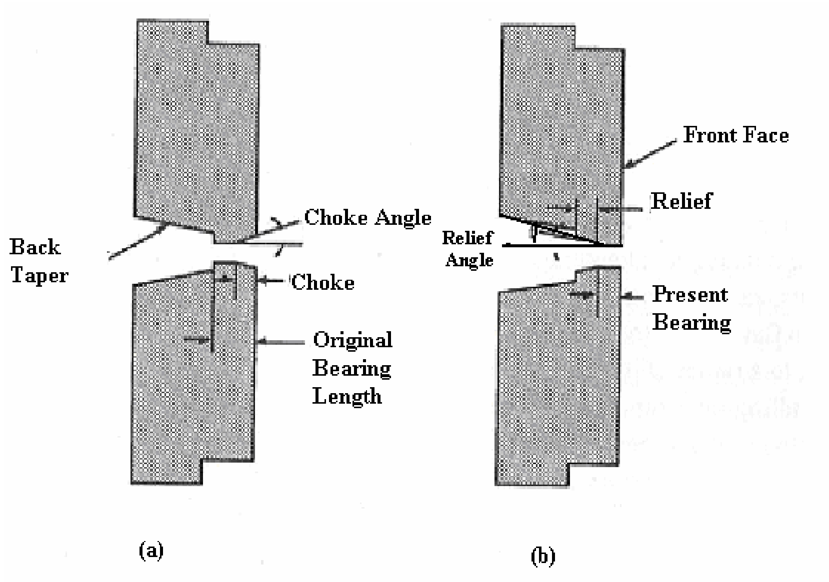


Figure 4.5. Choke and relief in die bearing. a) Choke at front of bearing. b) Increased relief angle at the back or exit side of the bearing [5]

Disregarding the fact that a weld pocket is a necessity when using a puller system in the extrusion process, recess pocket dies can be very useful. Pockets can be used to manipulate flow by feeding areas that are running slow, or by constricting areas that tend to run fast. Constriction actually occurs by preventing the metal from flowing along optimum flow angles set up in the dead metal zones, while feeding allows these optimum angles to exist. In cases of a close pocket, control is given by restricting flow to varying degrees, but always constricting the flow. While the use of pockets can reduce the need for large variations in bearing length that lead to surface variations, it cannot correct acute flow discrepancies that result from small details on profiles [23].

4.2. Wear and Protection of Extrusion Dies

The durability of a tool is a function of many parameters including mechanical and physical properties of the tool material, the nature and parameters of the forming process, and properties of the material to be formed. In aluminium extrusion, dies suffer complex stress conditions and high temperatures, and consequently, the properties of the die material play a significant role in ensuring the durability of a certain tool. Currently, H 13 tool steel is applied as a die material for aluminium extrusion [24]. Wear of extrusion dies has an important technological and economic significance, since it changes both the dimensions and surface finish of the extrudate. In order to minimize wear, the extrusion dies are made of hot work tool steels and surface treated, typically by nitriding [25].

The H13 hot work tool steel is the tool material that is used almost exclusively on extrusion dies. It is characterized by high strength and ductility, good tempering resistance and moderate cost. It is also well suited and established for surface treatments such as nitriding. The steel is used in a quenched and tempered condition at a hardness range of 450–500HV [25].

In most cases, two factors limit the lifetime of a die: severe wear in the region of the bearing channel and fracturing in stress concentration areas, the mechanism of which is related to cyclic softening. While wear of the bearing surfaces can be prevented by applying surface hardening techniques, a material possessing higher fatigue resistance should be used to avoid fatigue cracking. In this connection, superalloys are being examined as candidate die materials for aluminium extrusion [24].

Sheikh *et al*. [4] worked on die failure mechanisms and had made series of experiments on 17 different die profiles and 616 die failures in commercial extrusion of Al-6063. In experiments both solid and hollow dies were used. It was concluded that, on an overall basis, when all types of dies considered together, the predominant failure mode was fracture (46%), followed by wear (26%), deflection (19%), mixed mode (4%), miscellaneous (2%) and mandrel related (3%). From these experiments, it can be said that wear is a very serious problem in aluminum extrusion dies.

Traditional methods for hardening hot-work die steels involve the quenching from salt bath of controlled atmosphere or air atmosphere furnaces into salt, oil or forced air. While these methods are usually effective, they are not environmentally friendly and often produce undesirable oxides on the surface of the steel. Of even greater concern is the degree of severity of the quenching process. The use of liquid quenchants such as oil can cause distortion or cracking of the die, particularly when complex die geometries are involved. While air-cooling reduces the risk of distortion, it may not always be effective for through hardening of thick sections [26].

These shortcomings led to the development of vacuum heat-treating furnaces for hardening of extrusion dies. Vacuum heat-treating is far more environmentally friendly than most traditional heat treating processes. It produces an end product that is especially clean and free of detrimental surface oxides. Furthermore, when equipped with advanced control systems, vacuum heat-treating furnaces can be fully automated for consistent quality of the end product [26].

After vacuum hardening and final machining, most extrusion dies are nitrided to improve their performance. Nitriding is a case hardening process that introduces atomic nitrogen into the surface of an alloyed steel to form a layer with improved wear and corrosion resistance. There are several techniques for nitriding now in use, but gas nitriding is among the most popular. In gas nitriding, the source of the nitrogen is ammonia, which dissociates catalytically into nitrogen and hydrogen upon contact with the heated surfaces of the steel and nitriding retort. Most of the ammonia dissociates into inert nitrogen, with only a fraction in the form of atomic nitrogen. The atomic nitrogen diffuses into the surface of the steel to form a hard and brittle iron nitride layer, commonly know as the white layer. Deeper diffusion of nitrogen results in the formation of nitrides of elements such as aluminum, chromium, manganese, titanium and vanadium that improve the hardness and wear properties of the steel [26].

Nitriding in a gaseous environment increases the service life of the die substantially by protecting the bring surface against wear. Generally, nitriding of steel involves diffusion of nitrogen into the surface at temperatures ranging from 450 to 580°C in a liquid, gaseous or vacuum process. The treatment generates a 50–300 µm thick nitrogen enriched diffusion zone and a two to ten µm thick iron nitride compound layer on top (often referred to as the white layer) which attains a hardness of 1000–1200HV. The compound layer may be relatively brittle and the opinions are divided whether its presence is advantageous for the wear resistance or not [25].

For more than a decade, thin hard coatings have been employed to a small but increasing extent on extrusion dies. As compared to conventional nitriding, they are considered economically viable by increasing tool lifetime for long production series. Several techniques are utilized for coating deposition, PVD being one of the most versatile. The advantage with PVD is foremost the relatively low process temperature 200–500°C, allowing most industrially important substrate materials (hot work tool steels included) to be coated. One limitation is that the PVD process is a line-of-sight process, i.e. it is difficult to deposit coatings on surfaces with a complex geometry, e.g. slits and cavities in forming tools. The general opinion is that it is not possible to coat cavities deeper than their width. This limitation hinders PVD to be applicable on all extrusion dies since most dies are designed with such slits [25].

Duplex coatings have been developed in recent years to improve the conditions of PVD coating of relatively soft materials (as compared to the coating hardness), e.g. the tempered hot work tool steels used for extrusion dies. With a large mismatch in hardness to the substrate, the benefits of the coating are not fully used, since it is very brittle and also sensible to deformation in the substrate. Therefore, the plasma nitriding of the steel substrate prior to coating during a duplex treatment aims at increasing the substrate hardness and thereby extend the service life of the coating [25].

The PVD coating method is carried out in a vacuum atmosphere of around 10^{-2} to 10^{-5} mbar and temperatures of 250-500°C. PVD is a gas coating technology where gas in the coating reactor is distributed physically by a sputtering process, for instance. The evaporation of the desired coating materials like titanium, aluminum, chromium etc.

executed together with a gas mixture (nitrogen, hydrogen, etc.). A standard coating layer thickness range between one and four µm. Even though PVD technology is successfully applied in many other industries, it turned out to be not the perfectly suitable solution for the application of aluminum extrusion dies [27].

There is also another coating technology for extrusion dies that is CVD Coating. The chemical vapor deposition (CVD) technology is a chemical precipitation from the gas atmosphere. The hard material is applied to the surface of the die from the gaseous phase. Base material and side product of the process are gases. The CVD method is carried out at a pressure of 30-400 mbar. The gas mixture and flow rate defines the layer, for instance, for a TiN layer, a mixture of $TiCl_4$ (titanium tetra chloride), nitrogen and hydrogen is needed. Standard CVD layers range between six and 15µm [27].

Three main methods of CVD coating are distinguished: the high-temperature CVD executed at temperatures of 900-1000°C, the medium temperature CVD at 700-900°C and the plasma activated CVD at 450°C-650°C. The CVD method creates good bonding combined with minimum sliding friction. This is caused by the metallurgical bond between coating and steel. Another reason for the good wear resistance lies in the relatively thick layer compared to PVD [27].

The chemical treatment has a good throwing power and is not restricted to geometry. Therefore almost every die contour can be coated with a uniform layer thickness. This is especially suitable for extrusion dies with their sometimes deep and thin slots as well as undercuts. PVD is more restricted in geometry due to the nature of the beam. Only parts of the dies are exposed to the PVD sources. Therefore not all parts of the die have the same layer thickness, which can cause different wear ratios during operation. A further advantage of the CVD process is the compact packing of the coating. Even very thin layers show good operation characteristics. A two-cavity multimicroport (MMP) die with CVD coated inserts and die plate can be seen in Figure 4.6 [27].

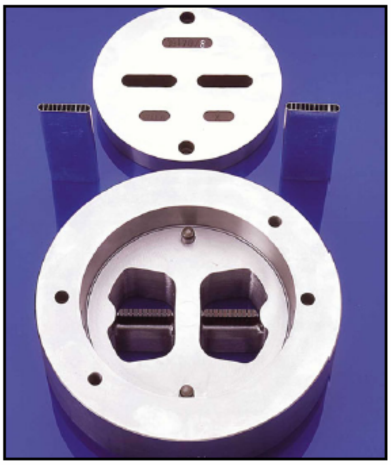


Figure 4. 6. Two cavity MMP die with CVD-coated inserts and die plate [27]

5. EXPERIMENTAL STUDY

5.1. Materials Used in Hot Extrusion Experiments

The pre-conditions to realize the differences between the extrudability of different aluminum alloys are suitable process, suitable alloys and homogenized billets prepared for extrusion.

The process introduced for series of experiments is the hot extrusion method, in which, the aluminum raw material, called billet, is being heated to a specific temperature to overcome the high flow stresses produced during extrusion process. As discussed in the previous sections, hot extrusion is a hot forming process. In hot extrusion, adding to billet, die container, ram and die holder parts are also heated to specific temperatures. Hot extrusion presses are installed in the aluminum plants on both horizontal and vertical axes, the billets used in these plants are can vary from 90 mm up to very high diameter values, to put a limit to the diameter value is impossible in today's technology because the presses are improving continuously. Today, in aluminum plants, horizontal axes extrusion plants are commonly used. Tool selection in the construction of presses is also having a vital role in the success of process. Some parts like container, ram, die holder etc. of extrusion press must be treated carefully and minimum hardness and strength requirements must have been achieved.

In experimental studies two kinds of aluminum alloys are used. One of them is AA 6063 and the other is AA 7075, which are fabricated by Cuhadaroglu Metal Sanayi ve Pazarlama A.S., Turkey. Both alloys are 30 mm in diameter and 81 mm in length, in Figure 5.1, pictures of these billets are shown. The alloy AA 6063 is used in various interior and exterior architectural applications, such as windows, doors, store fronts and assorted trim items, this alloy is also known as the best suited alloy for anodizing applications, either plain or in a variety of colors. The alloy AA 7075 is used in any place where highest strength is needed, aerospace applications, aircraft and automotive parts. The standard chemical composition of AA 6063 and AA 7075 alloys are shown in Table 5.1. The chemical composition of the AA 6063 and AA 7075 billets are investigated in a composition analyzer and results are shown in Table 5.2. It can be seen from Table 5.1 and 5.2 that theoretical and real chemical compositions are coinciding each other significantly.

(a)

(b)

Figure 5.1. Pictures of (a) AA 6063 and (b) AA 7075 billets

Table 5.1. Standard chemical compositions limits of AA 6063 alloy and AA 7075 alloy in wt per cent [28]

		Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
AA 6063	Max(percent)	98.9	0.6	0.35	0.1	0.1	0.9	0.1	-	0.1	0.1
	Min(percent)	98	0.2	0.1	0.05	0	0.35	-	-	0	0
AA 7075	Max(percent)	90.0	0.45	0.6	2	0.3	2.9	0.28	-	6.1	0.2
	Min(percent)	89	0.4	0.5	1.2	0	2.1	0.18	-	5.1	0

Table 5.2. Chemical composition of AA 6063 and AA 7075 billets in wt per cent according to KOSGEB report

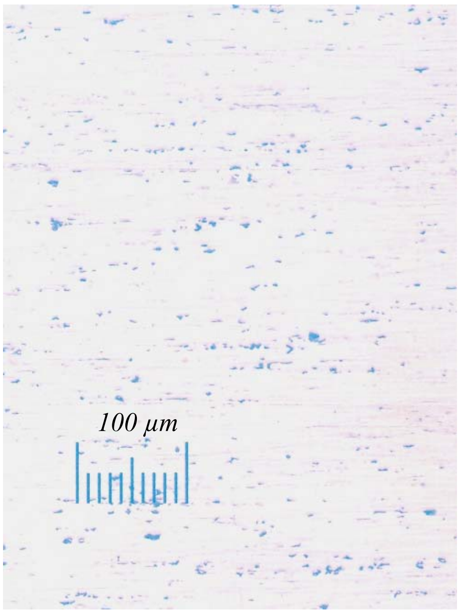
		Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
AA 6063	(percent)	98.81	0.501	0.19	0.082	0.119	0.399	0.002	-	0.022	0.008
AA 7075	(percent)	89.22	0.417	0.565	1.83	0.055	2.69	0.052	-	5.22	0.007

When the mechanical properties of the alloys AA 7075 and AA 6063 are compared to each other, the significant differences can be easily seen, in the Table 5.3, hardness values of AA 7075 and AA 6063 are compared with each other according to the test done by 62.5 kg / ϕ 2.5 mm WC hardness load. Hardness values are measured for the four arbitrary points of the both billets.

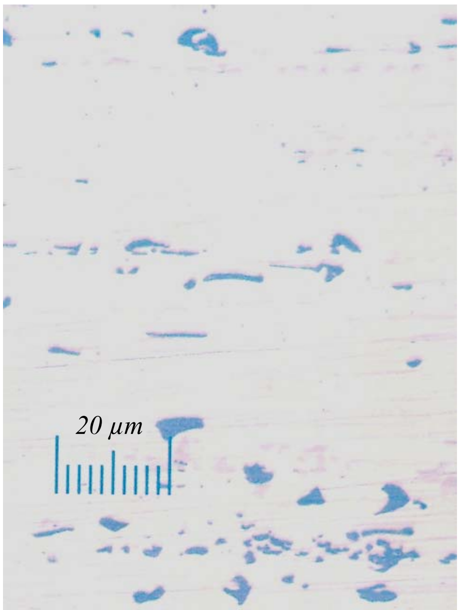
Table 5.3. Comparison of hardness values of AA 7075 and AA 6063 billets

	AA 7075	**AA 6063**
Hardness Brinell (HB)	88,7	40,9
	88,7	40,9
	90,7	41,5
	90,7	41,5

In Figure 5.2 and Figure 5.3, micrographs of AA 7075 and AA 6063 billets can be seen. In Figure 5.2 and Figure 5.3, second phases in the microstructures of these alloys can easily be detected.

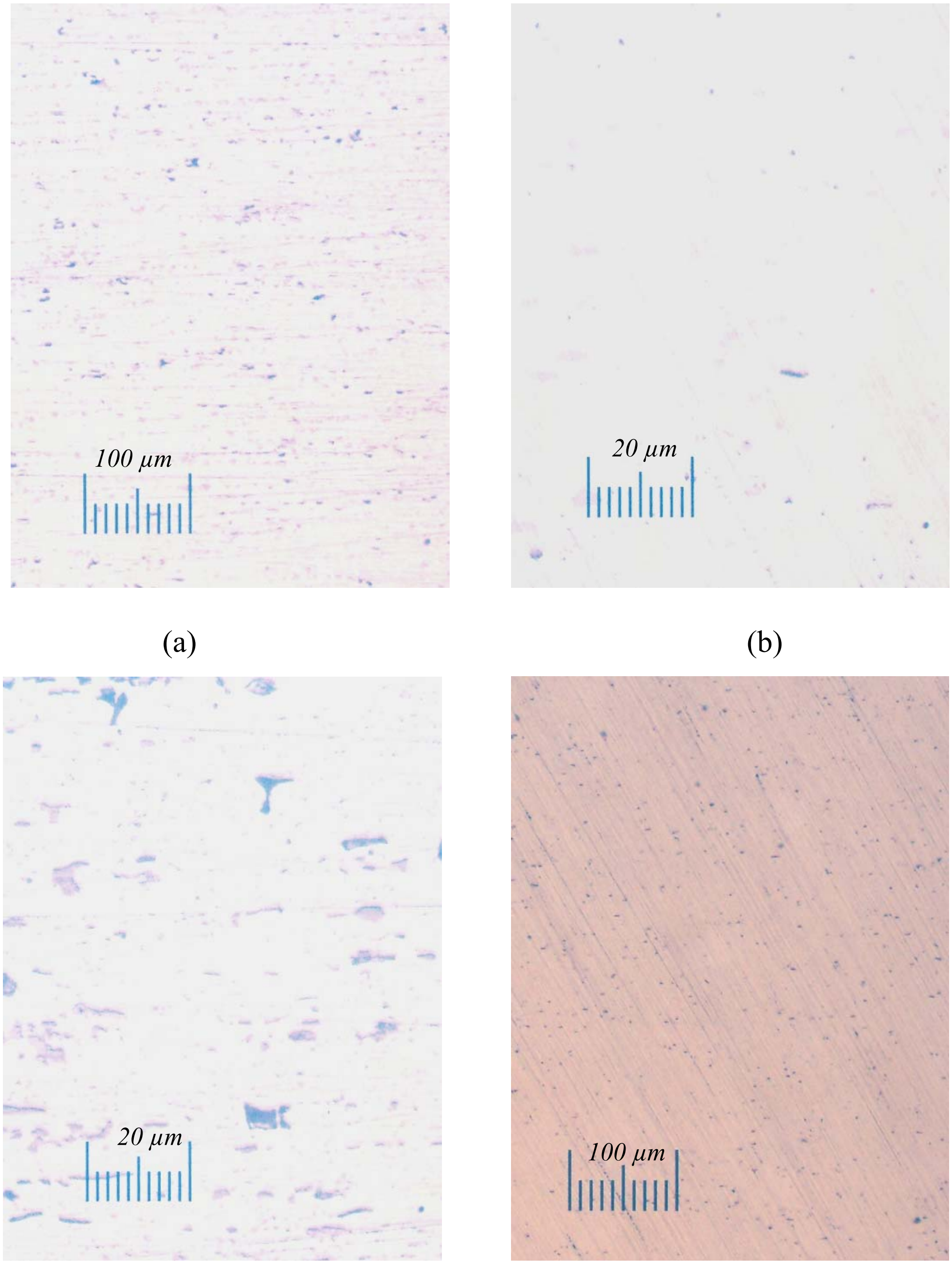


(a)



(b)

Figure 5.2. Micrographs of AA 7075 (a,b) billets from the mid portion



(c) (d)

Figure 5.3. Micrographs of AA 7075(a, c) and AA 6063(b, d) billets from the mid portion

In Figure 5.2 and in Figure 5.3, the micrographs of AA 7075 and AA 6063 billets can be seen. Figure 5.2 (a), (b) and Figure 5.3 (a) and (c) are the micrographs of AA 7075 billet and among these micrographs Figure 5.2 (a) and (b) are provided by only polishing, figure 5.3 (a) and (c) are provided by both polishing and etching with Keller etcher. Figure 5.3 (b) and (d) are the micrographs of AA 6063 billet; (b) is provided by only polishing, (d) is provided by polishing and etching by Keller etcher. From the Figure 5.2 (b) and

Figure 5.3 (c) micrographs of AA 7075 billet, it can be easily mentioned that second phase can be seen very clearly and second phase is at about nine percent of the whole micrograph area. This result is very proportional with the chemical composition results given in the Table 5.2. From the Figure 5.3 (d) micrograph, it can be easily said that the second phase of AA 6063 billet is not obvious. The second phase is only one percent of whole micrograph. This result is also proportional with the Table 5.2.

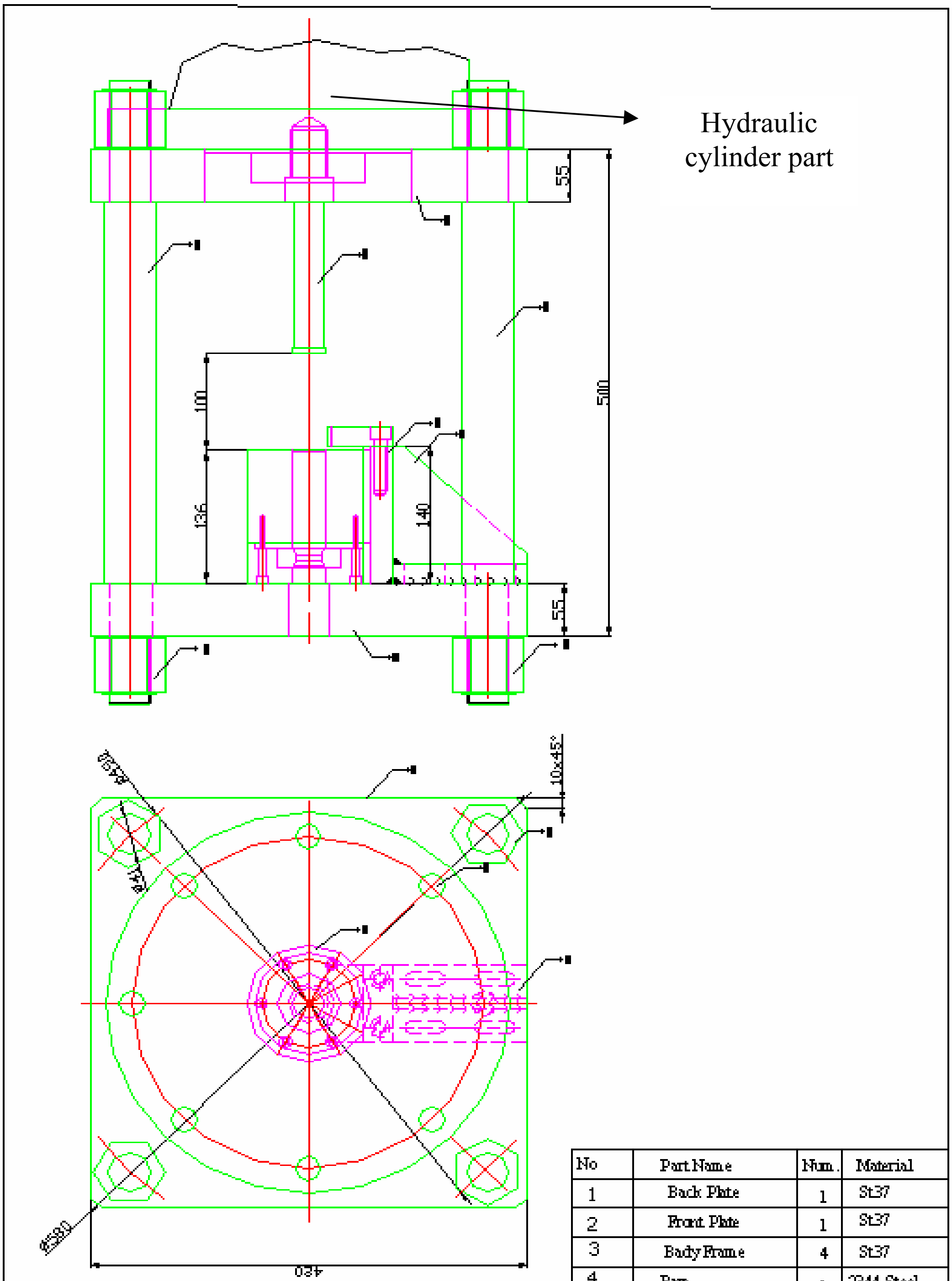
5.2. Experimental Apparatus

5.2.1. Hot Extrusion Press Unit

The hot extrusion press unit consists of a hydraulic cylinder, a container, a die backer, a container holding and centering system, a hydraulic power generator to apply necessary load, a ram, a press body frame and a special designed table to fix all the press body and tools.

AutoCad which is a CAD program is used to design hot extrusion press and its tools. Hot extrusion press unit is shown in Figure 5.4; technical drawing of press is given in Figure 5.5. When electric motor is started and hydraulic valve opens and hydraulic fluid starts to circulate and as a result of this circulation hydraulic cylinder and the main ram fixed to the cylinder can be moved forward and back by the help of manual control bar. The main ram which is screwed in front of the hydraulic cylinder, has a ten mm thick dummy plate in the front part and diameter of the dummy part and ram is 31 mm which can easily move inside of the container. When billet, container, die and ram reach to the required temperature, container and die set (die and die backer bolted to container) extrusion process starts and continues till a 20 mm butt thickness remains at the end part of the billet. Afterwards ram is moved backwards and extruded part is cut. Butt part which has remained in the container is taken from inside of container by again using the press. Die and die backer (die set) are unbolted from the container and container put onto the container holding part, second time engine is started and by the help of the load created by hydraulic unit, by this way butt part is taken away from the container.

Figure 5.4. Hot extrusion press unit



No	Part Name	Num.	Material
1	Back Plate	1	St37
2	Front Plate	1	St37
3	Bady Frame	4	St37
4	Ram	1	2344 Steel
5	Bolt	4	M45
6	Container Holding Part	1	St42
7	Bolt	8	M6
8	Die Backer	1	St60
9	Centering Part	1	St42

Hot Extrusion Press Unit	
Draw By	H.C.ÇITAK
Check By	C.GAVRILIDIS

Figure 5.5. Technical drawing of hot extrusion press unit

Body frame of the press is constructed by two plates, which are fixed with M45 bolts and the distance between these plates is provided by four steel bars, these bars have 41 mm diameter each and made from St 37 steel. Front plate has 55 mm thickness, in the center there is a hole which has 40 mm diameter and from this hole extruded product is coming out. The size of the plate is 420x420x55mm, technical drawing of the front plate is shown in Figure 5.6. Back plate has also 55 mm thickness, size is same as the front plate but for setting the hydraulic cylinder, a hole with 200 mm diameter is opened, technical drawing of the back plate is shown in Figure 5.7.

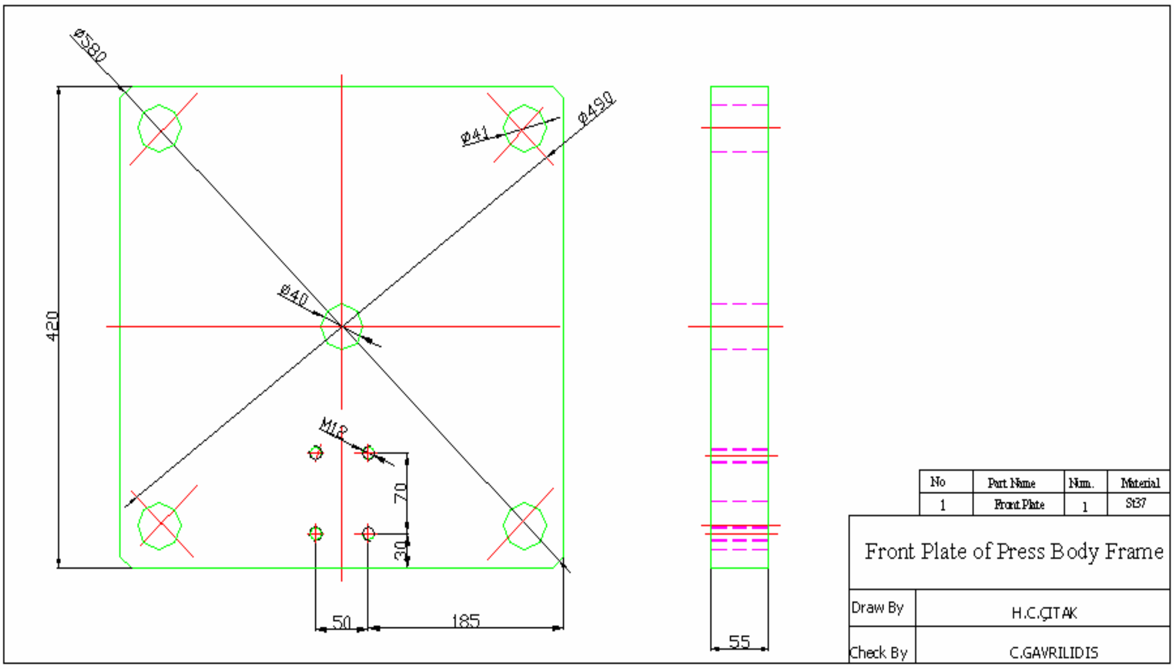


Figure 5.6. Front plate of press body frame

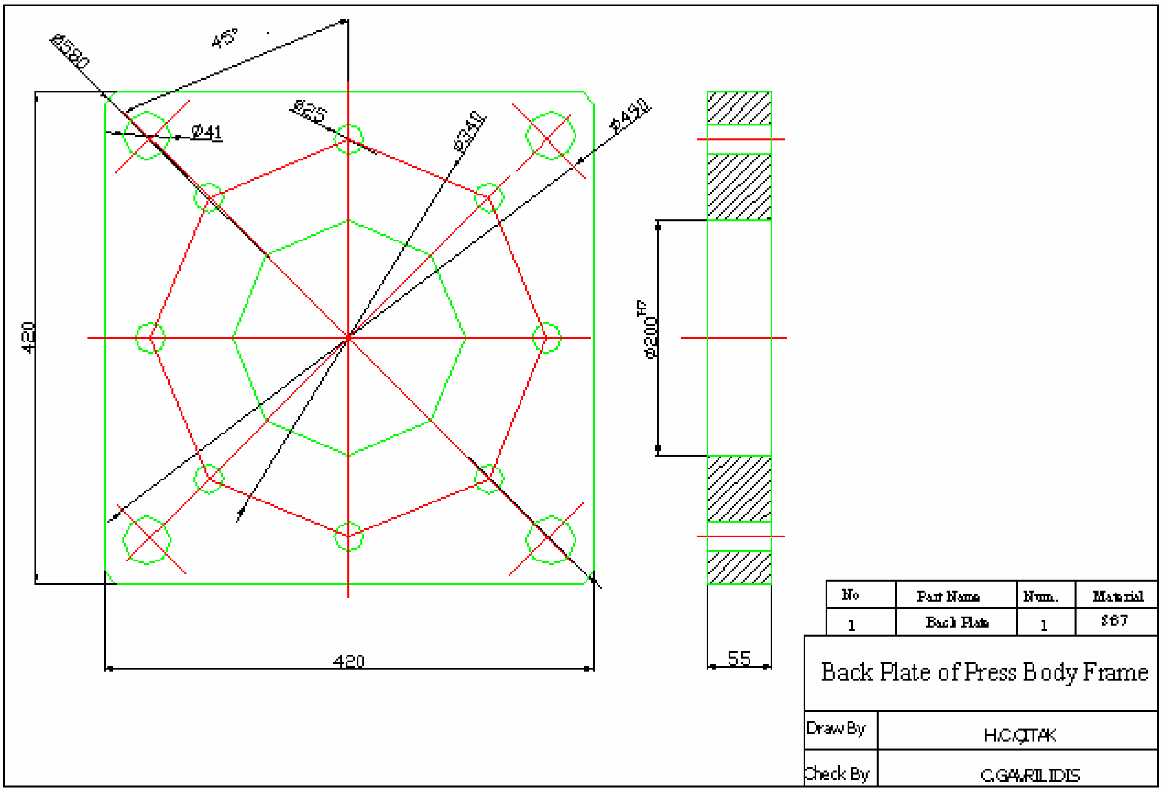


Figure 5.7. Back plate of press body frame (Hydraulic cylinder holder)

Container is one of the most important parts of the hot extrusion press. Container is subjected to large mechanical and thermal stresses as most of the extrusion process is becoming inside of this part. Container is heated to temperatures between 390 – 475 ^{o}C, according to the alloy type, and this heating up process is the main reason of the thermal stresses. Owing to these conditions, material selection and design of the container must be made properly. Container part of the hot extrusion press is made from H13 (2344) hot working steel and the hardness of the container is 50-52 Rockwell. Container is shown in Figure 5.8 and the technical drawing of the container is shown in Figure 5.9. H13 steel is a special kind of steel used in the parts subjected to high temperature conditions. Hardness value is provided by a special heat treatment process. In order to connect die and die backer (die set) to the container, six M6 bolts are used. In Figure 5.8, the holes opened for these bolts can be seen.

Figure 5.8. Container Part

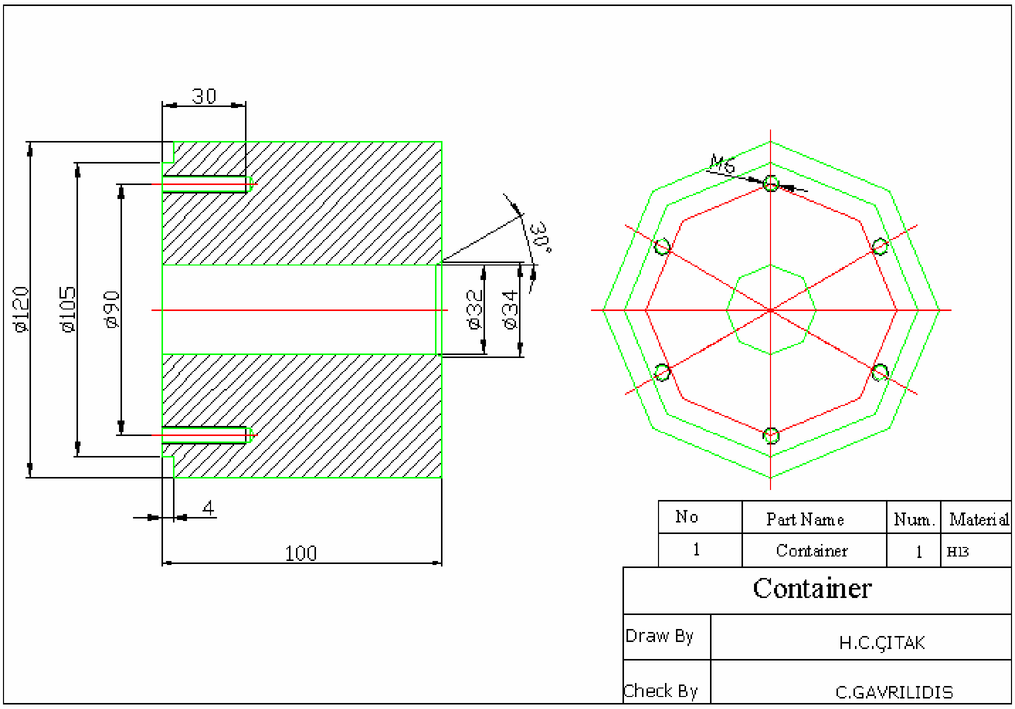


Figure 5.9. Technical drawing of the container part

Die backer and dies (die set) are the critical parts of the unit. Die backer is made from St 60 steel. Inside the die backer, die is set and after that process, they are bolted to container. Dies are made up of H13 (2344) steel and it is heat – treated. Its hardness value is about 54-56 HRC. Five different dies used in experiments. 0.5^o, 1^o, 1.5^o choke dies (brake), 0.3^o relief die (speed) and one standard 0^o die. Schematic view of dies are shown in Figure 5.10.

Figure 5.10. Dies used in experiments

Container is set on a special construction, which is called container holding and centering part. This is a very special design that is made for this unit. This part is made up of St 42 steel and bolted to the front plate by four M10 bolts. The end part is welded to the front part with a 45^o angle steel bar, to prevent the risque of distortion by the weight of container. There is a power screw under the body frame of the press; this screw is used to center the container on y-axis. Functions of this part are to hold the container, prevent to lose centering with ram on x-axis and by the help of the power screw on y-axis. Technical drawing of this part is shown in Figure 5.11 and schematic view can be seen on Figure 5.4.

Ram is the part used to apply the force created by hydraulic unit to the hot aluminum billet. Ram is made up of 2344 steel as ram is also heated up to a specific temperature. It is heat –treated and hardened to 50-52 HRC.

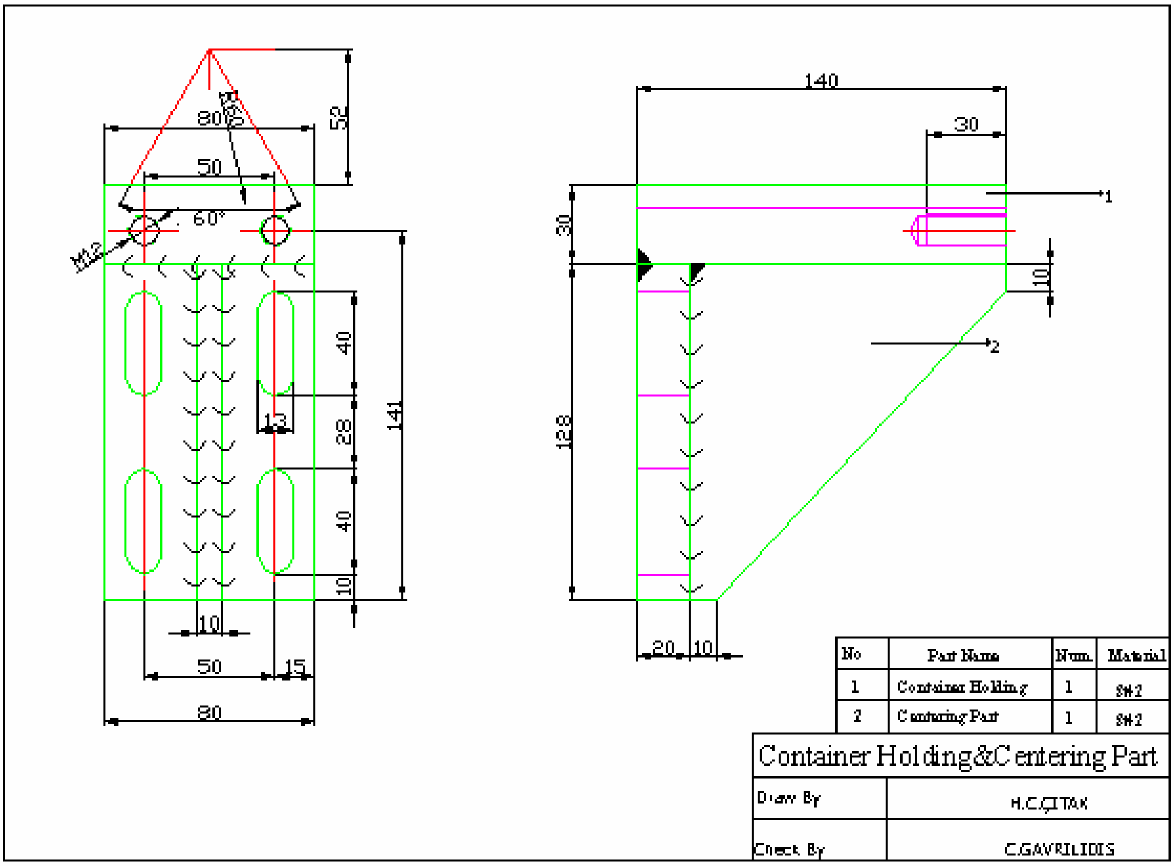


Figure 5.11. Technical drawing of container holding and centering part

Hot extrusion unit is a horizontal extrusion system. In the horizontal systems, to provide the necessary hydraulic power, hydraulic cylinder diameters are chosen bigger. In the unit, there is cylinder of 200 mm diameter and the machine is designed to work at pressure range of 250 – 300 bar. If the force is calculated in these conditions, it can be said that a hydraulic force of 65 – 90 tones is created in this unit. Therefore a 5.5 kW electric motor is used to provide the necessary pump flow and operational pressure. Movement of the ram and hydraulic piston is controlled with a control bar. In the extrusion process, speed of the ram is a very important parameter, the highest speed of ram is designed as five mm/s but this value can be decreased to three mm/sec in the required operations like AA 7075 extrusion. The photo of the controlling and hydraulic cylinder part of the unit is shown in Figure 5.12.

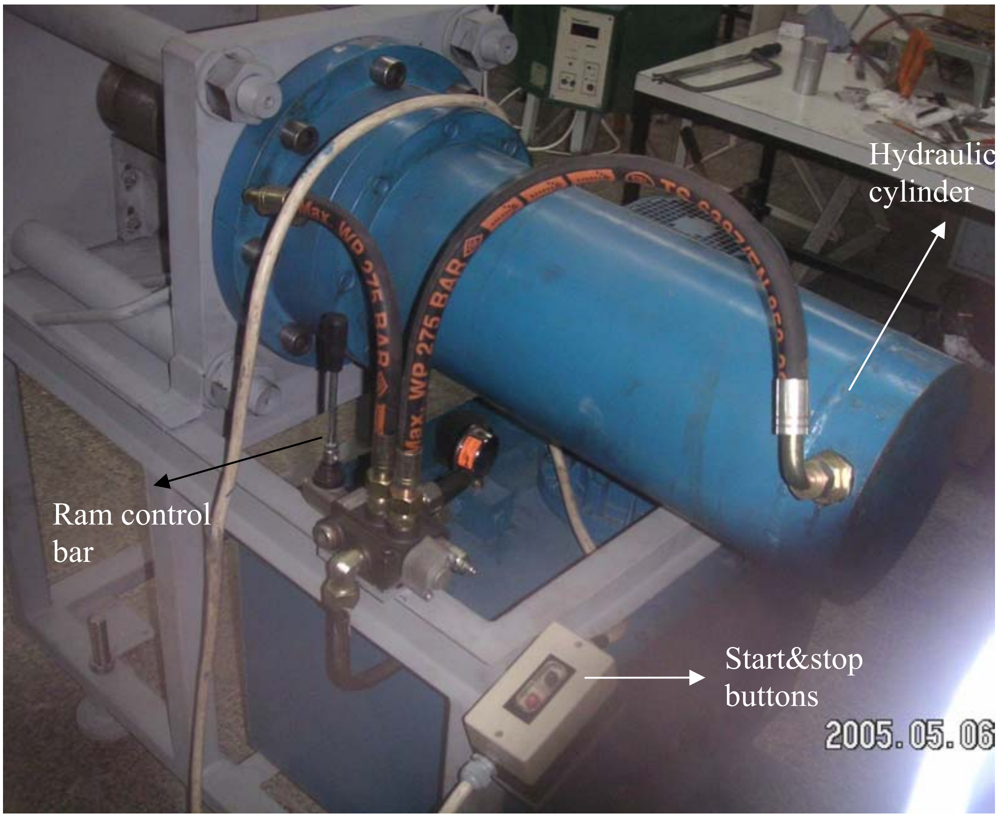


Figure 5.12. Hydraulic cylinder and ram control parts of the unit

5.2.2. Heating of Billet, Container and Dies

As discussed before, container, die set (die backer and dies) and billets are heated to specific temperatures. If the extrusion process is started without heating one of these parts, the results will be catastrophe; if billet is not heated extrusion can not be generated and if it is tried, the pressure values will be so high that machine can be distorted. If billet is heated but container and die set is not heated then hot billet will cool down fast and consequently ram can not be moved further neither back nor front. Adding to that in inside part of the container, small cracks can be generated. So heating is very important in hot extrusion. During the experiments, heating is made by a furnace; photo of this furnace is shown on Figure 5.13. Billet, container and die set temperature for extruding AA 6063 alloy is 475^{o}C, to heating up the cold furnace to that temperature takes about 30 minutes after reaching that temperature billet and other parts are put into the furnace and stay there about 75 minutes. For extruding AA 7075 alloy, the procedure is different because if critical temperature for hot AA 7075 alloy is exceeded the extrusion product can be scrap. From many experiments, it was found that for having a high quality product from AA 7075 alloy, the billet, container and die set must be heated up at 392°C for two hours. In the early trials, at lower temperatures like 375°C, it was not successful.

Figure 5.13. Furnace used to heat billet, container and die set

5.2.3. Hydraulic Power Unit

Hydraulic power unit is designed according to the calculations for extruding the AA 7075 and AA 6063 alloys. In the early design steps of the hydraulic unit, the maximum force requirements for extruding AA 7075 and AA 6063 alloy is calculated first theoretically by using the values obtained from literature on extrusion and then some benchmark studies are done on the real extrusion presses in Cuhadaroglu Metal Sanayi ve Pazarlama A.S. After all these studies the force and pressure requirements for extruding AA 7075 and AA 6063 alloys are calculated in a safe range. The system is designed to provide high efficiency and a rigid construction. Security is one of the most important parameter that has a vital role during design process. Security is important because the system reaches to 250 – 350 bar pressure and if some precautions are not provided, results can be very bad. All of the connecting pipes and frame parts are designed by using a safety factor of average two. For providing high security in control systems of hydraulic power unit, an emergency stop system is installed in the extrusion press, if the ram is out of control during the extrusion process by using this button all of the electricity can be closed and this system is very essential for protecting die and container from the uncontrolled deformation loads applied by the hydraulic system. Properties of the components used in hydraulic unit are given in the Table 5.4. In this table ram stroke is given as 400 mm, this is a very long ram stroke and some of the serious actions are made to decrease the danger provided by such a long stroke. The distance that ram must move during extrusion is calculated carefully and this distance is set on the ram, by this method die safety is provided adding to that ram is protected from buckling. In the Figure 5.14, the hydraulic scheme of the unit is given and all of the components are shown in this figure. The system contains all of the basic components of a hydraulic machine:

- The electric motor provides the power for the system. The motor is attached to a hydraulic oil pump.
- The hydraulic oil pump which is a gear pump creates a stream of high-pressure oil, which runs to a valve.
- The tank holds the hydraulic oil that feeds the pump and a filter keeps the oil clean.
- The pressure relief valve lets the flow of oil when safe pressures are exceeded, then closes again when pressure drops to a preset level.
- The monoblock directional control valve controls the start, stop and direction of flow.
- The double acting pneumatic cylinder where fluid under pressure can be applied to either side of the piston to apply force and provide movement. The two fluid ports, one near each end of the cylinder, alternate as inlet and outlet ports, depending on the direction of flow.

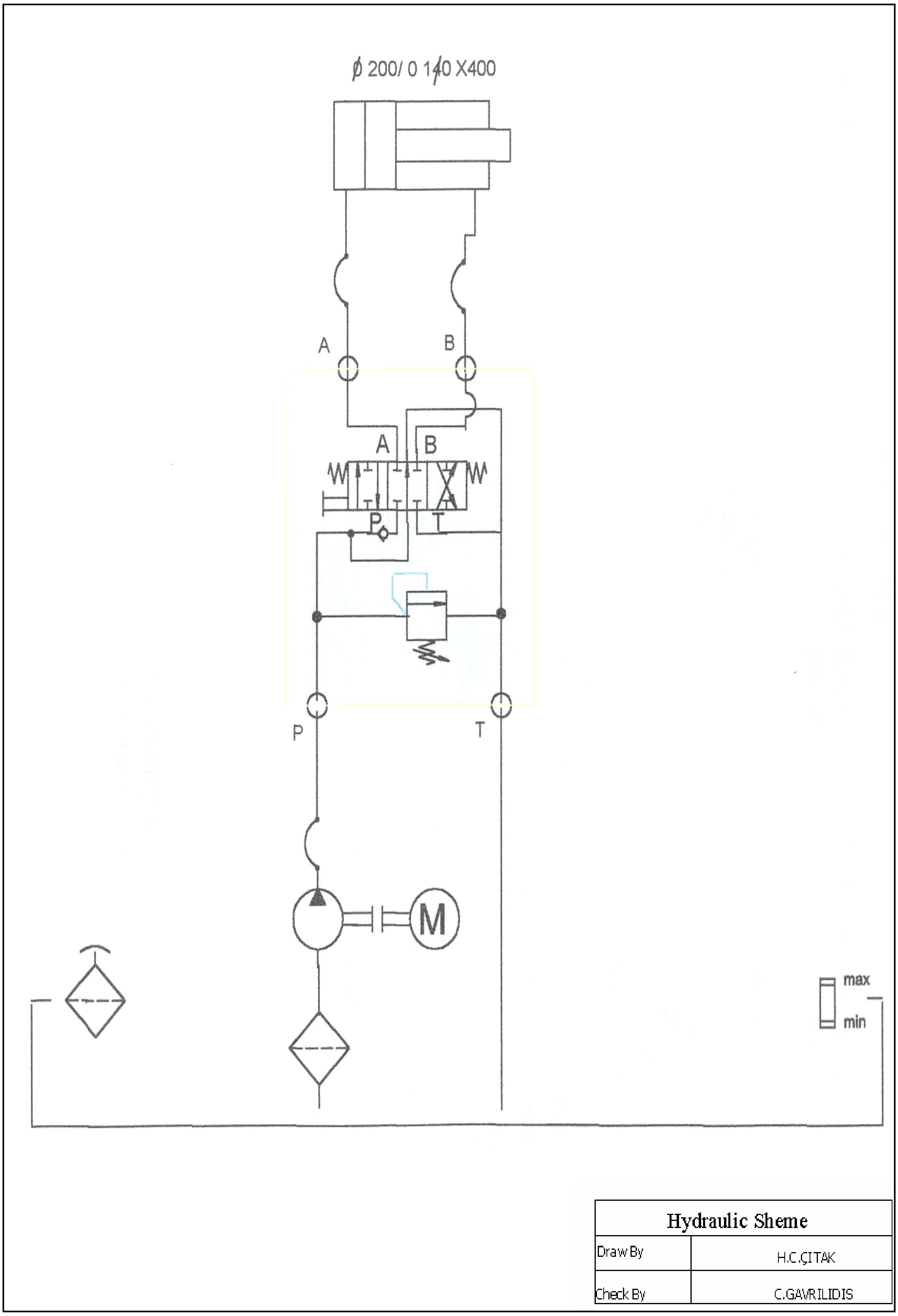


Figure 5.14. Hydraulic scheme of the unit

Table 5.4. The properties of the components used in the Extrusion Press

Cylinder (h-NHS-200x400)	
Number of bolts	8
Diameter	200mm
Stroke	400mm
Directional Control Valve (Hidroirma-HDM140)	
Max. flow rate	40 l /min
Max. operating pressure	320 bars
Max. back pressure	30 bars
Pressure Relief Valve (Hidroirma-HDM140)	
Settled flow rate	30 l/min
Electrical Motor	
Voltage	380V
Power	5.5KW
Revolution	3614 1/min
Hydraulic Pump (Hidroirma-AP200/8.5)	
Type	Constant Displacement Internal Gear Pump
Displacement	$8.3cm^3$

5.3. Hot Extrusion of AA 6063 and AA 7075 Alloys

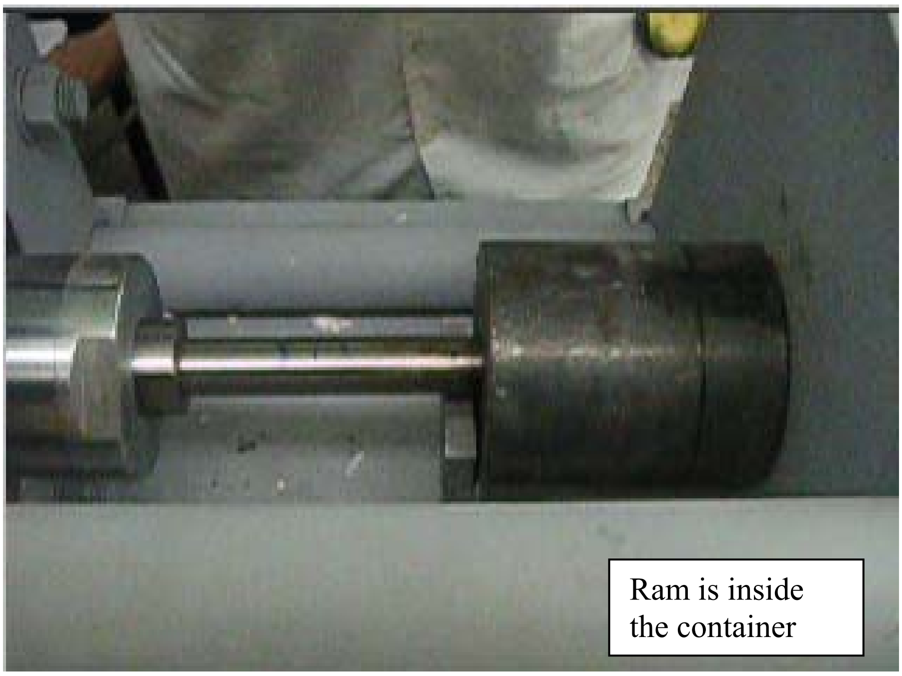
In experimental studies homogenized type aluminum alloys are used. AA 6063 and AA 7075 aluminum alloys are fabricated by Cuhadaroglu Metal, Turkey. Billets are machined to a diameter of 30 mm and these billets are cut to 80 mm samples.

Die and die backer (die set) is assembled to the container before hot extrusion process starts. For assembling the die set to the container six M6 bolts are used, but before this assembling procedure, bolts, front face of the die, back face of die backer and container hole are lubricated by graphite oil, to prevent sticking of hot billet to the container, to decrease the friction inside of the container and to provide easy disassembling of bolts and die set after the process. Adding to these parts, tip of the ram is also lubricated by graphite oil to prevent the sticking of the hot billet to the ram. After assembling the die set and container, this assembled part is set into furnace and also the billet (either AA 6063 or AA7075) is set into furnace.

For extruding AA 6063 billet, furnace is set to 370^{o}C temperature, all of the parts in furnace stay there for one hour and after one hour the temperature is increased to 475^{o}C and for reaching that temperature, homogeneous in every part, parts stays in furnace at 475^{o}C for 30 minutes. For extruding AA 7075 billet, the furnace is set to 392^{o}C and the parts are heated in the furnace for two and a half hours. Hot extrusion process of AA 7075 alloy is very different from AA 6063 and other aluminum alloys. Temperature is very critical, if the temperature is lower than 392^{o}C, the extrusion would not be succeed, if the temperature is higher then 392^{o}C, the aluminum billet has failures especially from sides of the profile. In the first try of extruding AA 7075, the temperature of furnace is set to 375^{o}C but the extrusion was not possible.

After that, the billet and container is again put to furnace and this time temperature is increased to 392^{o}C, after subjecting the parts to this temperature, extrusion process is possible. When container, die set and billet reach to the desired temperature, they are put over the container holder and the billet is put into the container. Lubricated ram is heated to 250^{o}C by using a special heater.

Afterwards, ram moves through the container hole and billet is squeezed between die and ram. This provides the extrusion process and the ram moves till billet has a 25 mm butt thickness. Afterwards, punch moves back and profile is cut from the container. During the process, ram is coated by aluminum because of the back and forward moves of the ram. The beginning and the end of hot extrusion process is shown in Figure 5.15. The photograph of reverse-coating of aluminum is shown in Figure 5.16.



(a)

(b)

Figure 5.15. Beginning (a) and end (b) of hot aluminum extrusion

Figure 5.16. Reverse-coating of aluminum over the ram during the extrusion

Hot extrusion experiments are conducted with five different dies and two different alloys. Dies are as mentioned before, 0.5^{o}, 1^{o}, 1.5^{o} angled choke dies (brake), 0.3^{o} angle relief die(speed) and one standard 0^{o} die, by using these dies the speed of metal flow can be controlled and dimensional stability can be achieved. The main aim is to investigate the effects of these choke and relief dies on the extrudability of aluminum alloys AA6063 and AA 7075. Extrusion process is repeated for each alloy with these five different die. During the trials, maximum 94 tones of hydraulic load and maximum ram speed of five mm/s is applied. Maximum pressure, measured during experiments is 300 bar.

Hot extrusion experiments are conducted at 475^{o} C for AA 6063 alloys and at 392^{o} C for AA 7075 alloys. Container and die set is preheated before the experiments. Ram speeds are also different for these alloys, for AA 6063 alloys ram speed is about five mm/s and AA 7075 alloys ram speed is about three mm/s. In the trials, applied load by ram is varied between 60 tones to 94 tones. Process time for AA 7075 alloys is about 17-19 seconds and for AA 6063 alloys is about 10-12 seconds. The pressure curves of alloys are shown are shown in Figures 5.17 – 5. 26.

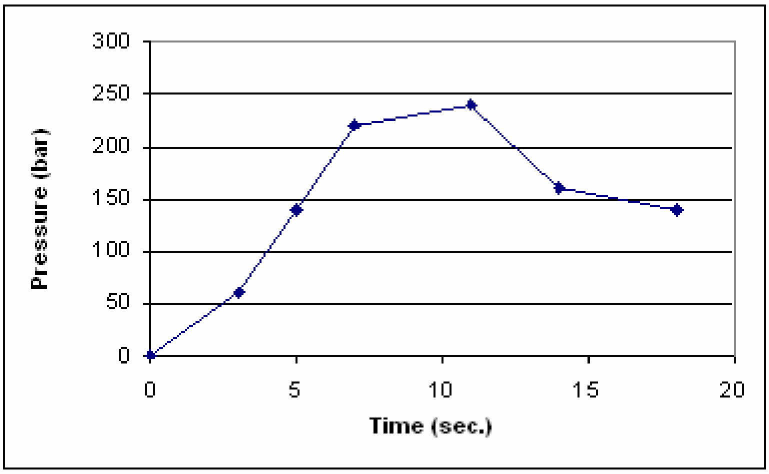


Figure 5.17. Hot extrusion of AA 7075 alloy at 392° C with 0° angled die

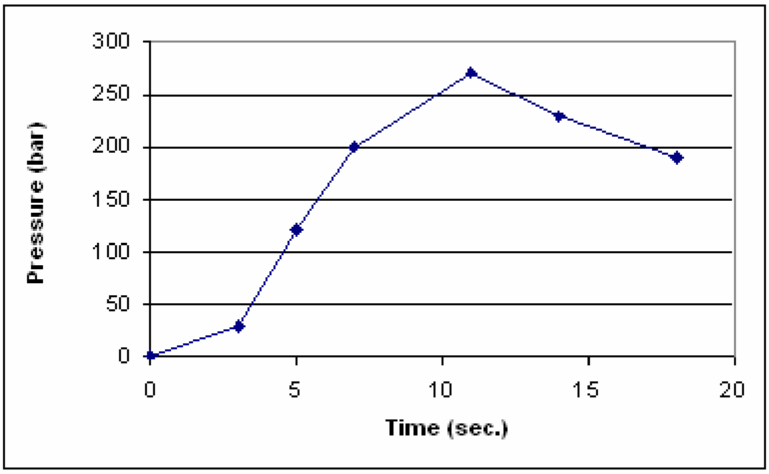


Figure 5.18. Hot extrusion of AA 7075 alloy at 392° C with 0.5° angled choke die

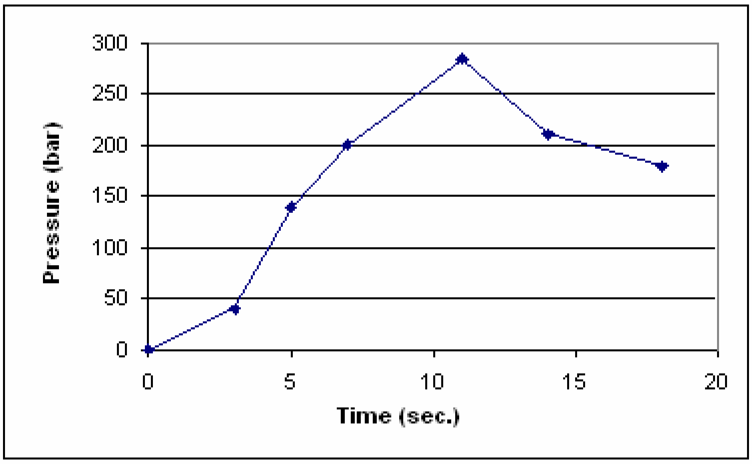


Figure 5.19. Hot extrusion of AA 7075 alloy at 392° C with 1° angled choke die

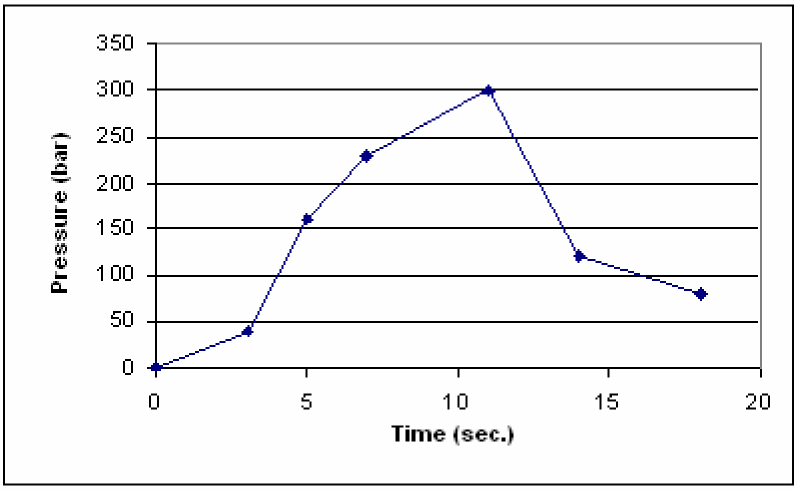


Figure 5.20. Hot extrusion of AA 7075 alloy at 392° C with 1.5° angled choke die

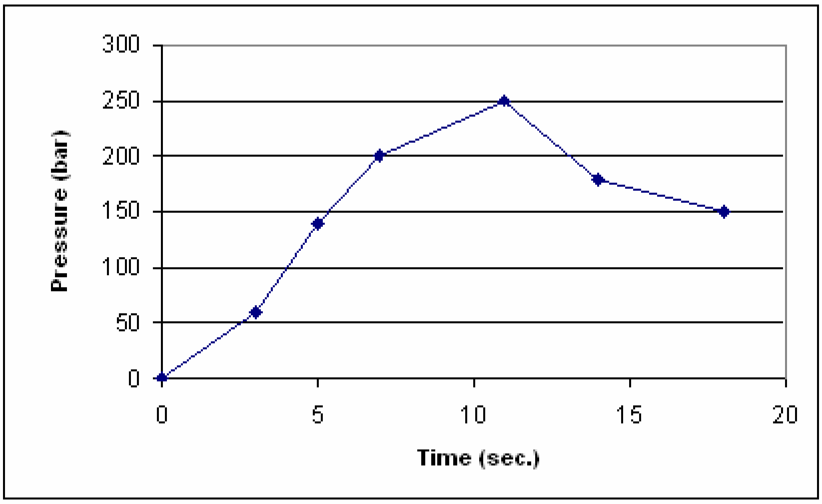


Figure 5.21. Hot extrusion of AA 7075 alloy at 392° C with 0.3° angled relief die

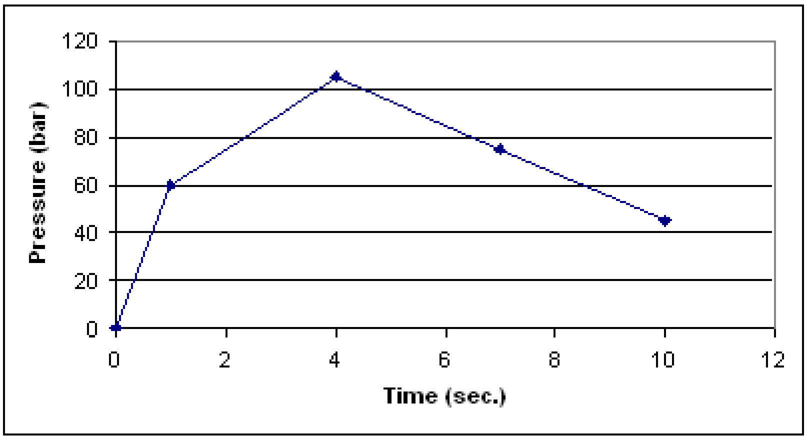


Figure 5.22. Hot extrusion of AA 6063 alloy at 475°C with 0° angled die

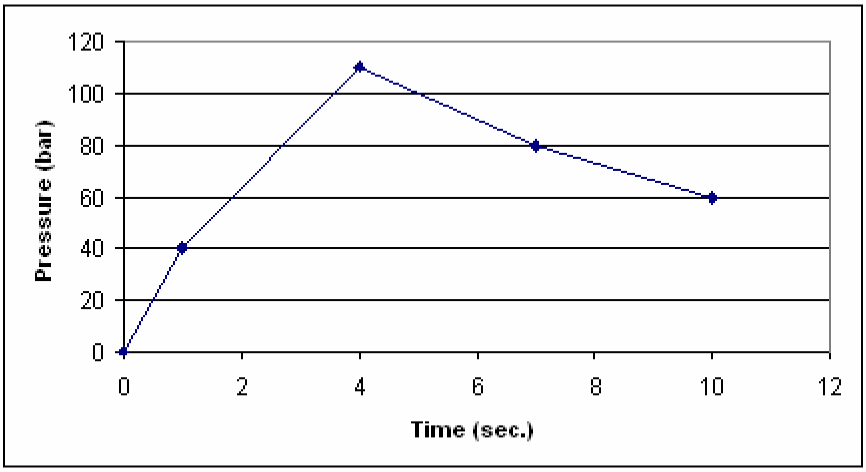


Figure 5.23. Hot extrusion of AA 6063 alloy at 475° C with 0.5° angled choke die

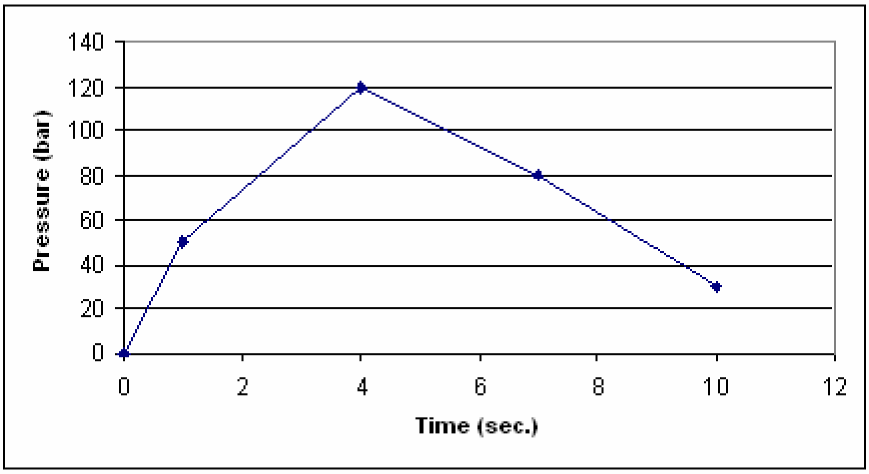


Figure 5.24. Hot extrusion of AA 6063 alloy at 475° C with 1° angled choke die

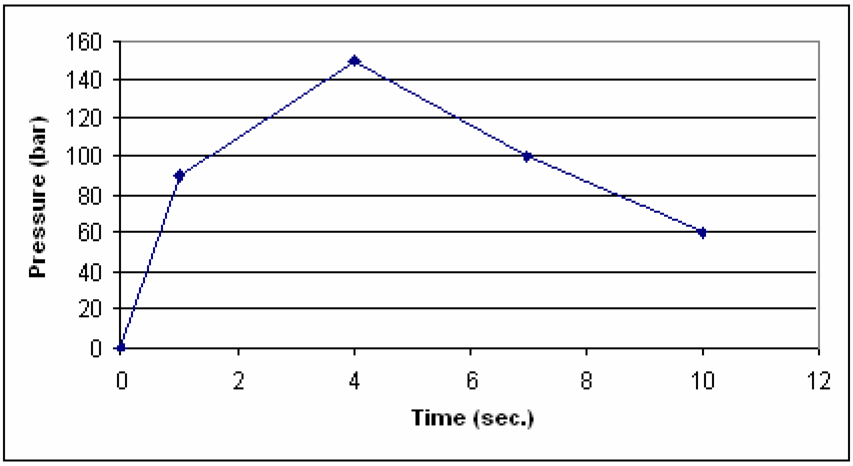


Figure 5.25. Hot extrusion of AA 6063 alloy at 475° C with 1.5° angled choke die

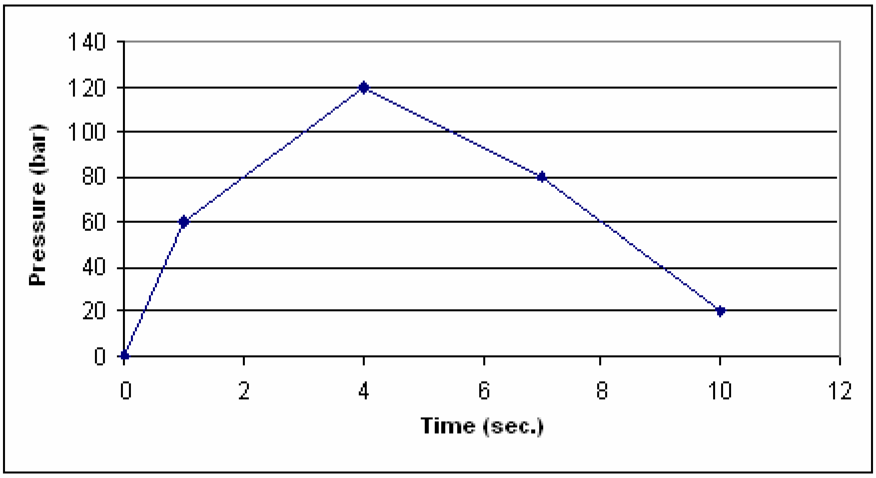


Figure 5.26. Hot extrusion of AA 6063 alloy at 475° C with 0.3° angled relief die

From the Figures 5.17 – Figure 5.26, it can be seen that when the die bearing angle systems of choke is used, the extrusion load increases with the increasing choke angle.

6. RESULTS AND DISCUSSION

6.1. Mechanical Evaluation of Extruded Samples (Profiles) of AA6063 and AA 7075 Alloys

In the hot extrusion of aluminum alloys, extrusion temperature, ram speed and press capacity are important key factors that are effecting the quality of product. If the term extrudability is discussed simply, it can be said that it means, to have the highest quality products, by using the optimum press capacity. Optimum press capacity means that to extrude the billet with a high ram speed but with lower force requirements.

The aim of the extrusion experiments is to investigate the extrudability properties of AA 6063 and AA 7075 alloys, and to investigate if different bearing angles influence the extrudability positively or negatively. During the experiments, billets are heated to their ideal extrusion temperatures but this ideal temperature is detected by doing some trials and also ideal holding time for homogenous heating of billets and dies is detected after some trials. The ideal extrusion temperature for AA 6063 billet is 470^{o}C-475^{o}C and holding time is about one hour. The ideal extrusion temperature for AA 7075 billet is 390^{o}C-395^{o}C and holding time is about two hours. In the early trials of AA 6063, the temperature is set as 425^{o}C and then to 450^{o}C but holding time for these temperatures are very high and it is not efficient. In the early trials of AA 7075 alloy, the temperature is set to 420^{o}C and holding time is chosen as one hour but in these conditions extrusion process is not succeed, then temperature is lowered and set to 392^{o}C, and holding time is decided as two hours in this conditions, process succeeded. In the other trials, some modifications on process is tried to be done, like lowering the holding time and increasing the extrusion temperature. According to Karahan [29], initial temperature effects the mechanical properties of the product. By increasing the extrusion temperature, the main goal that is wanted to be achieved is to lower the extrusion force. For this purpose, in some trials temperature is set to 400^{o}C-405^{o}C but in this position, extrusion process succeeded but profiles tear from right and left sides. Lowering the holding time results unsuccessful extrusion process so it is concluded that holding AA 7075 alloy two hours in a 392°C temperature is the ideal heating condition.

In the discussion of the extrudabilities of the different alloys, AA 7075 and AA 6063, mechanical, surface quality and micro structural investigations must be take place. In Figure 6.1 and Figure 6.2, the maximum pressure values of different angled dies with relief and choke angles (0.3° relief, 0° standard die, 0.5° choke die, 1° choke die, 1.5° choke die) are compared, these values are measured during the experiments. Pressure values are given in bar measurement unit and by multiplying these values with the cross-sectional area of billets, maximum force applied for each billet can be calculated, so it can be easily said that, pressure values are directly proportional with the force values. In the Figure 6.1 and Figure 6.2, x-axis shows die bearing angles and to have better comparison capability, relief angle 0.3° is put to negative side and choke angles 0.5°, 1° and 1.5° to positive side of the x-axis. In the both graphs, it can be concluded that maximum required force for extruding the AA 6063 and AA 7075 billets is increasing when the choke angle is increased and force requirement to extrude billets for both choke and relief angled dies are bigger than the standard 0° die. During experiment by using these five different dies maximum pressure value is measured during the extrusion with 1.5° choke die for both AA7075 and AA6063 alloys.

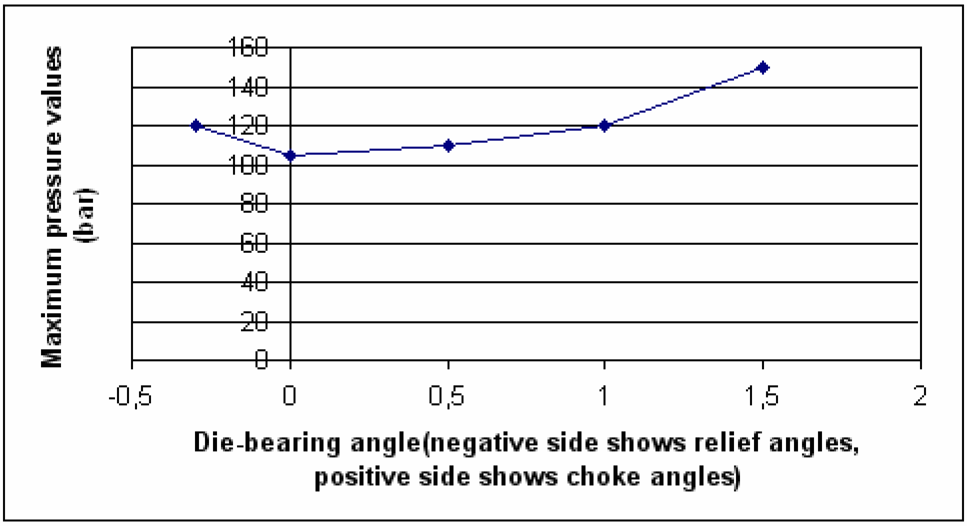


Figure 6.1. Comparison of maximum pressure values of 0.3° relief, 0° standard, 0.5° choke, 1° choke and 1.5° choke dies measured during extrusion experiments of AA6063 billets

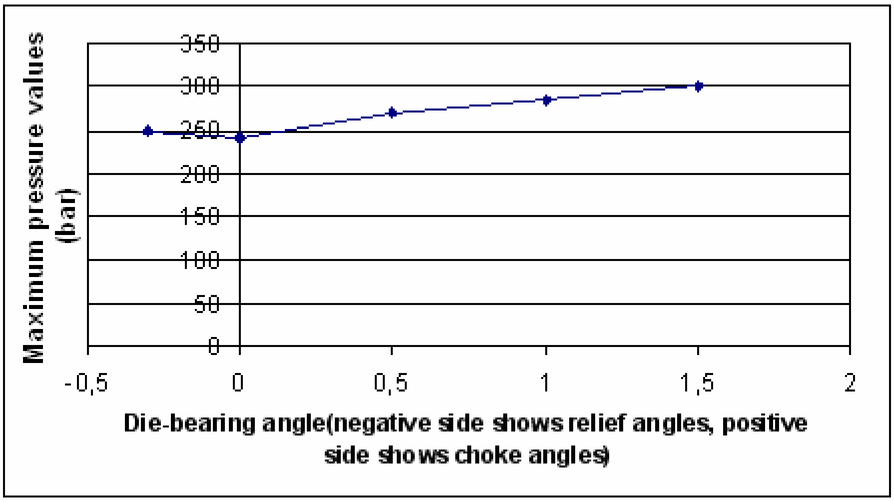


Figure 6.2. Comparison of maximum pressure values of 0.3° relief, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die measured during extrusion experiments of AA 7075 billets

After the extrusion experiments, profile samples are investigated to determine the extrudability properties. After polishing samples, the Brinell hardness values are examined. For this purpose five different measurements are conducted for each sample. Hardness comparisons of AA6063 profiles of 0.3° relief, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die for every five point is given in Figure 6.3 and comparison of average hardness of AA 6063 profiles according to their bearing angle type is shown in Figure 6.4. In Figure 6.4 error bars are shown where the error amount is the standard deviation from the mean value.

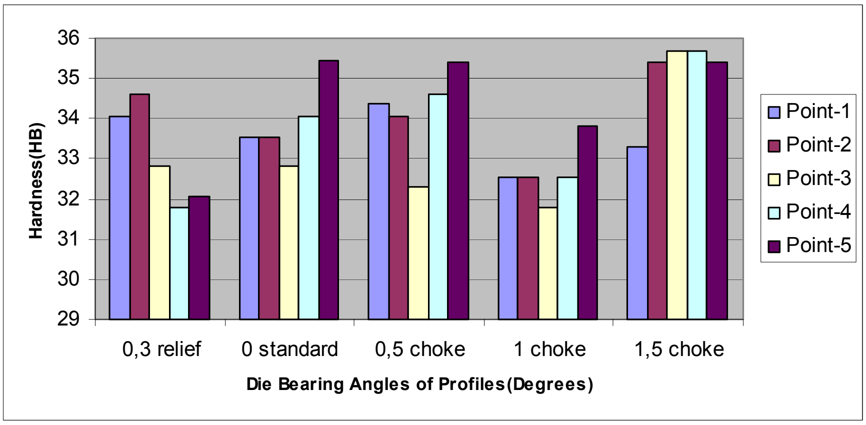


Figure 6.3. Hardness comparisons of AA 6063 profiles of 0.3° relief, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die for five points

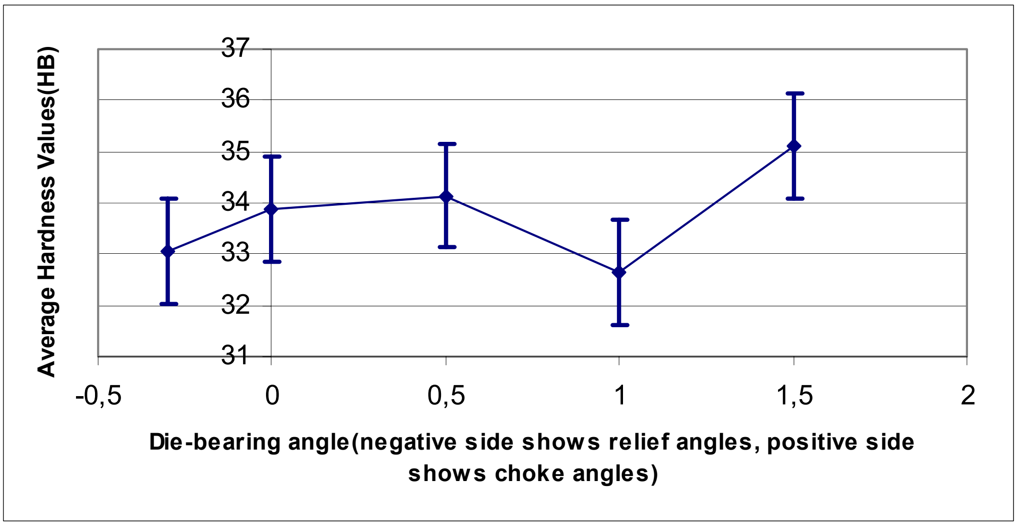


Figure 6. 4. Average hardness of AA 6063 profiles with different die-bearing angles of 0.3^o relief, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die

Hardness comparisons of AA7075 profiles of 0.3^o relief, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die for every five point is given in Figure 6.5 and comparison of average hardness of AA 7075 profiles according to their bearing angle type is shown in Figure 6.6. Also in this figure error amount is the standard deviation from the mean value of the hardness value.

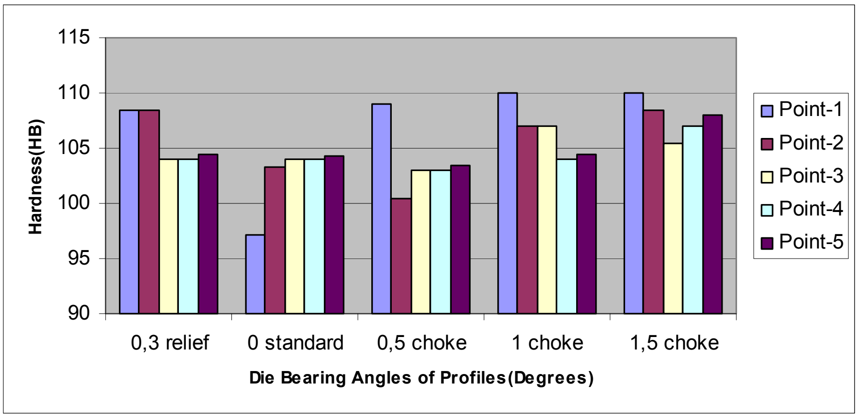


Figure 6. 5. Hardness comparisons of AA 7075 profiles of 0.3^o relief, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die for five points

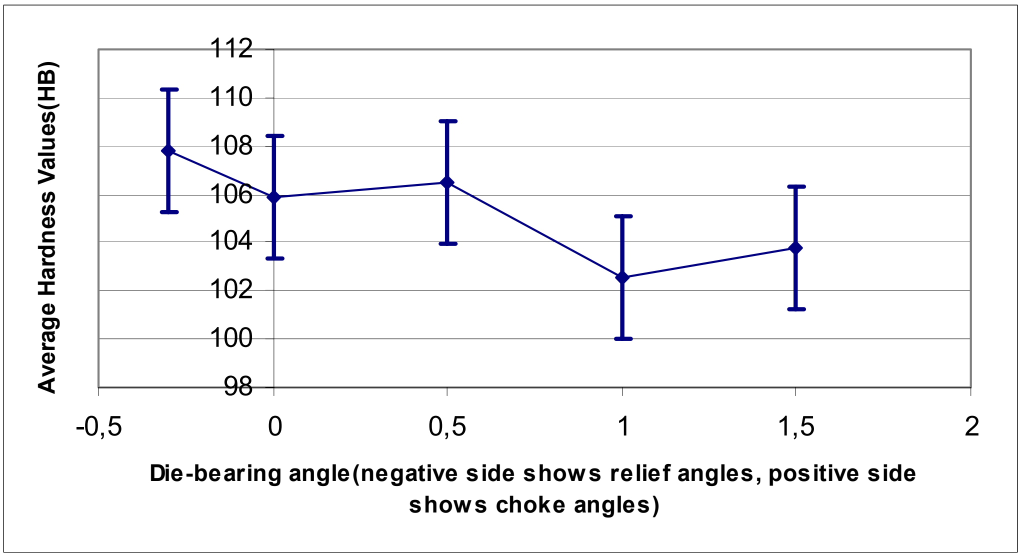


Figure 6.6. Average hardness of AA 7075 profiles with different die-bearing angles of 0.3° relief, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die

It can be said that, the graph of hardness values of AA 6063 and AA 7075 samples are resembling to the pressure graphs as in both there is an increasing with increasing die-bearing angle. But it is also significant that some hardness values of AA 6063 alloy is acting different, for example hardness of the 0.3° relief die sample has lower hardness than expected also 1° choke die sample has a lower hardness than the expected hardness value. The reason for these lower hardness values of these samples can be explained by the cooling conditions that are applied to the samples after the extrusion. All of the samples are air quenched (cooled) and their cooling conditions is tried to be kept standard, but one exception in cooling condition may result an interesting hardness value. If the cooling is performed faster after the extrusion, the hardness values will be lower because when sample cools down more faster the secondary phases will solutionized less in the alloy and this will result lower hardness values but if the cooling exists slower than the secondary phases solutionized more in the alloy and hardness values would increase. If the exceptions are not taken into account, it can be concluded that hardness values of the AA 6063 and AA 7075 profiles are increasing when the choke angle is increased. Adding to all these, it is possible to say that behaviours of the hardness graphs in Figures 6.4 and 6.6 resembles the behaviour of the graphs in Figures 6.1 and Figure 6.2 which are showing the maximum pressure values for extruding each sample. Especially for AA 7075 alloy hardness value graph resembles to the pressure graph shown in Figure 6.2. The maximum hardness values are occurred in 1.5^o choke die for both AA 6063 and AA 7075 profiles. In general, high pressure and force requirements to extrude the material often can result in high hardness values.

In 7075 samples when the angle is increased (choke angle), more energy is needed to extrude the samples and the heat during the extrusion increases proportionally with the increasing energy and as a chain reaction this causes deformation at higher temperatures. As a result of the deformation at higher temperatures, samples are deformed at higher temperatures and samples reach higher temperatures after the extrusion. Cooling from that higher temperature results better solutionizing of secondary phases in the micro structure. Better solutionizing of secondary phases results solid solution hardening, the reason for the rise of hardness with increasing angle that is seen in Figure 6.6 can be explained with the solid solution hardening.

The reason for this can be explained by different extrusion process temperatures and different solutionizing temperatures of AA 6063 and AA 7075 alloys. Extrusion temperature of AA 6063 alloy is 475^{o}C and extrusion temperature of AA 7075 alloy is 392^{o}C. Solutionizing temperature of AA 6063 alloy is 520^{o}C and solutionizing temperature of AA 7075 alloy is 466 – 482^{o}C. Extrusion process temperature of AA 6063 alloy is very close to the solutionizing temperature but extrusion process temperature of AA 7075 is not very close to solutionizing temperature when compared with AA 6063 alloy. When extrusion process temperature is close to the solutionizing temperature, this effects the hardness value negatively.

In the Table 6.1, the results of the tensile tests that are applied to the profile samples are given. This table is constructed by taking the average of three tensile tests applied to each profile sample. Elongation, yield stress, ultimate tensile stress values of each sample can be found in Table 6.1. Three tensile tests are applied to each sample, Table 6.1 is constructed from average of these three tests.

Table 6.1. Tensile test results of profiles (Average of three tests)

	Width (mm)	Height (mm)	Cross-sectional Area (mm²)	Initial Length (mm)	Final Length (mm)	Elongation (per cent)	Yield Strength (N/mm²)	Ultimate Tensile Stress (N/mm²)
AA 7075 0.3° relief die	12,8	2,5	32	32,0	36,7	14,7	266	416
AA 6063 0.3° relief die	12,4	2,5	31	31,5	38,1	21	54	116
AA 7075 0° standard die	12,5	2,5	31,25	31,6	34,7	9,8	282	405
AA 6063 0° standard die	12,5	2,42	30,25	31,1	37,0	19	58	116
AA 7075 0.5° choke die	12,7	2,45	31,12	31,5	36,3	15,2	281	426
AA 6063 0.5° choke die	12,6	2,5	31,5	31,7	37,0	16,7	64	107
AA 7075 1° choke die	12,7	2,3	29,21	30,5	35,8	17,4	298	431
AA 6063 1° choke die	12,6	2,35	29,61	30,7	38,1	24,1	59	110
AA 7075 1.5° choke die	12,7	2,5	28,6	30,2	34,0	12,6	267	385
AA 6063 1.5° choke die	12,4	2,5	27,9	29,8	35,4	18,8	63	127

During the tensile test application of the test profiles, a TS EN 10002 standard is used to determine the initial lengths of the samples, this standard equation is given below;

$$l_1 = 5.65\sqrt{A_1} \tag{6.1}$$

where l_1 = initial length of the test sample

A_1 = initial cross-sectional area of the test sample

Comparison of the tensile test results of the AA 6063 samples can be seen in Figure 6.7. In Figure 6.7 choke angles are shown in positive side of x-axis and relief angles are shown in negative side of x-axis. It can be suggested that the behaviour of the comparison graph resembles hardness comparison graph in Figure 6.4 and pressure comparison graph in Figure 6.1. Comparison of the AA 7075 tensile test samples can be found in Figure 6.8, again choke angles are shown in positive side of x-axis and relief angles are shown in negative side of x-axis. The behaviour of this graph also resembles the hardness comparison graph in Figure 6.5 and pressure comparison graph in Figure 6.2.

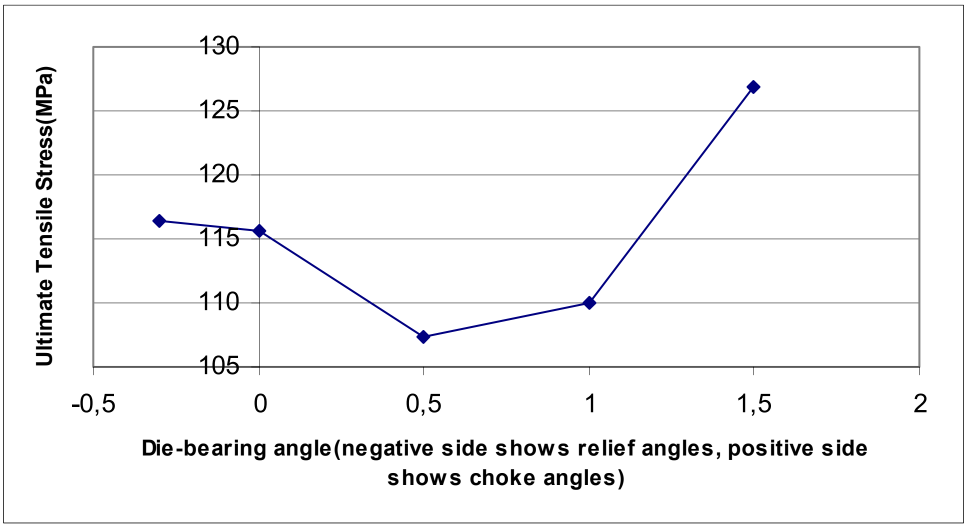


Figure 6.7. Comparison of the test results of AA 6063, 0.3° relief, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die samples

Comparison of the AA 7075 tensile test samples can be found in Figure 6.8, again choke angles are shown in positive side of x-axis and relief angles are shown in negative side of x-axis. The behaviour of this graph also resembles the hardness comparison graph in Figure 6.5 and pressure comparison graph in Figure 6.2.

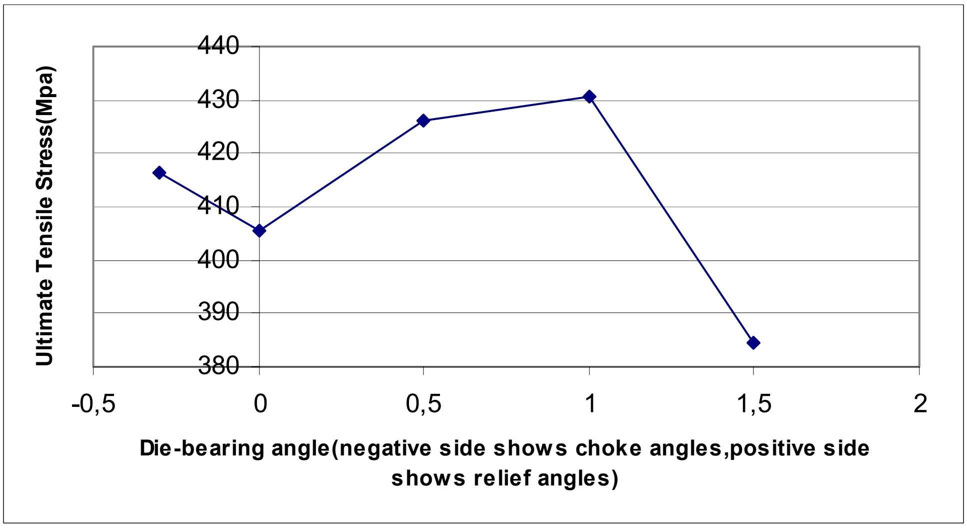


Figure 6.8. Comparison of the test results of AA 7075, 0.3^{o} relief, 0^{o} standard die, 0.5^{o} choke die, 1^{o} choke die and 1.5^{o} choke die samples

In Figure 6.7, it can be seen that 1.5^{o} choke die sample has highest ultimate tensile stress value also the behaviour of the graph is resembling the hardness and pressure graphs of AA 6063 as the ultimate tensile stress increases with the increasing choke angle but the main difference from the mentioned graphs Figure 6.1 and Figure 6.4 is that ultimate tensile stress values of 0.5^{o} choke die and 1^{o} choke die samples are lower than both 0.3^{o} relief and 0^{o} standard die samples. In Figure 6.8, it is significant that 1.5^{o} choke die has lowest ultimate tensile stress value, it is an unexpected variable. In Figure 6.9, elongation-die-bearing angle graphs of samples are given. It is seen for both AA 7075 and AA 6063 alloy samples that maximum elongation is obtained for 1^{o} choke die samples. It is also seen that minimum elongation in AA 6063 alloy samples are obtained for 0.5^{o} choke die sample but in AA 7075 alloy samples, minimum elongation exists for 0^{o} standard die sample. Elongation of AA 6063 alloy samples are higher than AA 7075 alloy samples. Except for 1.5^{o} choke die sample, in AA 6063 alloy samples, it can be stated that there is direct proportionality between elongation and die-bearing angle, increasing die-bearing angle results with rise in elongation but same kind of proportionality does not exists for AA 7075 alloy samples.

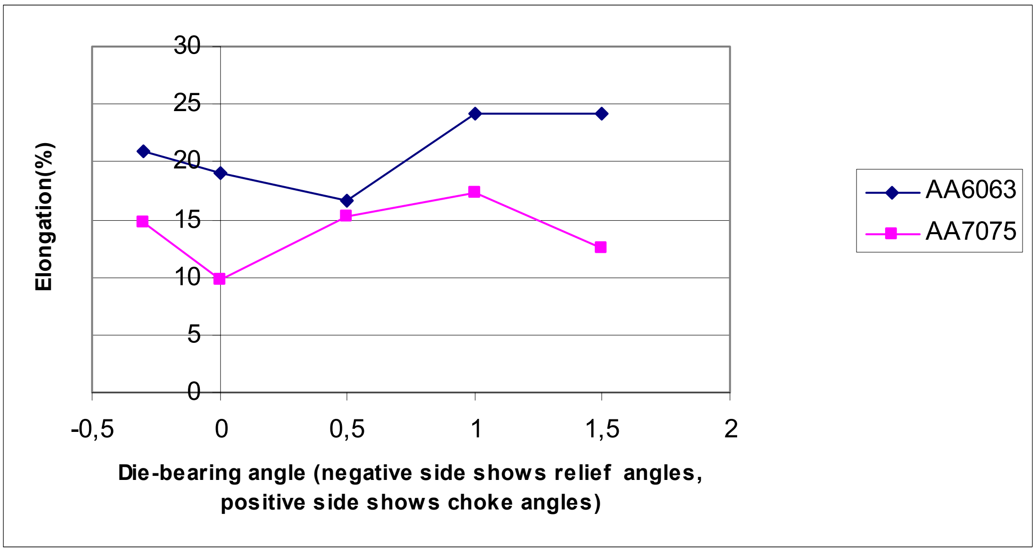


Figure 6. 9. Comparison of the elongation (per cent) values of AA 7075 and AA 6063 samples with 0.3° relief die, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die samples

6.2. Surface Quality Extruded Samples (Profiles) of AA 6063 and AA 7075 Alloys

Mechanical properties and microstructure of the extruded samples are important parameters in investigation of extrudability. But surface quality of the product is as important as the mechanical properties and microstructure. In classical definition, extrudability is the ability to be extruded at high speed with optimum force and energy but this definition is not enough for having a high quality product. Extrusion at high speed with optimum force and energy may result with low quality extrusion products. High surface quality and good mechanical properties are important factors for having a high quality product. Surface roughness test is a method to evaluate the surface qualities of extruded samples. In order to investigate the surface qualities of the samples a roughness test was done and the results provided by surface roughness test can be seen in Table 6.2.

Surface roughness test has been used to measure the roughnesses that are parallel to the extrusion direction. The roughness test is made by using a Mitutoyo surface roughness measurement unit. Before investigating the roughness results in Table 6.2, meaning of the roughness amplitude parameters given in the following Table 6.2 must be defined properly.

R_a is the average roughness; average roughness is the area between roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length.

$$R_a = \frac{1}{L}\int_0^L |r(x)|\,dx \tag{6.2}$$

where R_a = average surface roughness

L = evaluation length

r(x) = roughness profile height

R_q is root mean square roughness; it is another surface roughness of a surface calculated from another integral of roughness profile. R_q values are proportional to R_a values and usually they are about 1.11 times larger than R_a values.

$$R_q = \sqrt{\frac{1}{L}\int_0^L r^2(x)\,dx} \tag{6.3}$$

R_y is the maximum roughness height within a sample length; R_y is the maximum peak to lowest valley vertical distance within a simple sample length. It is a new ISO term and also known as R_{ymax}. R_z is a parameter that averages the height of the five highest peaks plus the depth of the five deepest valleys over the evaluation length.

Table 6.2 shows the surface roughness values of 0.3^o relief, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die samples due to the roughness amplitude parameters of R_a, R_y, R_z and R_q.

Table 6.2. Roughness measurements of 0.3^o relief, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die samples

	Ra(µm)	**Ry(µm)**	**Rz(µm)**	**Rq(µm)**
AA 7075 0^o standard	0.8	9.4	5.9	1.0
AA 6063 0^o standard	0.2	2.1	1.4	0.3
AA 7075 0.3^o relief	0.5	4.3	3.5	0.6
AA 6063 0.3^o relief	0.2	2.1	1.3	0.2
AA 7075 0.5^o choke	0. 1	2.9	1.3	0.2
AA 6063 0.5^o choke	0.5	4.6	2.8	0.7
AA 7075 1^o choke	0.4	5.8	3.7	0.6
AA 6063 1^o choke	0.4	4.7	3.1	0.6
AA 7075 1.5^o choke	1.5	12.5	8.5	1.7
AA 6063 1.5^o choke	0.4	7.5	3.2	0.6

From Table 6.2, it can be seen that the maximum, R_a, R_y, R_a and R_q values are measured for the 1.5^o choke sample of AA 7075 alloy. By using this result, it can be suggested that because of the high roughness effect, ultimate tensile stress value of 1.5^o choke sample of AA 7075 alloy is measured lower than expected and it can be said that this high roughness effect causes instantaneous fracture in the sample and this causes low ultimate tensile stress value.

Surface roughness is a key parameter that shows the profile quality. Profile quality is an important parameter because it directly effects the extrudability rate of an alloy. In Table 6.2, it is seen that average surface roughness values (R_a) measured for AA 6063 alloys are significantly lower than the average surface roughness values (R_a) values measured for AA 7075 alloys. This shows us that surface quality of AA 6063 alloys are much more better than the surface quality of AA 7075 alloys. It is stated that these measurements are taken for the roughnesses that are in the parallel to the extrusion direction. These roughness are the roughness that are produced during the extrusion when passing from the bearing land and it can be said that the flowing of AA 7075 samples from the 0.3° relief dies', 0° standard dies', 0.5° choke dies', 1° choke dies' and 1.5° choke dies' bearing lands is more difficult and disturbing than the flow of the AA 6063 samples. This is a key result for comparing the extrudabilities of AA 7075 samples and AA 6063 samples.

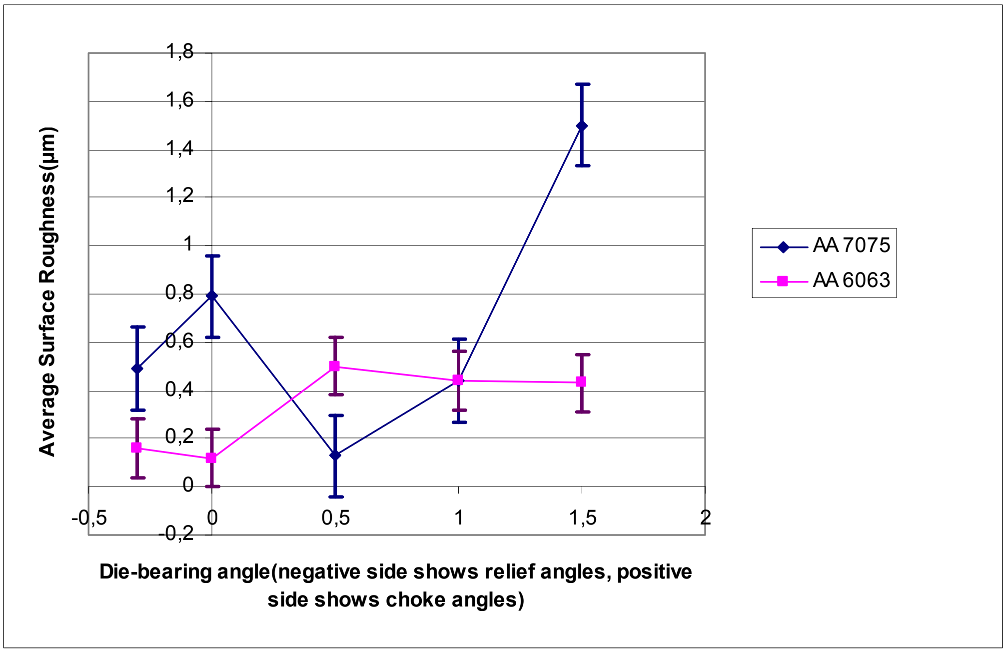


Figure 6.10. Comparison of the surface roughness values of AA 7075 and AA 6063 samples with 0.3° relief die, 0° standard die, 0.5° choke die, 1° choke die and 1.5° choke die samples

Figure 6.10 shows that roughness values of AA 6063 samples are lower compared with AA 7075 samples, only for 0.5° choke die the roughness value of AA 6063 sample is bigger than the roughness value of AA 7075 sample. This can be occurred by a wear or distortion in the extrusion die and it must be noted that experiments of 0.5° choke die samples of AA 6063 alloys are conducted after the experiments of AA 7075 samples with the same 0.5° choke die. A small distortion or a very small wear can effect surface roughness values significantly. It is seen that surface roughness values of AA 7075 samples increases with increasing die-bearing angle. Especially in AA 7075 1.5° choke angle sample, surface roughness values are very high. It can be stated that surface roughness AA 6063 alloy samples are not effected much from the increasing die-bearing angle.

6.3. Microstructure Evaluation of Extruded Samples (Profiles) of AA6063 and AA 7075 Alloys

In the previous section, mechanical evaluation of extruded samples has been investigated. Microstructure evaluation is also an important study to decide and compare the extrudabilities of alloys and samples. Dead metal zone has an important role in the flow of the billets through the die and die bearing and it can effect the extrudabilities of the samples. A dead-metal zone occurs in the area that is up in the corners or close to the corners of the die. These zones are important because the material shears along this dead metal zone face. After the early stages of extrusion, dead-metal zone starts to act like a conical die surface. The size and shape of the dead metal zone area is important in the investigations of the extruded samples. In order to investigate the dead metal zones and differences of these zones, a 25 mm of butt thickness is remained after the extrusion and by dividing this butt part longitudinally; the flow of the billet and dead metal zone can be detected. In Figure 6.11., flow and dead metal zone of each sample can be seen.

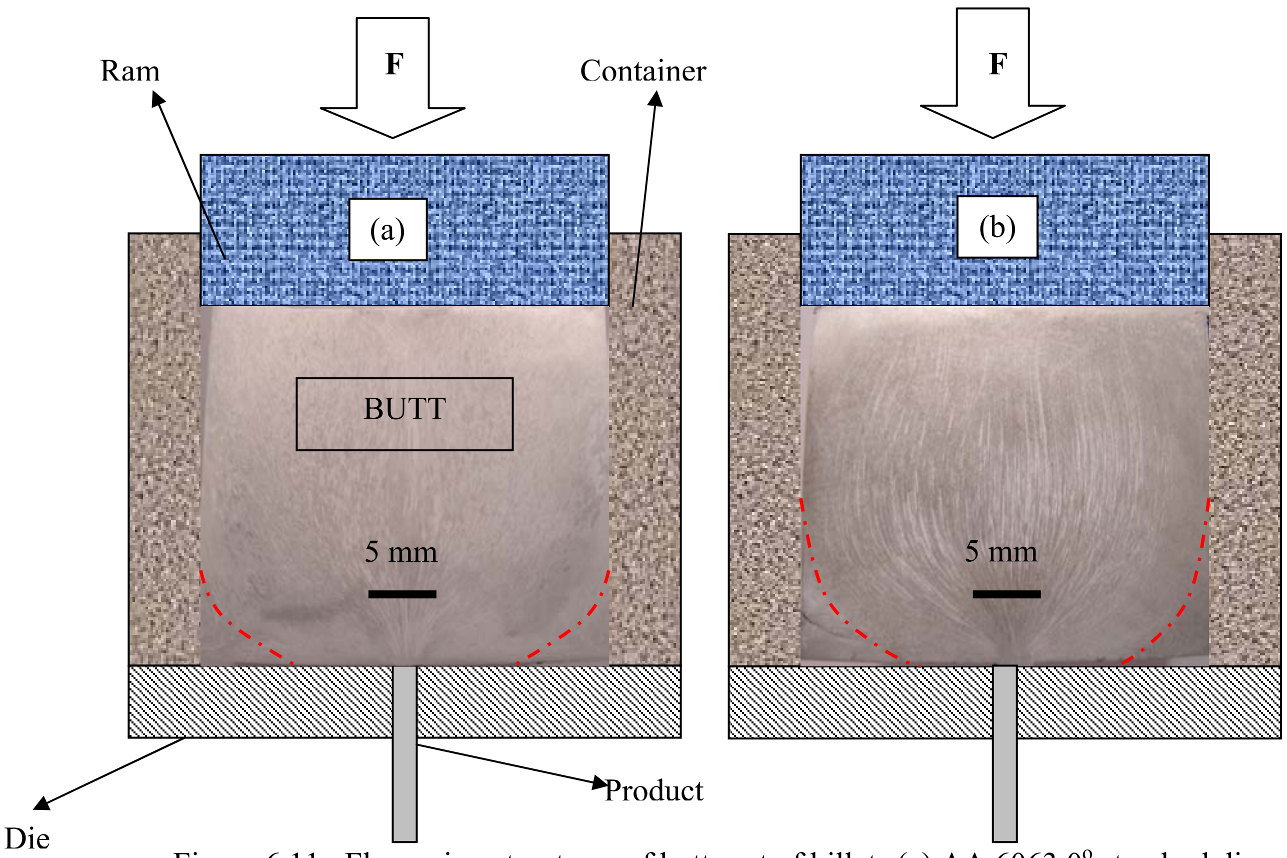


Figure 6.11. Flow microstructures of butt part of billets (a) AA 6063 0° standard die sample (b) AA 7075 0° standard die sample

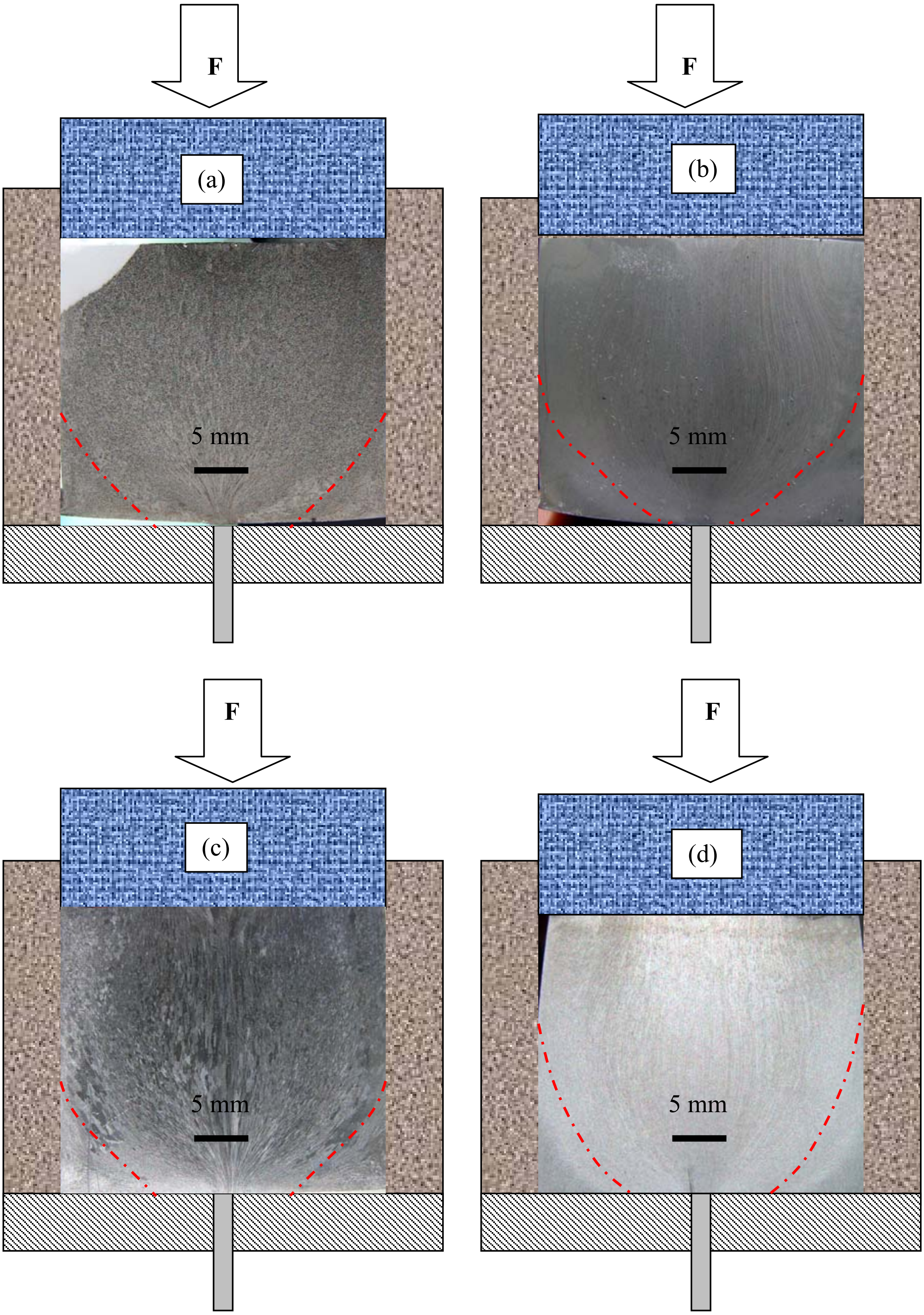


Figure 6.12. Flow microstructures of butt part of billets (a) AA 6063 0.3° relief die sample (b) AA 7075 0.3° relief die sample (c) AA 6063 0.5° choke die sample (d) AA 7075 0.5° choke die sample

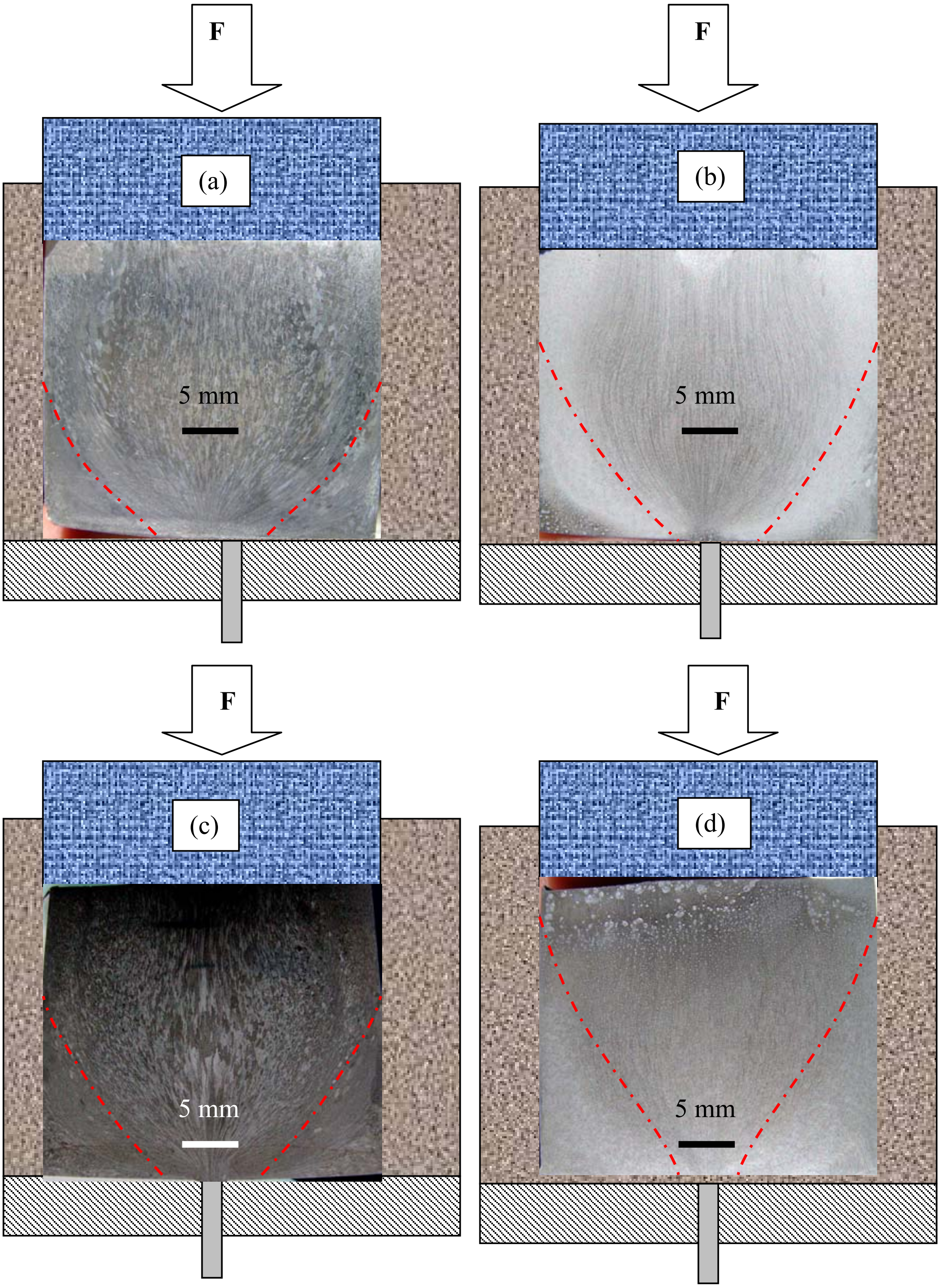


Figure 6.13. Flow microstructures of butt part of billets (a) AA 6063 1° choke die sample (b) AA 7075 1° choke die sample (c) AA 6063 1.5° choke die sample (d) AA 7075 1.5° choke die sample

In Figure 6.11, 6.12 and 6.13 flow microstructures of the butt parts of the billets during extrusion can be seen. AA 7075 and AA 6063 samples with 0.3^o relief die, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die microstructure schemes are taken. In the Figures 6.11, 6.12 and 6.13 dead-metal zone is marked with lines. It is significant that dead metal zone in the AA 6063 samples butt flow microstructures are smaller than the dead metal zone in AA 7075 billets flow microstructure. In the chapter two, in the Figure 2.7, flow types in the extrusion processes are described briefly. Mostly in AA 6063 butt flow microstructures, an extended dead –metal zone is formed but for AA 7075 butt flow microstructures a more extended dead-metal zone is formed. Shear deformation will be more for extended dead – metal zones and in this case AA 7075 samples undergo bigger shear deformation than AA 6063 samples. The reason for the more extended dead-metal zone of AA 7075 samples can be in homogeneous material properties or a nonuniform temperature distribution in the billet.

In Figure 6.13, it can be seen that especially for AA 7075 1.5^o choke die sample the dead metal zone is very extended compared with other AA 7075 samples. Smallest dead metal zones for both AA 7075 and AA 6063 samples are provided in 0^o standard die samples as shown in Figure 6.10 and it can be said that dead metal zones for 0.3^o relief and 0.5^o choke dies in Figure 6.12 have almost same size but when angle is increased, dead-metal zone size also increases, in 1^o choke sample of AA 7075 alloy, a big extended dead metal zone area occurs. All in all it can be suggested that dead metal zone area produced in AA 6063 samples are not effected with die bearing angle as much as AA 7075 samples.

As mentioned before, extended dead metal zone causes bigger shear deformations and it is significant that AA 7075 samples have more extended dead metal zones when compared with AA 6063 samples, bigger shear deformation will decrease the extrudability of the material and when looking from this point of view, it can be suggested that extrudabilities of AA 6063 samples are better than AA 7075 samples, in the case of flow behaviour. If the extrudabilities due to die bearing angles is wanted to be compared, it can be said that in AA 7075 samples, when die bearing angle increases, dead metal zone gets larger and extrudability decreases, it is significant especially for 1^o choke and 1.5^o choke dies. It can be said that flow microstructures of AA 6063 alloy samples are not effected much from the increasing die bearing angle but flow microstructures of AA 7075 samples are effected from the increasing die bearing angle.

In order to identify the extrudabilities of AA 6063 and AA 7075, 0.3^o relief die, 0^o standard die, 0.5^o choke die, 1^o choke die and 1.5^o choke die samples, mechanical behaviour of these samples must be specified clearly, having a brittle behaviour or ductile behaviour can help to identify the mechanical properties more easily. For this purpose, the samples which are fractured at the end of the tensile test are subjected to Scanning Electron Microscope (SEM) detection. But before showing the SEM Photos, it is better to show the real photographs of the surfaces that are investigated in the Scanning Electron Microscope, the real photos of these fractured surfaces can be seen in Figure 6.14 .

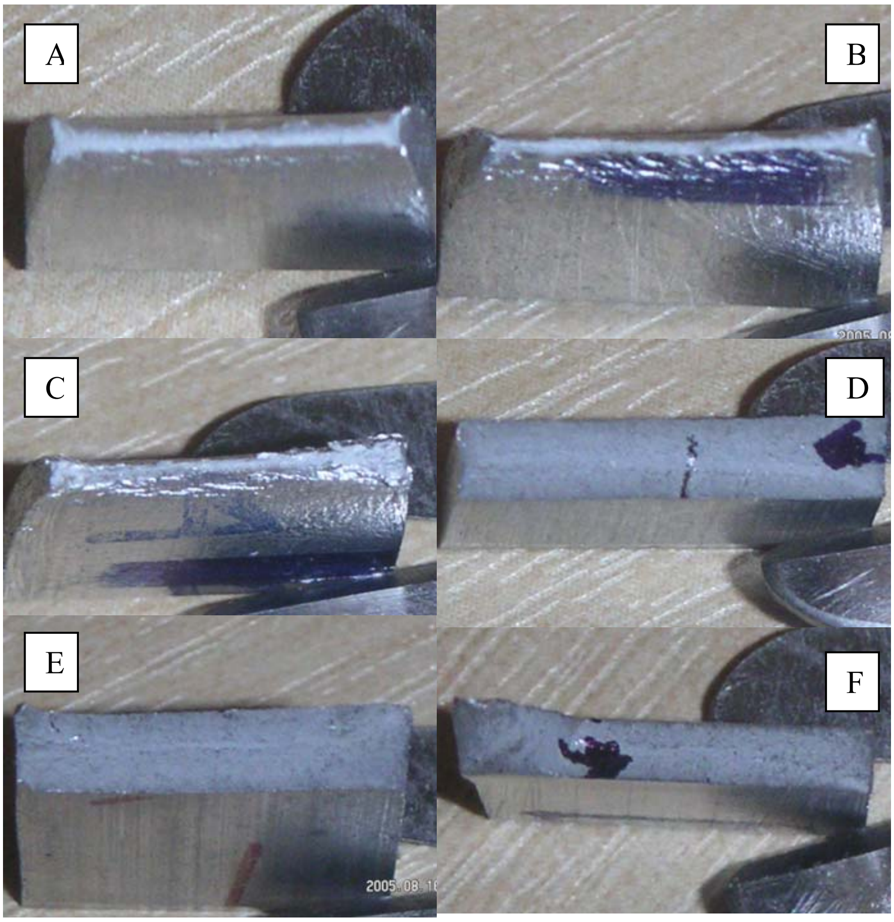


Figure 6.14. Real photos of fractured surfaces of (a) AA 6063 0.3^o relief die sample (b) AA 6063 0^o standard die sample (c) AA 6063 1.5^o choke die sample (d) AA 7075 0.3^o relief die sample (e) AA 7075 0^o standard die sample and (f) AA 7075 1.5^o choke die sample

Scanning Electron Microscope photographs shown in Figures 6.15 and 6.16 are taken from center and mid portion of the samples. It is seen from Figure 6.13 that crack surfaces of AA 6063 samples are very ductile and as an opposite of this crack surfaces of AA 7075 samples are perfectly brittle. AA 7075 samples show a brittle fracture character, surfaces are fractured with an angle of 45^o. More Scanning Electron Microscope photos with higher magnifications are taken in order to identify the fractured surfaces better.

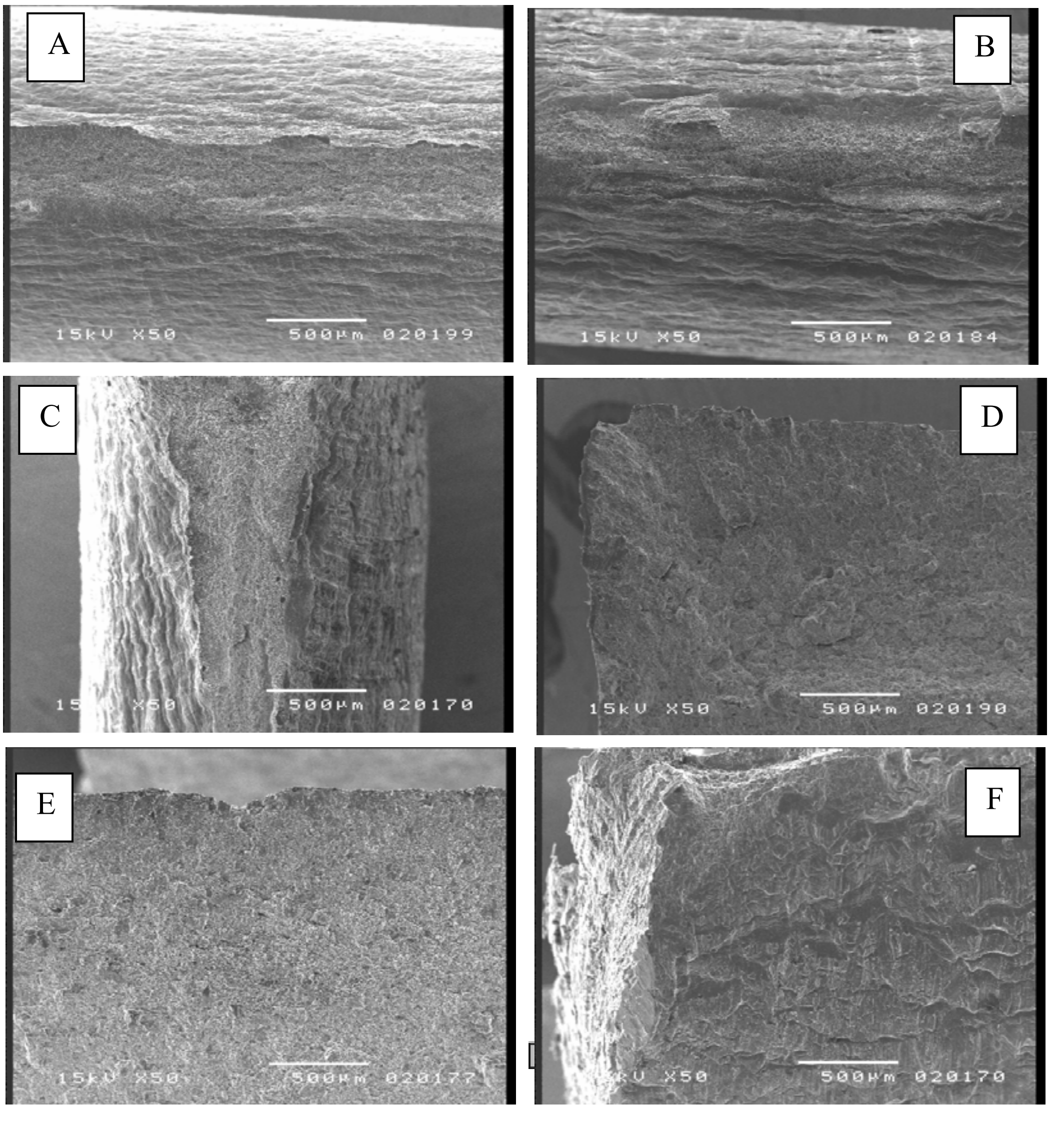


Figure 6.15. SEM photos of the (a) AA 6063 0.3 relief die sample from mid-portion (b) AA 6063 1.5^o choke die sample from mid-portion (c) AA 6063 0^o standard die sample from mid portion (d) AA 7075 0.3^o relief die sample from edge-portion (e) AA 7075 1.5^o choke die sample from mid-portion (f) AA 7075 0^o standard die sample from edge-portion

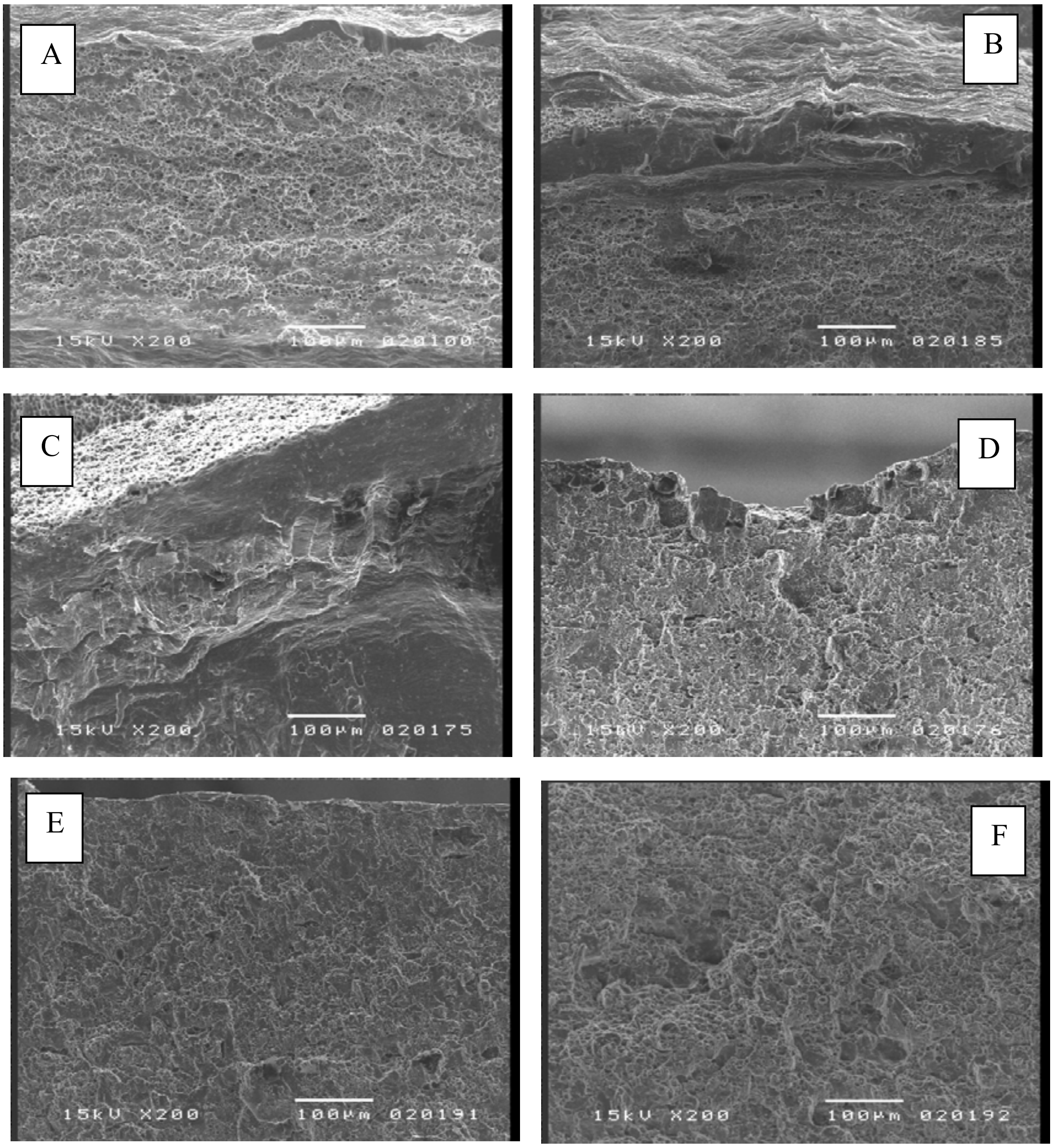


Figure 6.16. SEM photos of (a) AA 6063 0.3 relief die sample from mid-portion (b) AA 6063 1.5^{o} choke die sample from mid-portion (c) AA 7075 0^{o} standard die sample from edge - portion (d) AA 7075 1.5^{o} choke die sample from mid-portion (e) AA 7075 0.3^{o} relief die sample from mid-portion (f) AA 7075 0.3^{o} relief die sample from mid portion

Scanning Electron Microscopy photos given in Figure 6.15 are 50 times magnified and photos given in Figure 6.16 are 200 times magnified. It is seen in the Figure 6.15 that AA 6063 samples shows ductile behavior but AA 7075 samples shows completely brittle behavior. From the Figure 6.15 (a), (b) and (c), it can be seen that crack interface surface area is only 35% or 40% of whole crack surface, according to this it can be suggested that

AA 6063 samples shows ductile behavior. In order to support this idea, photos that are taken with a higher magnification (x200 times) in Figure 6.16. must be investigated properly. It can be seen in Figure 6.16 (a) and (b) photos that dimpled structures can be seen in the mid portion of the samples. When the real photos of the AA 6063 1.5^o choke sample in Figure 6.14 investigated carefully and then investigating the SEM photos in Figure 6.15 (c) and Figure 6.16 (b), it can be stated that ductility decreases significantly when the bearing angle is increased to 1.5^o of choke. In the extrusion of 1.5^o choke die of AA 6063 sample, as friction factor increases, the deformation occurs at higher temperatures as a result of this deformation at higher temperature, the ratio of solid solution increases and when solid solution increases, ductility decreases. For this reason, the samples of AA 6063 1.5^o choke die sample shows less ductile behavior compared with 0.3^o relief die sample and 0^o standard die sample. In order to identify the dimpled structures better in AA 6063 samples, higher magnification is needed. For this purpose, SEM photos with higher magnification (x750 times) are taken and shown in Figure 6.17.

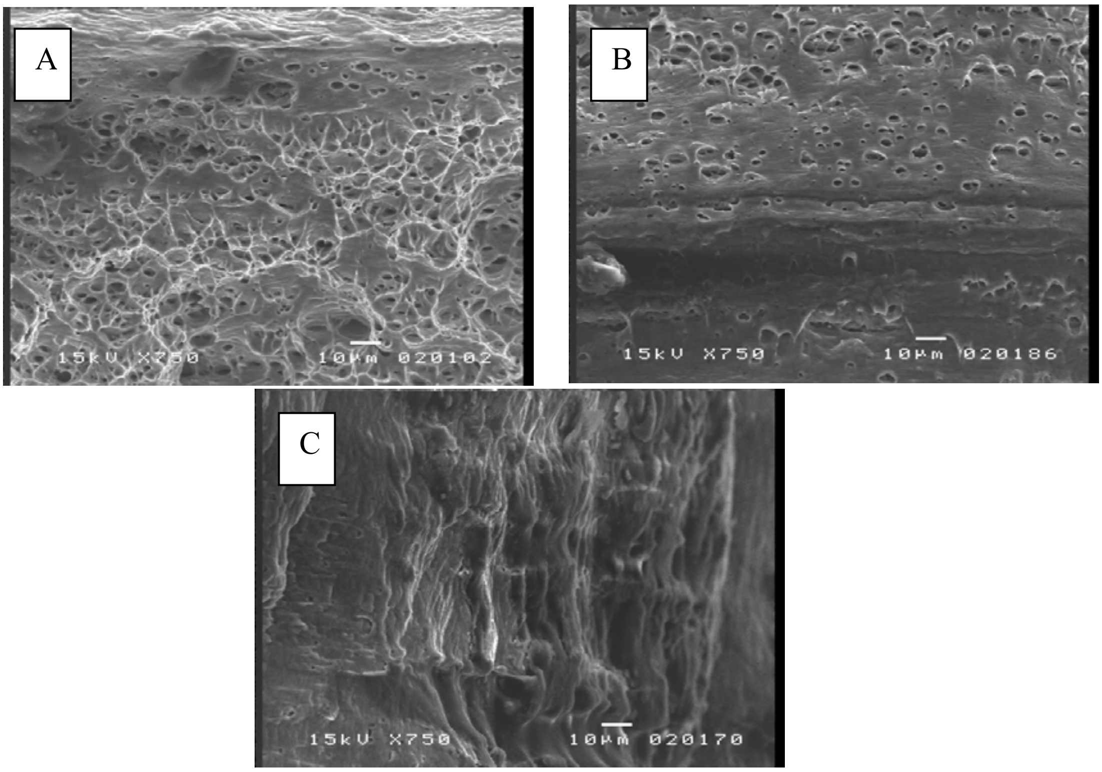


Figure 6. 17. SEM photos of the (a) AA 6063 0.3 relief die sample from mid-portion (b) AA 6063 1.5^o choke die sample from mid-portion (c) AA 6063 0^o standard die sample from mid portion

It is better seen in Figure 6.17 that, dimpled structures are clearly identified in AA 6063 samples and when moving from edge to mid portion number of dimpled structures increase.

In this part of the discussion, relation of flow microstructures and size dead-metal zone with angle is discussed briefly. In order to relate size of dead-metal zone, friction force and bearing angle, the friction factor between flowing metal and die bearing interface must be investigated properly. It is stated in chapter three that;

$$F_F = m'kA \tag{6.4}$$

where m' = friction factor between flowing metal and die bearing interface

k = shear strength of the material

A = the real area of contact

F_F = Friction force

In Equation (6.4), k is constant; A is constant for different die types. There is a direct relation between friction factor and friction force. Experiments show that, larger forces are needed to extrude samples when die-bearing increases. When extrusion force increases, friction force also increases proportionally. Consequent of the direct relation between friction factor and friction force, it can be said that according to Equation (6.4), friction factor between flowing metal and die bearing interface has a relation with die-bearing angle. With increasing die-bearing angle, friction factor between flowing metal and die bearing interface increases. When friction force increases during extrusion process, more energy is produced in the extrusion system and this rise in energy results with flowing of metal from an bigger dead metal zone. Larger dead metal zone causes larger shear deformations and this causes a drop in extrudability.

7. CONCLUSIONS

In the experiments, the effect of die-bearing angle on the extrudability is investigated. It is seen that maximum pressure values increases with the increasing die bearing angle and the same result occurs for the hardness case, hardness increases with the increasing angle. Ultimate tensile stress and elongation of both AA 6063 and AA7075 samples increase with increasing bearing angle but for AA 6063 samples, ultimate tensile stress value in 0^o standard die sample and 0.3^o relief die sample are higher than choke die samples. Roughness test is made and it is seen that roughness values increases with increasing die bearing angles and roughness values of AA 7075 samples are higher than AA 6063 samples except for few exceptions. Dead-metal zones of the samples are investigated properly and it is seen that especially in AA 7075 samples when die-bearing angle is increased, dead-metal zone increases proportionally. As a final investigation Scanning Electron Microscope photos of the 0.3^o relief die, 0^o standard die and 1.5^o choke die samples of AA 6063 and AA 7075 billets are taken from the fractured surfaces which are produced in the tensile test. It is seen that AA 6063 shows ductile behavior and have dimpled structures in the microstructure but opposite to this AA 7075 shows completely brittle behavior and fractured with an angle of 45^o.

Pressure values measured during experiments are directly proportional with the extrusion force and it can be said that increasing pressure values in the case of increasing die bearing angle results decrease in extrudability. It is seen that with increasing die-bearing angle, especially in AA 7075 alloy samples surface roughness increases but surface roughness test results of AA 6063 alloy samples are not effected much from increasing die-bearing angle. Especially, high roughness is an important factor that decreases the surface quality and product quality. Dead-metal zone investigation shows clearly that, dead-metal zone increases with increasing die-bearing angle especially for AA 7075 samples , bigger dead-metal zone causes bigger shear deformation and bigger shear deformation decreases the extrudability. In the Scanning Electron Microscopy, it is seen clearly that AA 6063 shows ductile behaviour and AA 7075 shows completely brittle behaviour, but also ductility of AA 6063 alloys decreases with increasing die-bearing angle and 1.5^{o} choke die sample is found to be the least ductile sample, this shows that when die bearing angle increases, ductility decreases. A statement like that can not be made for AA 7075 samples because all samples show completely brittle behavior, fractured with an angle of 45^{o}. As a result of all these parameters, it can be concluded that extrudabilities of AA 7075 and AA 6063 samples decrease with increasing die-bearing angle and also it can be said that among all samples 0^{o} standard die samples have best extrudability properties.

It is also possible to compare extrudability of AA 7075 and AA 6063 alloy samples. According to speed of extrusion and force requirement parameters extrudability of AA 6063 alloy is better than extrudability of AA 7075 alloy. AA 6063 alloys have smaller dead-metal zones, roughness values are significantly smaller than AA 7075 samples, and they have ductile behavior. Choke dies can be used in AA 7075 alloy extrusion to slow down the metal and to provide better dimensional stability but these dies have negative effect on extrudability of AA 7075 alloy extrusion. By classical definition, extrudability is ability to be extruded at high speed with optimum extrusion force but in industry quality term is also a very important factor. In extruded products most important parameter effecting the product quality is the surface quality of the products. Samples of AA 6063 alloy have better surface quality than samples of AA 7075 alloy also the effect of increasing die-bearing angle on surface quality is less in samples of AA 6063 alloy. Samples of AA 6063 alloy are ductile and this is an important factor effecting the product quality.

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