ANALYSIS AND DESIGN FOR ALUMINUM FORGING PROCESS

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submitted by **HÜSEYİN ÖZTÜRK** in partial fulfillment of the requirements for the degree of **Master of Science in Mechanical Engineering, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** ____________________

Prof. Dr. Süha Oral
Head of the Department, **Mechanical Engineering** ____________________

Prof. Dr. Mustafa İlhan Gökler
Supervisor, **Mechanical Engineering Dept., METU** ____________________

Prof. Dr. Haluk Darendeliler
Co-Supervisor, **Mechanical Engineering Dept., METU** ____________________

Examining Committee Members:

Prof. Dr. R. Orhan Yıldırım
Mechanical Engineering Dept., METU ____________________

Prof. Dr. Mustafa İlhan Gökler
Mechanical Engineering Dept., METU ____________________

Prof. Dr. Haluk Darendeliler
Mechanical Engineering Dept., METU ____________________

Prof. Dr. Haluk Aksel
Mechanical Engineering Dept., METU ____________________

(M.Sc.) Sertan Gülbahar
Aydın Yazılım ve Elektronik Sanayii A.Ş. ____________________

Date: December 16th, 2008

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Hüseyin Öztürk

Signature:

ABSTRACT

ANALYSIS AND DESIGN FOR ALUMINUM FORGING PROCESS

Öztürk, Hüseyin

M.Sc., Department of Mechanical Engineering
Supervisor: Prof. Dr. Mustafa İlhan Gökler
Co-Supervisor: Prof. Dr. Haluk Darendeliler

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Aluminum forging products has been increasingly used in automotive and aerospace industry due to their lightness and strength. In this study, aluminum forging processes of a particular industrial part for the two different alloys (Al 7075 and Al 6061) have been analyzed. The forging part, forging process and the required dies have been designed according to the aluminum forging design parameters. The proposed process has been simulated by using the Finite Volume Method. In the simulations, analysis of the part during forging process has been performed; and the required forging force, the temperature distribution and the effective stress distribution in the parts have been obtained. The forging dies were produced in the METU-BILTIR Center CAD/CAM Laboratory. The experimental study has been performed in the METU-BILTIR Center Forging Research and Application Laboratory. The parts were produced without any defects as obtained in the finite volume simulations. The results of the experiment and finite volume simulation are compared and it has been observed good agreement.

Keywords: Aluminum Forging, Aluminum Forging Design Parameters, Al 7075, Al 6061, Finite Volume Method.

ÖZ

ALÜMİNYUM DÖVME PROSESİNİN ANALİZİ VE TASARIMI

Öztürk, Hüseyin

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Tez Yöneticisi: Prof. Dr. Mustafa İlhan Gökler
Ortak Tez Yöneticisi: Prof. Dr. Haluk Darendeliler

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Alüminyum dövme parçalar hafifliği ve dayanıklılığından dolayı otomotiv, havacılık ve uzay sanayinde artarak kullanılmaya başlanmıştır. Bu çalışmada, belirli bir endüstriyel parçanın iki farklı alaşımda (Al 7075 ve Al 6061) alüminyum dövme uygulamaları analiz edilmiştir. Dövme parça, dövme prosesi ve dövme kalıpları alüminyum dövme tasarım parametrelerine göre tasarlanmıştır. Önerilen uygulamanın Sonlu Hacim Metodu kullanılarak benzetimi yapılmıştır. Benzetimlerde, parçanın dövme prosesi sırasındaki analizi gerçekleştirilmiştir ve gerekli olan dövme kuvveti, sıcaklık dağılımı ve parçadaki etkin gerilim dağılımı elde edilmiştir. ODTÜ-BİLTİR Merkezi CAD/CAM Laboratuarında kalıpların üretimi yapılmıştır. ODTÜ-BİLTİR Merkezi Dövme Araştırma ve Uygulama Laboratuarında deneysel çalışma yapılmıştır. Parçalar sonlu hacim benzetimlerinde elde edildiği gibi hatasız olarak üretilmiştir. Deneyin ve sonlu hacim benzetiminin sonuçları karşılaştırılmış ve sonuçların tutarlı olduğu gözlemlenmiştir.

Anahtar Kelimeler: Alüminyum Dövme, Alüminyum Dövme Tasarım Parametreleri, Al 7075, Al 6061, Sonlu Hacim Metodu.

To My Family

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TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

SYMBOLS

c	: Yield constant
$\dot{\bar{\varepsilon}}$	: Strain rate
m	: Strain rate hardening exponent
$\bar{\sigma}$	: Flow stress
σ_{UTS}	: Ultimate tensile strength
σ_{Y}	: Tensile yield strength
Q	: Total heat loss
q_{con}	: Heat loss by conduction
q_{conv}	: Heat loss by convection
q_{rad}	: Heat loss by radiation

CHAPTER 1

INTRODUCTION

Forging is a plastic deformation process. In forging, simple billet geometry is transformed into a complex geometry by applying required pressure on material with the aid of forging machines such as hammers and presses. Forging processes usually produce little or no scrap and produce the final part geometry in a very short time, usually in one or a few strokes of a press or hammer. Consequently, forging proposes possible savings in energy and material, especially in medium and large production quantities, where tool costs can be easily amortized [1].

Forging produces final products which exhibit better mechanical and metallurgical properties than products which are manufactured by casting or machining. Forging offers basic performance advantages over the casting or machining processes as follows [2]:

- Strength: Forging refines the grain structure and improves physical properties of metal such as tensile strength, ductility, impact toughness, fracture toughness and fatigue strength by means of developing the optimum grain flow.

- Structural Integrity: Forgings are free from internal voids and porosity. The forging process provides material uniformity, which results in uniform mechanical properties.

- Dynamic Properties: The forging process maximizes impact toughness, fracture toughness and fatigue strength through proper deformation and grain flow, combined with high material uniformity.

- Optimum Material Utilization: Forging can be made with varying cross sections and thicknesses to provide the optimum amount of material utilization.

Forging is chosen for all product areas where reliability and human safety is critical because of the reasons mentioned above and even its wide range of alloys. The most common application areas of the forging are can be stated as aerospace industry, automotive industry, space vehicles, electric power generation systems, compressors, and construction industry.

1.1 Classification of Forging

There are several aspects such as type of die set, forging temperature and forging machine to classify the forging process.

1.1.1 Classification of Forging According to Type of Die Set

Forging process can be classified as open die forging and closed die forging according to type of die set.

In open die forging, at least one of the workpiece surfaces deforms freely as shown in Figure 1.1 and as a result of this, open die forging process produces parts of lesser accuracy and dimensional tolerance than closed die forging process [3]. Open die forgings can be made with repeated blows in an open die, where the operator controls the workpiece in the die. During the forming process, as the height of the workpiece is decreased, cross-section area is increased by the rule of material volume conservation [4].

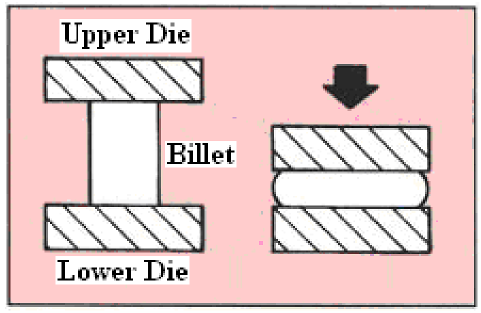

Figure 1.1 Illustration of Open Die Forging Process

Closed die forging is the most common type of forging process in which more complex shape parts are produced by filling the die cavities as shown in Figure 1.2. In closed die forging operations, flash, the excess material to the outside of the dies may occur and high tool stresses are generated. In order to reduce high stresses and to fill the die cavities without a defect, the processes can be planned as a sequence of operations [5].

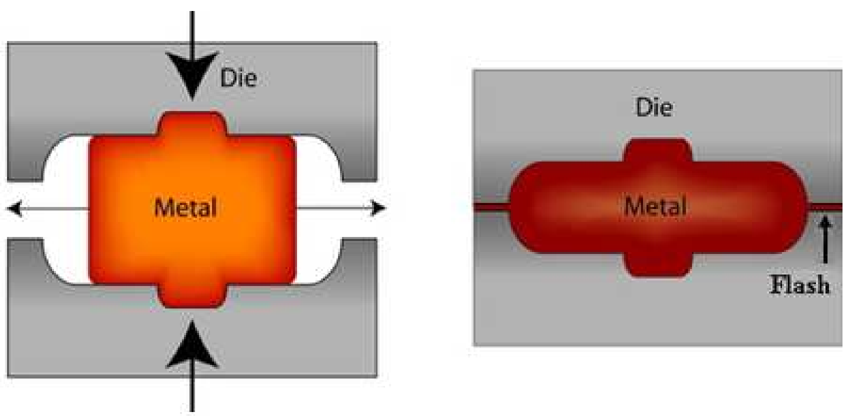

Figure 1.2 Illustration of Closed Die Forging Process

1.1.2 Classification of Forging According to Temperature

Forging operations are classified according to temperature as hot forging, warm forging and cold forging.

In hot forging process, billet is heated above its recrystallization temperature. Greater deformation is attained, die wear is reduced and dimensional accuracy is low in hot forging process. In warm forging process, billet is heated to a temperature which is between its recrystallization temperature and work hardening temperatures. Warm forging process provides products with better dimensional tolerances than hot forging process although forging loads and die wear is greater. On the other hand, in cold forging process, billet is forged usually at the room temperature. Cold forging improves mechanical properties and greater dimensional accuracy is achieved. However, higher force is necessary in cold forging process [6].

1.1.3 Classification of Forging According to Type of Machine

Forging process can be classified in three main groups, which are press, hammer and roll forging, according to machine type. Several forging parts can be produced by either hammers or presses, but the processing characteristic of each type of machines influence the behavior of the metal being forged [7].

Forging press applies a compressing action on the workpiece. Forging presses can be classified as hydraulic and mechanical according to their actuation. Hydraulic presses are operated by large pistons and cylinders driven by high pressure hydraulic or hydro pneumatic systems. They move usually slow speed under pressure after rapid approach speed. Mechanical presses differ from hydraulic presses in that they force two working surfaces together by offset cams, cranks and other rigidly connected mechanical systems. The strokes of mechanical presses are shorter than that of hammers and hydraulic presses [8].

Forging hammers apply force by the impact of a large ram. The hammer is dropped from its maximum height, usually raised by steam or air pressure. Metals forged in hammers are usually display a significant temperature rise during rapid deformation.

This is a problem when forging metals like aluminum close to its melting temperatures. The temperature rise is usually less significant in press forging [8].

1.1.4 Classification of Forging According to the Billet Material

Forging process can be classified in two main groups, which are forging of carbon and alloy steels and; forging of nonferrous metals such as aluminum alloys, magnesium alloys and titanium alloys, according to the billet material. Carbon and alloy steels are the most commonly used forging materials. However, forging of nonferrous metals have been demanded increasingly and the proper forging design should be considered according to the specified nonferrous metal. Since, this study is related to forging of aluminum alloys, the detail of the aluminum forging will be given in Chapter 2.

1.2 Basic Design Considerations of Forging Process

Forging process has several design parameters that should be considered in forging process design. The control of the design parameters aids to predict the characteristics of the final product and as well tooling of the forging process before the forging operations.

The following design sequence consists of design parameters as can be given in Figure 1.3 for the forging process and the die design [9].

- Suitable material and its properties should be defined.
- Grain orientation should be controlled by the proper parting line design.
- Flash and machining allowances should be considered.
- Corners, fillets and forging draft should be specified
- Scale allowance should be considered.
- Billet geometry should be defined.

- Preform design should be done if necessary.
- Forging loads are predicted.

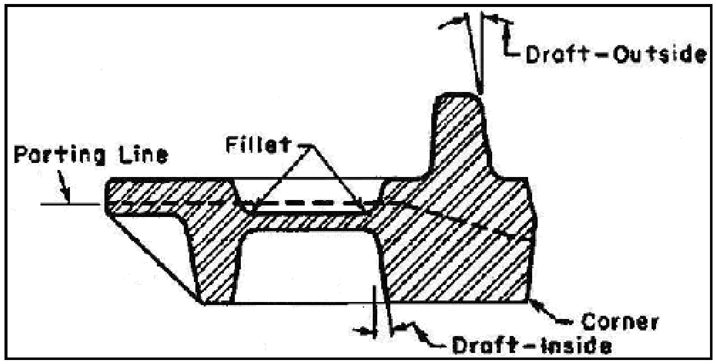

Figure 1.3 Design Parameters of Forged Part [9]

The various design details, such as the number of preforms, the initial shape of billet to assure the die filling and flash thickness are often a matter of experience. Each component is a new design entity and brings its own unique challenges [10].

The details of these parameters for aluminum forging will be mentioned in the following chapters.

1.3 Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) Applications and Computer Aided Engineering (CAE) in Forging Process

The main problem for forging process is the high cost and long lead time for the design and production of tooling. For this purpose, CAD, CAM and CAE techniques are used to get faster the design and manufacture of tooling by decreasing the trial and error time to produce successful forgings [11].

3-D modeling of forging dies is usually made by the aid of CAD software such as PRO/ENGINEER, CATIA, etc. Designer of the forging process can easily change their design parameters in the software if there are any problems in the simulation of the process by using this type of software.

The usage of process simulation programs is common for research and development of forging processes. By using this type of programs, forging tool designer could decrease costs by improving achievable tolerances, increasing tool life, predicting and preventing flow defects, and predicting part properties. CAD, CAM and CAE programs develop satisfactory die design for the required process parameters [12];

- To ensure die fill
- To prevent the flow induced defects such as laps and cold shuts.
- To predict processing limits that should not be exceeded so that internal and surface defects are avoided.
- To predict temperatures so that part properties, friction conditions and die life can be controlled.

Finite Element Method is a method in which parts are divided into a number of elements interconnected at a finite number of nodal points. In finite element method, from the unknown element velocity, equations are formed and stresses and displacements of the each element are calculated.

Finite Volume Method is a simulation method in which the grid points are fixed in space and the elements are simply partitions of the space defined by connected grid points. The finite volume mesh is a fixed frame of reference. The material of a billet under analysis moves through the finite-volume mesh; the mass, momentum, and energy of the material are transported from element to element. The finite-volume solver, therefore, calculates the motion of material through elements of constant volume, and therefore no remeshing is required. The most common finite volume software used in forging is MSC SuperForge to predict to forging variables [13].

MSC. SuperForge is very supportive in optimizing the forging process and defining its parameters. Forging process can be simulated, problems related with current design are observed easily, various dies can be tried and forging process can be analyzed closely by using SuperForge. After the different simulation processes, optimum die set for which die cavity is filled completely while maintaining a lower stress can be selected by using SuperForge [14].

1.4 Previous Studies

Several previous studies have been conducted in METU-BILTIR Research and Application Center [15-27]. In the study of Alper, he developed a computer program for axisymmetric press forgings, which designs the forging geometry and the die cavity for preforms and finishing operation [16]. Elmaskaya studied on upset forging process and the design limits for tapered preforms had been conducted by using the finite element method [17]. Kutlu performed the design and analysis of preforms in hot forging for nonaxisymmetric press forgings [18]. In the study of İşbir, the finite element analysis was realized to examine trimming operation on forged parts [19]. Kazancı developed a program for the sequence and die design of solid hot upset forgings having circular shanks and upset regions with non-circular cross-sections [20]. Civelekoğlu performed analysis of hot forging for three different alloy steels. The effects of material selection on the processes were examined [21]. Also, in the study of Karagözler, the analysis and preform design for long press forgings with non-planar parting surfaces are realized [22]. Abachi performed the analysis of die wear. He compared simulation results and experimental results with the measurement on the worn die [23]. Gülbahar studied on the analysis and design of bent forgings with planar and non-planar parting surfaces [24]. Furthermore, Aktakka performed warm forging analysis of a part used in automotive industry [25]. Maşat studied on precision forging of a spur gear. He proposed a new die design for precision forging and performed the finite volume analysis and the experiment [26]. Saraç proposed the forging process sequence design with a preform design in warm forging temperature range. She performed a finite element analysis to find the die stresses. She also realized the experimental study [27].

Studies in METU-BILTIR Research and Application Center up to now have been related the forging of steel billets and there is no experience in aluminum forging. On the other hand, in the literature, there are some studies related to aluminum forging to be mentioned.

Kim, Ryou, Choi and Hwang analyzed the metal forming processes of aluminum alloy wheel forging at elevated temperatures by using finite element method. In their study, they adapted a coupled thermo-mechanical model for the analysis of plastic deformation and heat transfer in the finite element formulation. They carried out an experiment for a simplified small-scale model and compared with the simulation in terms of forging load to verify the validity of the formulation adapted in this study. Then, they simulated various processes with full-scale model for a 6061 aluminum-alloy wheel [6].

In the study of Wang, Seo, Cho and Bae, to reduce the press capacity and material cost in the production of a large aluminum flange, they proposed a forging process with optimum design parameters. They firstly performed a hot compression test with cast cylindrical billets in order to determine the optimum forging conditions for the aluminum flange. In order to find the change in mechanical properties depending on the effective strain of the cast aluminum billets, they performed a hot upsetting test with rectangular blocks and then they realized a uniaxial tensile test with specimens cut from the upset billets. They made finite element analysis to determine the configurations of the cast preform and die for an aluminum flange. In their study, they also performed an experiment for an aluminum flange and confirmed that the optimal configuration of the cast preform predicted by finite element analysis was very useful [28].

Jensrud and Pedersen investigated cold forging of high strength aluminum alloys and developed a new thermomechanical processing for the economical forging process by reducing the preform steps compared with cold forging. Their method is particularly suitable for parts with narrow geometrical tolerances, good concentricity, smooth surface finish and for near net shape products [29].

Tanner and Robinson studied on the methods to reduce the residual stress in 2014 aluminum alloy forging. Warm water and boiling water was used for quenching of aluminum alloy and results of these two types of quench method were compared to obtain which is the best method to reduce the residual stress in aluminum forging. In their study, closed die forgings manufactured from 2014 aluminum alloys have been subject to both standard and non-standard heat treatments in order to reduce the as-quenched residual stress magnitudes. They determined residual stress magnitudes by the centre hole drilling strain-gauge method and compared the results of two methods in their study [30].

In the study of Yoshimura and Tanaka, precision forging of aluminum forging and their parameters were investigated and results were compared with precision forging of steels. They introduced firstly outline of an enclosed die forging equipment and then explained some net shape forming examples of steel and aluminum alloys in detail [31].

Altan, Boulger, Becker, Akgerman and Henning clarified the design parameters of aluminum forging process in detail [32].

ASM Handbook Committee's Metals Handbook Volume 5 and Volume 14 explain the aluminum forging process and its properties fully [33-34].

1.5 Scope of the Thesis

Aluminum forging products are extensively used in automotive and aircraft industry due to their low weight, corrosion resistance behavior and their ability to achieve high strength and ductility.

In this study, design and analysis of an aluminum forging process will be examined. This study has been supported by TUBİTAK, METU-BILTIR Research and Application Center of Middle East Technical University and AKSAN Steel Forging Company as a "TUBİTAK-SANTEZ" project.

In Chapter 2, aluminum alloys, their forgeability, aluminum forging temperatures, die materials and aluminum forging process will be examined in detail; and in

Chapter 3, design parameters of aluminum forging process such as machining allowances, draft angles, corner and fillet radii, flash geometry and preform design will be given for the process design. In chapter 4, a particular part and dies will be designed by using a CAD program according to the aluminum forging design parameters and the finite volume simulation results such as die force diagrams, effective stress and temperature distribution figures will be presented by using commercially available program for the temperature values of 375 ^oC, 400 ^oC and 425 ^oC for 7075-0 type of aluminum alloy. Manufacturing of dies, their dimensions, assembly of the dies and manufacturing process of the aluminum forging will be explained in Chapter 5. The experiments will be realized for the 7075-0 type of aluminum alloy for the forging temperature of 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC and their results will be presented also in Chapter 5. In Chapter 6, for a case study, the finite volume simulations and the experiments will be performed for the 6061-0 type of aluminum alloy for the forging temperatures of 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC and their results will be compared with the results obtained in Chapter 5. Finally, in Chapter 7, conclusions, discussions and suggestions for future works will be given.

CHAPTER 2

ALUMINUM FORGING

2.1 Introduction

Demand for aluminum forging products especially in automotive and aerospace industry has been increased in recent years due to their lightness, strength and formability. Aluminum forging products are used in automotive and aerospace industry for the necessity to make modern vehicles lighter, safer and more environmental friendly. The automotive industry is one of the major users of aluminum forged parts since low-fuel-consumption cars have been demanded for the economy in recent years [35].

The aluminum parts are generally used in the car body, the wheels and the suspension in modern cars. The suspension components are the most important aluminum forging parts in modern cars [36]. For example, many of suspension components need better-quality and reliable properties such as high strength and toughness. Aluminum forging is a good alternative for such suspension parts with weight reduction up to 40% [35].

Aluminum forgings provide several advantages over the other types of metals as follows [37];

- Aluminum alloys are ductile, in high strength with low weight and have a good corrosion resistance.

- In aluminum forging, the grain structure can be arranged to correspond to the main loading direction leading to high strength and fatigue properties.

- Aluminum forging can be performed in dies heated to essentially the same temperatures as the workpiece.

- Aluminum alloys do not develop scale during heating.

- Aluminum forging processes require low forging pressure.

Aluminum alloys can be forged into a variety of shapes by open die forging, close die forging and ring rolling. Aluminum forgings are mostly closed-die forgings.

2.2 Aluminum Alloys

There are wide ranges of aluminum alloys from low-strength aluminum alloys such as 1100 and 6061 to high strength aluminum alloys such as 7075 in aluminum forging. Aluminum alloys are most often extruded in the form of aluminum bars initially, but in some cases, cast billets are also used for production. During the manufacturing process, a billet is produced which is characterized by a homogeneous structure completely free of pores and blowholes [36].

In Table 2.1, most common aluminum forging alloys and their nominal chemical compositions are given. As can be seen from Table 2.1 as the major alloying elements change in aluminum alloy, its alloy group also changes.

Aluminum alloys are mostly named and designated with its composition. The first of the four digits in the designation indicates the alloy group in terms of the major alloying elements as can be seen in Table 2.2. For example, if the amount of copper in aluminum alloy composition is high, it is called as 2XXX alloy group although if the amount of the zinc is high in aluminum alloy composition, alloy group is called as 7XXX.

Table 2.1 Aluminum Forging Alloys and Their Compositions [31]

Aluminum Alloy	Composition (Weight Percent)						
	Si	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Other**
1100	-	0.12	minimum 99 percent aluminum				
2014	0.8	4.4	0.8	0.5	-	-	-
2018	-	4.0	-	0.7	-	2.0	-
2025	0.8	4.5	0.8	-	-	-	-
2218	-	4.0	-	1.5	-	2.0	-
2219	-	6.3	0.3	-	-	-	0.06 Ti, 0.1 V, 0.18 Zr
2618	-	2.3	-	1.6	-	1.0	1.1 Fe, 0.07 Ti
3003	-	0.12	1.2	-	-	-	-
4032	12.2	0.9	-	1.1	-	0.9	-
5083	-	-	0.7	4.45	0.15	-	-
5456	-	-	0.8	5.1	0.12	-	-
6053	0.7	-	-	1.3	0.25	0.2	-
6061	0.6	0.27	-	1.0	0.2	-	-
6066	1.3	0.9	0.8	1.1	-	-	-
6151	0.9	-	-	0.6	0.25	-	-
7075	-	1.6	-	2.5	-		5.6 Zn
7079	-	0.6	0.2	3.3	0.2	-	6.8 Zn

Table 2.2 Aluminum Alloy Groups and Their Major Alloying Elements [37]

Alloy Groups	Major Alloying Elements
1XXX	Aluminum with 99.0 % minimum purity and higher
2XXX	Copper
3XXX	Manganese
4XXX	Silicone
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc
8XXX	Other elements
9XXX	Unused series

2.3 Forgeability of Aluminum Alloys

Forgeability is mainly based on the deformation per unit of energy absorbed in the range of forging temperatures. Also, forgeability can be considered as the difficulty of achieving specific degrees of severity in deformation. Forgeability is influenced by primarily the forging process, the forging strain rate, complexity of the shape to be forged, the lubrication conditions, and the forging and dies temperature [33].

Although aluminum alloys have good forgeability from the standpoint of ductility, the energy and force requirements change notably with chemical composition of aluminum alloy and forging temperature. High pressure requirement is the main reason of less forgeable material usage in forging operation. For example, pure aluminum, 1100, requires relatively low pressure than alloy 6061 at the same forging temperatures to produce the same shape [34].

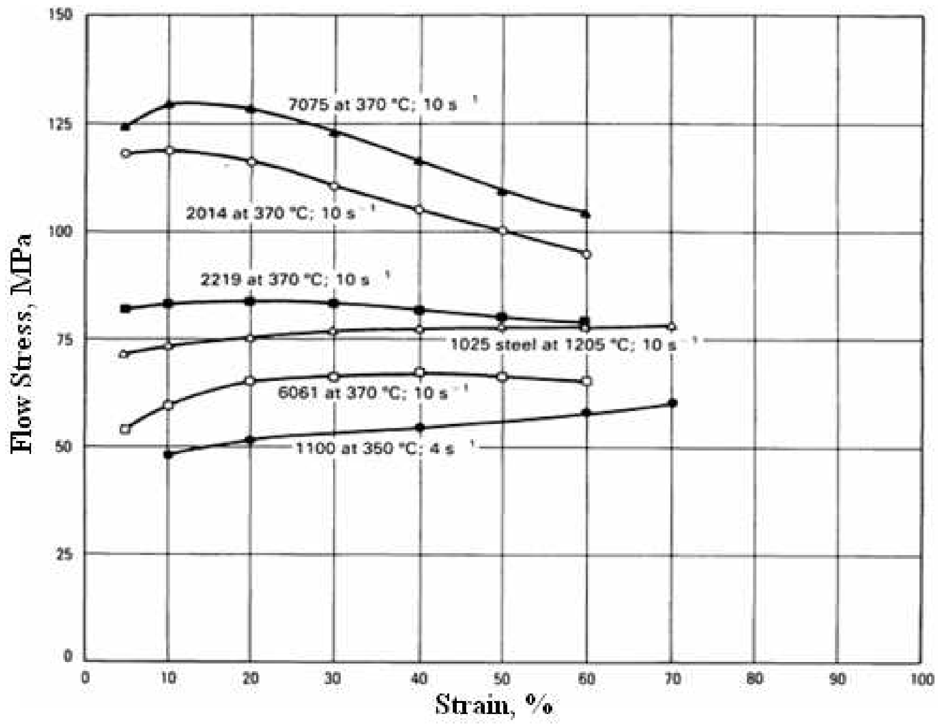

Figure 2.1 Flow Stresses of Commonly Forged Aluminum Alloys and of 1025 Steel at Typical Forging Temperatures and Various Levels of Total Strain [33]

Figure 2.1 compares the flow stresses of some commonly forged aluminum alloys at 350 to 370 °C and at a strain rate of 4 to 10 s^{-1} to 1025 carbon steel forged at an identical strain rate but at a forging temperature typically employed for this steel. For some low-to-intermediate strength aluminum alloys, such as 1100 and 6061, flow stresses are lower than those of carbon steel. For high-strength alloys, particularly such as 7075 flow stresses, and therefore forging pressures, are considerably higher than those of carbon steels. That is, high-strength aluminum alloys are less forgeable at same forging temperatures than low carbon steels as a class of alloys [33].

2.4 Forging Temperature for Aluminum

The metal temperature is a critical element in the aluminum forging process and careful control of temperature during heating is important. Aluminum alloy billets are heated fairly below their solidus temperature before forging, because the heat generated during forging deformation causes a temperature rise in the material. If summation of the initial billet temperature and the temperature rise during forging exceeds the melting temperature, forging begins to melt, leading to severe cracking of forging. This effect is mostly significant in high-speed forging, such as on a mechanical press or forging hammer, because the heat generated has little time to diffuse into the dies. This reduces the complexity of the shapes that can be produced on high-speed forging equipment and potentially increases the amount of machining required [11].

On the other hand, the forgeability of all aluminum alloys improves with increasing metal temperature, and there is considerable variation in the effect of temperature for the alloys. In Figure 2.2, forgeability of different aluminum alloys with respect to temperature changes are given. From the figure, it is easily observed that as the temperature increases forgeability increases. However, changes in high-strength alloys such as 7075 are relatively small when compared to the low strength alloys.

In Figure 2.3, effect of temperature on flow stress can be seen. A highly forgeable aluminum alloy 6061 at a strain rate of 10 s^{-1} is forged for different temperatures and dramatic reduction in flow stress is shown in the figure. It is easily seen from the figure that there is nearly a 50 % increase in flow stress between the highest forging temperature 480 °C and 370 °C.

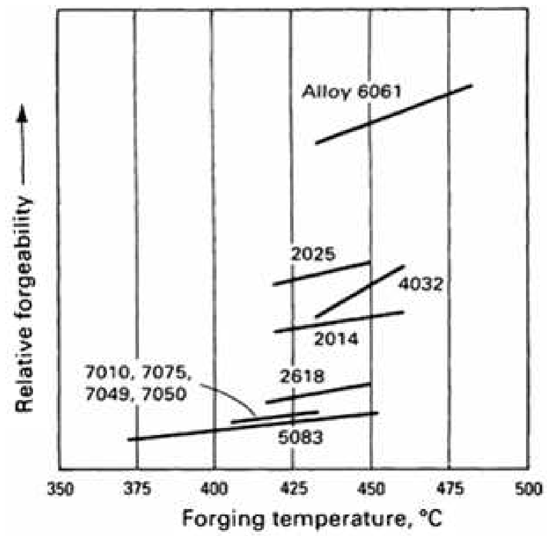

Figure 2.2 Forgeability and Forging Temperatures of Various Aluminum Alloys [33]

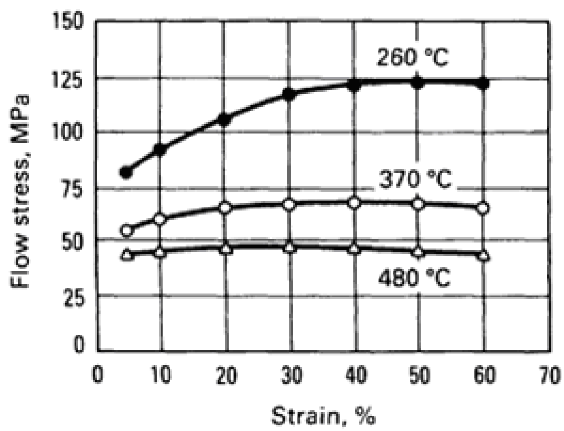

Figure 2.3 Flow Stress vs. Strain for Alloy 6061 at Three Different Forging Temperatures [33]

Temperature ranges which have been recommended for forging aluminum alloys are listed in Table 2.3.

Table 2.3 Recommended Forging Temperature Ranges for Aluminum Alloys [33]

Aluminum Alloy	Forging Temperature Range ^{o}C
1100	315-405
2014	420-460
2025	420-450
2219	425-470
2618	410-455
3003	315-405
4032	415-460
5083	405-460
6061	430-480
7010	370-440
7039	380-440
7049	360-440
7050	360-440
7075	380-440

In general, most aluminum alloys are forged at about 55 ^{o}C below the melting point temperature, but with dependence on the speed and on the total amount of deformation. Since the material becomes brittle at the beginning of melting, appropriate temperature should be chosen for the additional heat is generated during forging operation may result in melting of aluminum alloy in rapid deformation [38].

From Table 2.3, the forging temperature ranges for most alloys are relatively narrow. Because of this, obtaining and maintaining proper metal temperatures in the forging of aluminum alloys is critical to the success of the forging process [33].

2.5 Forging Equipment Used for Aluminum Forging

Aluminum alloys can be forged in almost all presses and impact equipment, with a few exceptions. Aluminum forging should be more carefully performed by hammers because of aluminum alloy’s lower melting temperatures and a tendency for temperature increase to occur in the forgings during the usually faster deformation rates [39].

Table 2.4 Forging Performance of Forging Presses and Hammers for Several Aluminum Alloys [8]

Alloy Designation	Presses	Hammers
1100	Excellent	Excellent
2014	Excellent	Excellent
2025	Excellent	Excellent
2218	Excellent	Good
6061	Excellent	Excellent
7075	Excellent	Fair
7079	Excellent	Fair

In Table 2.4, forging performances of forging presses and hammers for different aluminum alloys are given. As can be given, hammers have poor aluminum forging capabilities although presses are suitable most of the aluminum alloys as seen from the table.

2.6 Die Materials and Die Temperature in Aluminum Forging

The die materials used in the closed-die forging of aluminum alloys are the same as in steel forging except that, due to the forces applied in aluminum alloy forging and the complexity of the parts produced; such materials are typically used at lower hardness levels in order to improve their toughness. H11 (DIN 1.2343), H12 (DIN 1.2606), H13 (DIN 1.2344), or their proprietary variants are usually used at 44 to 50 HRC (i.e. Rockwell Hardness) in aluminum forging [33].

On the other hand, the heating of dies plays very important role in forging operation. As given in Figure 2.4, forging billets cool very rapidly if dies are not heated due to conduction between forging billet and the dies from the rule conservation of energy as shown in following formula;

$$Q = q_{con} + q_{rad} + q_{conv} \tag{2.1}$$

where; Q = total heat loss

q_{con} = heat losing by conduction

q_{rad} = heat losing by radiation

q_{conv} = heat losing by convection

These effects can be reduced when dies are heated close to the billet temperatures where these types of forging operations are called as isothermal forging. Isothermal forging is feasible with metals like aluminum.

Heating of dies can successfully raise the level of metal plasticity and flow properties, improve the homogeneity of metal flow, reduce die chilling and decrease the forging pressure on the material. Therefore, a forging of complicated shape, high dimension of accuracy and a well-distributed internal structure can be produced like in aluminum forging with the aid of heated dies [41].

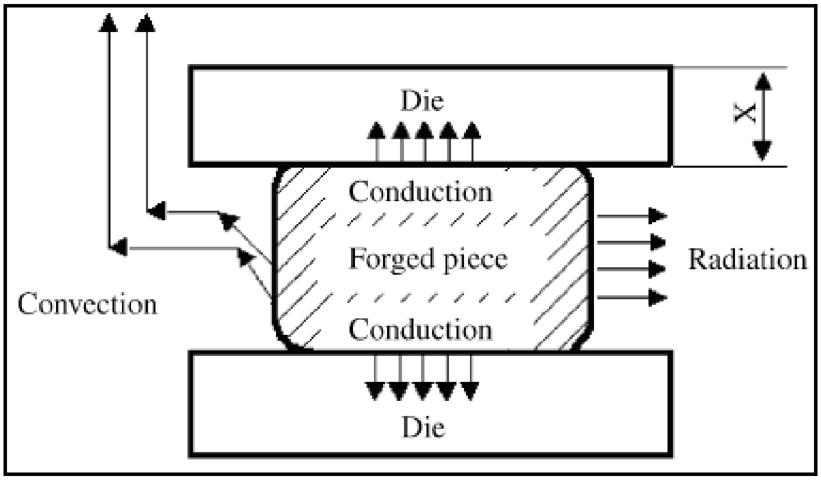

Figure 2.4 Cooling of Forging Billet [40]

Table 2.5 Die Temperature Ranges for Different Forging Equipment [33]

Forging Equipment	**Die Temperature Range** **^{o}C**
Mechanical Presses	150-260
Hammers	95-150
Hydraulic Presses	315-430
Roll Forging	95-205

In Table 2.5 die temperature ranges for different forging equipment are given. As seen from the table, the die temperature for the hydraulic presses is higher than the mechanical presses and hammers. Temperature is kept relatively low in mechanical presses and hammers because of the temperature raise during rapid deformation.

2.7 Heating Equipment Used for Aluminum Forging

The metal temperature and the die temperature are critical factors in aluminum forging process. As discussed in Section 2.4, aluminum forging has a very narrow temperature range and control of the temperature at those ranges is important for the successful forging operation.

Aluminum alloys billets are heated for forging process with a wide variety of equipment such as electric furnaces, fully muffled or semi-muffled gas furnaces, oil furnaces, induction machines. The heating equipment should have pyrometric controls by which temperature can be maintained within the range +/-5 ^{o} C. Most furnaces should have recording and control devices and are frequently checked for temperature uniformity [42].

The heating time for aluminum alloys is usually dependent on the section thickness of the billet and the furnace capabilities. In general, 4 to 8 minutes per 10 mm of section thickness are enough to ensure that the aluminum alloys have reached the desired temperature of preheating [36].

The heating of dies is also critical in the aluminum-forging process. Heating equipments for the dies are mostly gas-fired burners in aluminum forging.

2.8 Lubrication in Aluminum Forging

Lubricants and lubrication of dies are very important in forging operations. There are several advantages of lubrication in forging operation as followings [8];

- Metal flow can be controlled and improved.
- Lubrication decreases the die friction and helps die filling.

- Ease of removal of the forged part from the die can be achieved.
- Lubricants are used to reduce forging loads.

In the selection of lubricants, some important parameters should be considered. For example, insulating qualities, corrosiveness, permanence and ease of removal are important characteristics in the selection of lubricant. Water-based fluids, oil-based fluids and solids are three main lubricant groups in forging operations. The water-based fluids consist of aqueous solutions, emulsions and dispersions in which they are mixed with one of the materials such as soaps, fatty oils, fatty acids, mineral oils and solid fillers. The oil-based fluids range from light mineral oils to heavily compounded chemically active fluids. They usually contain solid inorganic fillers, such as mica, graphite and clay. The solid lubricants are either organic or inorganic solids such as certain plastics and graphite [8].

In aluminum forgings, there are different lubricants existing from kerosene to oil graphite suspensions. Water-based graphite is most widely used as lubricant in aluminum forging. Other organic and inorganic compounds are added to colloidal suspensions in order to achieve the desired results [36]. However, since graphite, has a black color, is not easily cleaned from the forging, the colorless water-soluble lubricants have been demanded recently for aluminum forging.

Lubricant application is usually performed by spraying the lubricant onto the dies while dies are assembled in the press and just before the forging. A pressurized-air or airless spraying system is usually employed in lubrication of dies [36].

2.9 Trimming in Aluminum Forging

Trimming is the simply flash removal operation after forging is completed. There are several methods to remove flash from the forging but most common method for removal of flash is trimming of flash in a trimming press.

Small aluminum forgings can be cold trimmed in same way as steel forgings. Larger forgings can be hot trimmed or band-saw trimmed, depending on size and configuration [39].

2.10 Heat Treatment of Forged Aluminum Parts

Aluminum forgings are rarely used in the as forged condition. All aluminum alloy forgings, except from 1xxx, 3xxx and 5xxx series, are heat treated with solution treatment, quench and artificial aging processes in order to achieve final mechanical properties. The required mechanical properties are difficult to achieve in aluminum forging by heat treatment if complex shape and varying cross-sections are forged, and due to this reason, heat treatment should be performed uniformly and also carefully [33].

CHAPTER 3

DESIGN PARAMETERS OF ALUMINUM FORGING PROCESS

There are several aspects during the design procedure of the forging operations. Part design and perform design are some of the design steps investigated in this chapter for aluminum forging.

3.1 Part Design

Parts design mainly includes the standards for machining allowances, parting line location, draft angles, corner and fillet radii for the aluminum forging.

Machining Allowances

Recommended machining allowance for aluminum forging is given in Table 3.1.

Table 3.1 Recommended Machining Allowances [7]

Greatest Dimension (mm)	Minimum Finish Stock per Surface (mm)
Less than 200	1.6
200 to 400	2.4
400 to 600	3.2
600 to 900	4.0
More than 900	4.8

As shown in Table 3.1, according to FIA (Forging Industry Association), the allowance is referred to as minimum finish stock per surface and is related to the largest dimension of forging. Machining allowance may be applied over the entire forging or to the surfaces to be machined. The finish allowance is applicable to all metals [7].

Location of Parting Line

Parting line is located along the largest cross-section of the part where the upper and lower dies meet. Thus, parting line is applicable only to forgings produced in closed die forging. Parting line is necessary in closed die forging to remove the finished part easily by separating upper and lower dies.

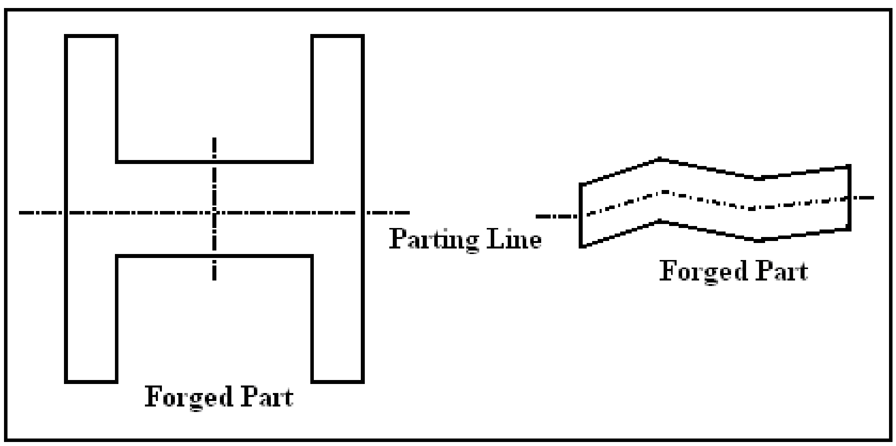

Figure 3.1 Illustration of Parting Line Location

If the parting line remains straight around the periphery of the forging, it will lie in a plane corresponding to that of the mating die surfaces, which is called as the forging plane. Parting line may be in a single plane or it may be curved with respect to the forging plane, depending on the geometry of the final part. Parting line is called as straight parting line if it is on the forging plane and parting line is called as broken parting line if it does not follow the forging plane continuously as shown in Figure 3.1 [32].

Draft Angle

Draft is the angle or taper on the sides of a forging. Draft is necessary for releasing the forging from the dies. Draft can be either applied or natural. Natural draft comes from the part geometry. On the other hand, the applied draft is the taper applied to the walls of a forging to provide sufficient taper to remove the forging easily. If close tolerance forging is made, there is zero or one degree draft is specified in the design of the dies. Thus, strippers or knockout pins are necessary to remove the forging part from the dies in close tolerance forging. The location of maximum draft on any vertical surface usually coincides with the parting line [7].

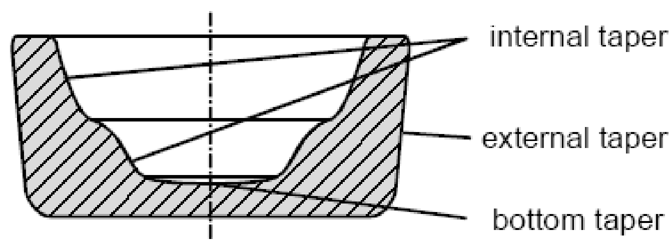

Figure 3.2 Illustration of Draft [37]

There are basically three types of draft as seen in Figure 3.2. External draft is draft applied to the outer surfaces of perpendicular elements of a forging to the parting line. Internal draft is applied to the inner surfaces of perpendicular elements of a forging to the parting line, including the draft in pockets or cavities. Also bottom draft may exist to provide material flow easily.

In Table 3.2, there are recommended draft values with stripper and without stripper according to DIN 1749/EN 586-3 standard for aluminum forging process.

Table 3.2 Recommended Draft Angles [37]

	External and Internal Draft Angle	**Bottom Draft Angle**
Die with Stripper	1^o	1^o
Die without Stripper	3^o	1^o

Corner and Fillet Radii

Corner and fillet radii are provided to connect smoothly intersecting sides of forging. Corner and fillet help for a smooth, gradual connection rather than sudden angular connection. Corner and fillet radii are usually chosen as large as possible to increase the metal flow and decrease the high forging pressure during forging. If small radius is chosen during design, stress concentration occurs at the small radius and cracks may occur at that point. Choosing of corner and fillet radii also affects grain flow, die wear, the amount of material to be removed in machining [7]. Schematic illustration of the corner and fillet radii is given in Figure 3.3.

Figure 3.4 and Table 3.3 summarize the corner and fillet radii values according to DIN 1749/EN 586 standard.

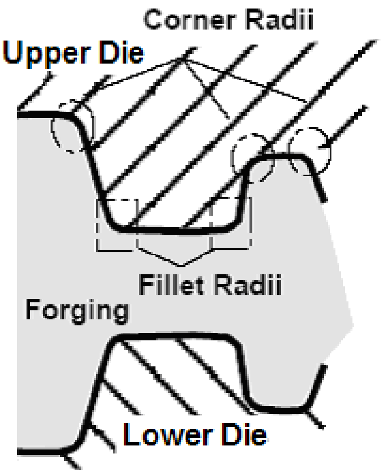

Figure 3.3 Illustrations of Corner and Fillet Radii on Part [43]

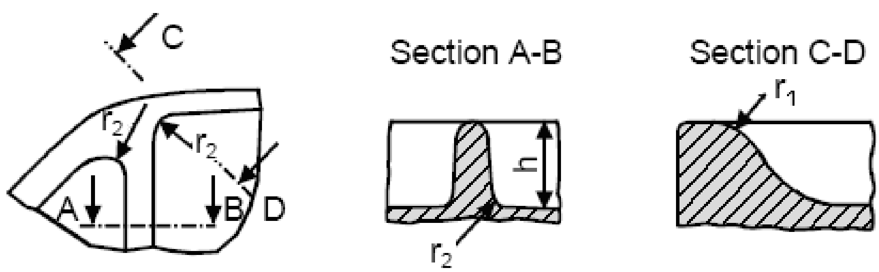

Figure 3.4 Determinations of Corner and Fillet Radii [37]

Table 3.3 Recommended Corner and Fillet Radii on Part [37]

Height (h) mm	0-4	4-10	10-25	25-40	40-63	63-100	100 -
r_1 (Corner)	1.6	1.6	2.5	4	6	10	16
r_2 (Fillet)	2.5	4	6	10	16	20	15

Ribs and Webs

A rib is a brace-like projection that is located either at the periphery or on the inside of a forging. Rib can be forged in either the upper or lower die or both. Ribs are called as flange when ribs are along the periphery of a forging. The length of ribs is usually more than three times their width. The design of a rib should reflect the maximum efficiency in use of materials. Efficiency is related to the load carrying capacity of a rib. On the other hand, web is the comparatively thin, plate-like element of the forging. Webs connect ribs and other forged elements. Webs are usually flat and coincide with the forging plane. Because of their physical connection to other elements of a forging, the design of webs should be considered with the design of ribs, the location of parting line, draft and the selection of corner and fillet radii. Due to the material flow in the vertical sides, webs are very difficult to produce [7].

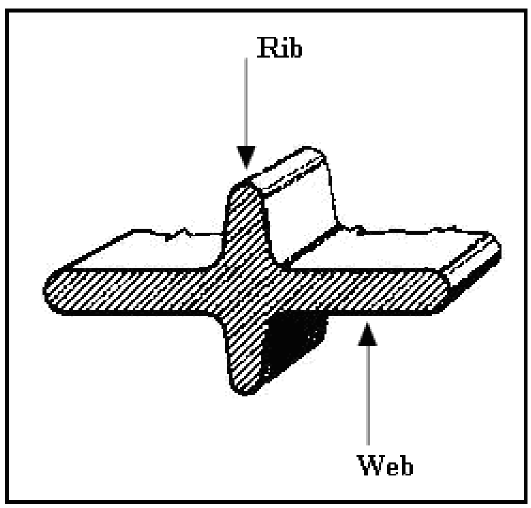

Figure 3.5 Illustrations of Rib and Web

3.2 Shape and Size Factors in Forging

There are limitations to the geometric complexity that can be obtained during forging process. The force applied to the material by the forging equipment generates pressure that forces metal to flow into complex cavities of the dies. Spherical and block like shapes are the easiest to forge in closed dies. Thin and long cavities such as ribs and webs require high pressure to force the material into them and maximize the effects of friction and temperature changes. If too much pressure is required, the total forging load may exceed the capacity of the forging equipment. Also, the localized stresses in the die due to high pressure in the die cavities may become large enough to cause overloading failure of the die, fatigue cracking due to repeated loading and rapid die wear in high metal flow regions. Furthermore, shape complexity is the possibility of defect formation in the material during forging. As the material flows around small corner and fillet radii on the dies, laps and cracks may occur. There is a direct relationship between the surface-volume ratio of a forging and the difficulty of producing it [11].

3.3. Flash Geometry

Flash is an excess metal around the periphery of the forging in the surrounding area of the parting line. Flash occurs around the forging part when leaving the closure of the mating surfaces of the dies. Flash is always related with the parting line and parting line can divide flash into two pieces [7].

The flash basically serves two main functions. Firstly, flash compensates variation in billet volume. That is, oversized billets can be used to prevent the billet cutting errors and metal loses by oxidation during forging. Secondly, flash is useful for controlling the metal flow. The constriction caused by the flash helps metal to flow and fill the die cavities [43].

In Figure 3.6, flash and its components are shown. Flash land is the short, flat portion of flash extending outward from its intersection with the forging as seen from the figure. Flash gutter is a space after the flash land where excess material is accumulated. The gutter is designed to be slightly oversize to accommodate all the excess metal [7].

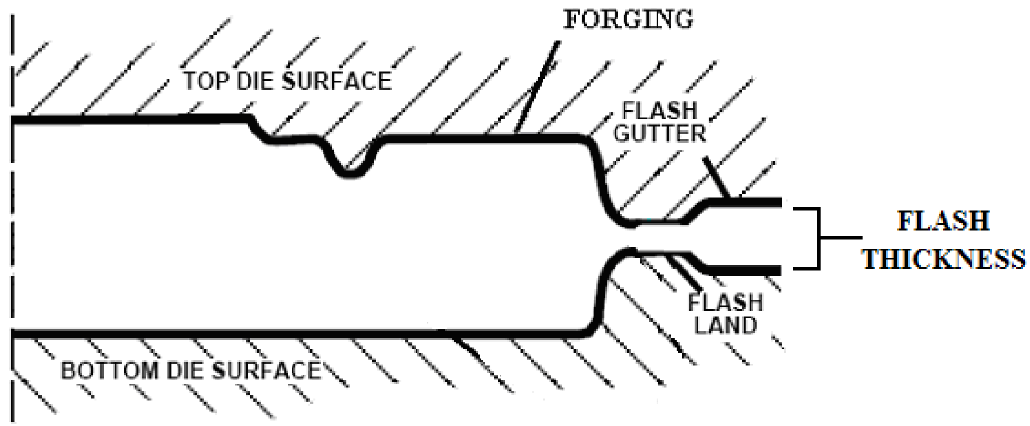

Figure 3.6 Flash Designs [43]

There are significant differences in the design of flash for aluminum from steel forging. Flash and flash land thicknesses are usually much thinner in aluminum forging. However, relatively small changes in the flash thicknesses can result in great changes in the forging pressure requirements. Thus, the flash design should be made carefully to avoid overloading during forging operation. In Table 3.4, minimum recommended die closure or flash thickness according to FIA (Forging Industry Association) are given for the several types of materials. Flash thickness tolerances are related to type of metal and on the plan area of the forging at the parting line as can be seen form the table. Although as the plan area increases, flash thickness differences increases between aluminum and steel forging. Since the forging loads are lower in aluminum forging, flash thicknesses are relatively thinner as given in the table.

Table 3.4 Flash Thicknesses for Different Materials According to Plan Area at the Trim Line [7]

	Plan Area (mm^2)		
Materials	**< 6500**	**6500-19350**	**19350-32250**
Carbon Steel and Low Alloy Steel	0.8	1.6	2.4
Heat Resisting and Titanium Alloys	1.6	2.4	3.2
Aluminum and Magnesium Alloys	0.8	0.8	1.6
Refractory Metals	2.4	3.2	4.0

3.4 Upsetting and Preform Design

Upsetting is a forging process where cross sectional area of the initial billet is increased by decreasing length of the billet with using mostly flat dies as seen from Figure 3.7. Upsetting is usually used in forging process for the initial step of producing desired products.

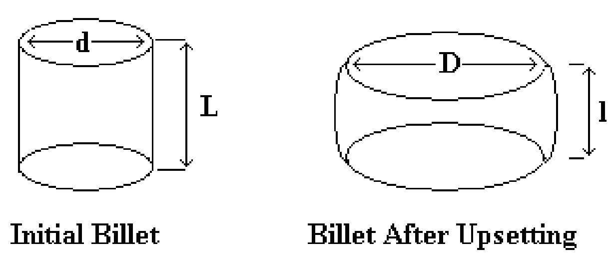

Figure 3.7 Upsetting Operation

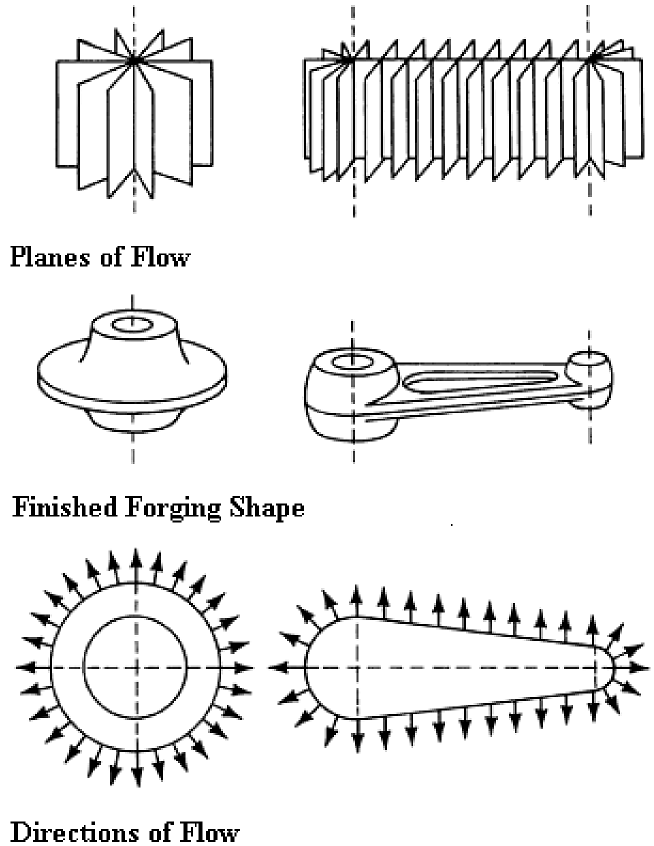

Figure 3.8 Planes and Directions of Metal Flow during Forging [32]

On the other hand, design of the preform in closed die forging is one of the most important aspects. Defect free metal flow, complete die fill and minimum metal losses into flash can be achieved in the final forging operation with proper forging process design. However, determination of the preform geometry is a particularly difficult design step. Metal flow in the preform die should be clearly understood to make the proper preform design. In the study of metal flow for designing the preform, it is very useful to consider various cross sections of a forging where the flow is almost in one plane as given in Figure 3.8. It is common practice in designing a preform to consider planes of metal flow, that is, selected cross sections of the forging, and to design the preform configuration for each cross section based on metal flow. The basic design parameters of the preform design can be given as follows [32];

- The area of each cross section along the length of the preform should be equal or less than the finished cross sections.
- All corner and fillet radii should be larger than the radii of finished part in preform.
- The dimension of the preform should be larger than those of the finished part in the forging direction so that metal flow is mostly of the upsetting type rather than of the extrusion type (Figure 3.9).

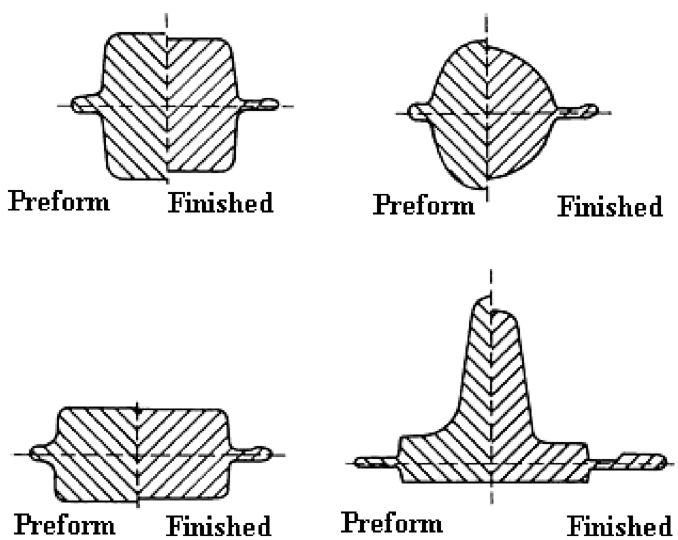

Figure 3.9 Examples of Preform Cross Section Design [33]

In Table 3.5, the recommended preform dimensions for aluminum forging according to the finish forging dimensions are given. In table, first subscript F and P in the dimension refer to finish and preform respectively. In addition, as seen from the table the draft angles in preform are nearly same as finish forging and other dimensions are larger in preform.

Table 3.5 Dimensions in Preform for Aluminum Forging [32]

Dimensions in Finish Forging	**Dimensions in Preform**
Fillet Radii, R_{FF}	R_{PF} = (1.2 to 2) R_{FF}
Corner Radii, R_{FC}	R_{PC} = (1.2 to 2) R_{FC}
Draft Angle, α_F	$\alpha_P \approx \alpha_F$

CHAPTER 4

DESIGN OF ALUMINUM FORGING AND FINITE VOLUME ANALYSIS OF ALUMINUM FORGING PROCESS

4.1 Case Study for Aluminum Forging Process

In this study, a part which was previously forged in three stages from a cylindrical steel billet with a diameter of 30 mm and a height of 30 mm at AKSAN Steel Forging Company as given in Figure 4.1 will be considered. A study was previously completed in METU-BILTIR Center for warm forging of the part with the steel material [27]. In this thesis, aluminum forging will be analyzed to produce the similar geometry from aluminum billet.

Figure 4.1 Steel Forged Part

Based on the part geometry given in Figure 4.1, 3-D modeling of the part and dies has been realized by using PRO/ENGINEER Wildfire 3.0 [44]. In the simulation process, aluminum forging in different temperatures for the modeled part has been investigated and proper forging stages have been defined to fill the forging dies without any defects by using Finite Volume Method (FVM) with sfForming 8.0 module of Simufact 3.0 [45]. Results for the finite volume simulation of the process will be provided in this chapter for the aluminum alloy 7075-0. In the following section, 3-D modeling of the part will be explained in detail.

4.2 3-D Modeling of Forging Part

3-D model of the forging is given in Figure 4.2 and its technical drawing is given in Appendix A.

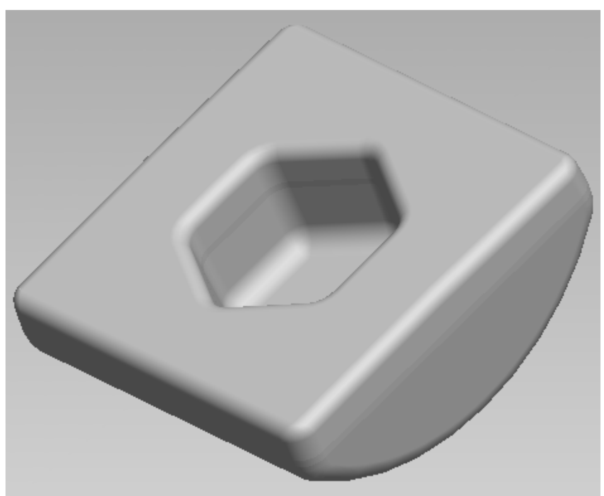

Figure 4.2 3-D Modeling of Forging

There are some important parameters such as draft angles, parting line location and flash thickness in modeling of the part for the design of the forging.

Recommendations and experiences about these have been already discussed in Chapter 3. Draft angle should be created to ease for releasing forged part with defining proper parting line location. Parting line is located at the 5.1 mm from the top of the forging part as shown in Figure 4.3 since parting line is always located along the largest cross-section.

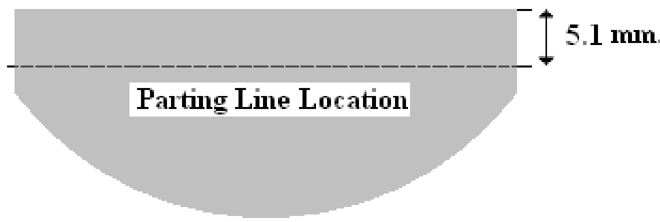

Figure 4.3 Parting Line Location on Forged Part

According to Table 3.4, the flash thickness is defined for the plan area of the forging. Plan area, at square cross-section of the part along the parting line, is calculated as 1600 mm^2 since one edge of the square is 40 mm. As be seen from the Table 3.4, the minimum recommended flash thickness for the plan area less than 6500 mm^2 is given as 0.8 mm for aluminum forging alloys. However, the flash thickness, i.e. the face clearance between upper and lower die, is taken as 1.8 mm by considering an additional 1 mm for the safety of the forging operation to avoid any clash of the upper and lower dies as can be shown in Figure 4.4.

After defining location of the parting line and value of the flash thickness, the draft angles of 3^o are applied to the outer surface of the part and to hexagonal hole on the part as recommended in Table 3.2. A bottom draft of 1^o is provided for the upper surface of the part to prevent the sticking the part to the upper die at the bottom of stroke and to remove the part easily. The application of draft is shown in Figure 4.5.

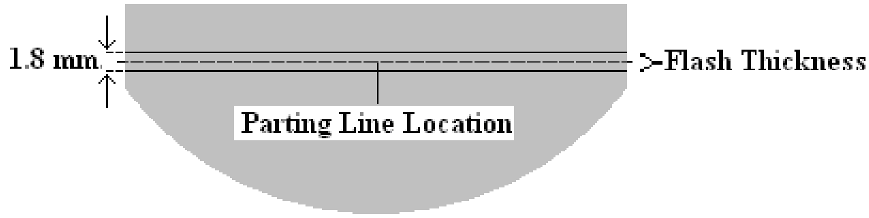

Figure 4.4 Illustration of Flash Thickness on Part

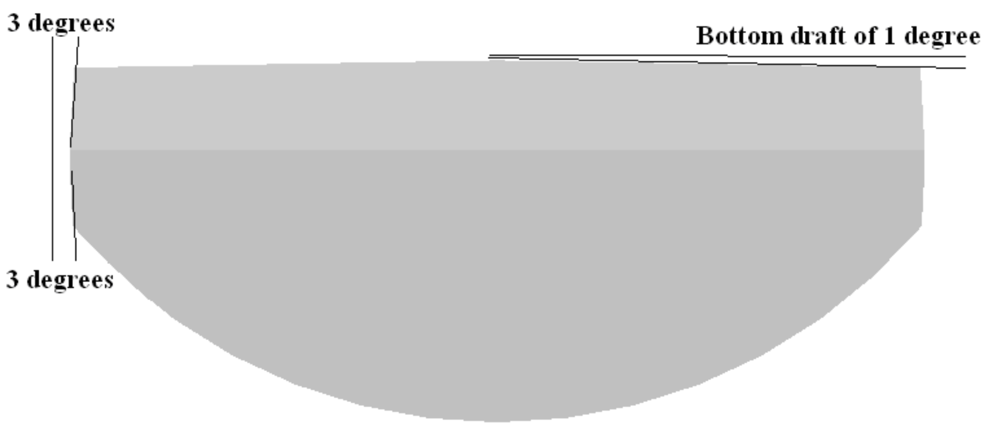

Figure 4.5 Draft Angles on Part

The corner and fillet radii are considered as described in the technical drawing of the particular forging in Appendix A.

4.3 Aluminum Forging Die Design

In aluminum forging die design, different type of die configuration should be considered according to forging process stages such as upsetting, preform and finish stages.

Before the design of the dies, it should be cleared that what type of forging machine is going to be used and design should be made according to that forging machine. In the experiments, the 10 MN SMERAL mechanical press available in METU-BILTIR Center Forging Research and Application Laboratory is going to be used. The technical information about the 10 MN SMERAL mechanical press is given in Appendix B. In this machine, a die holder is used to mount die blocks. There are three housings on the die holder to fasten three die blocks as seen in Figure 4.6.

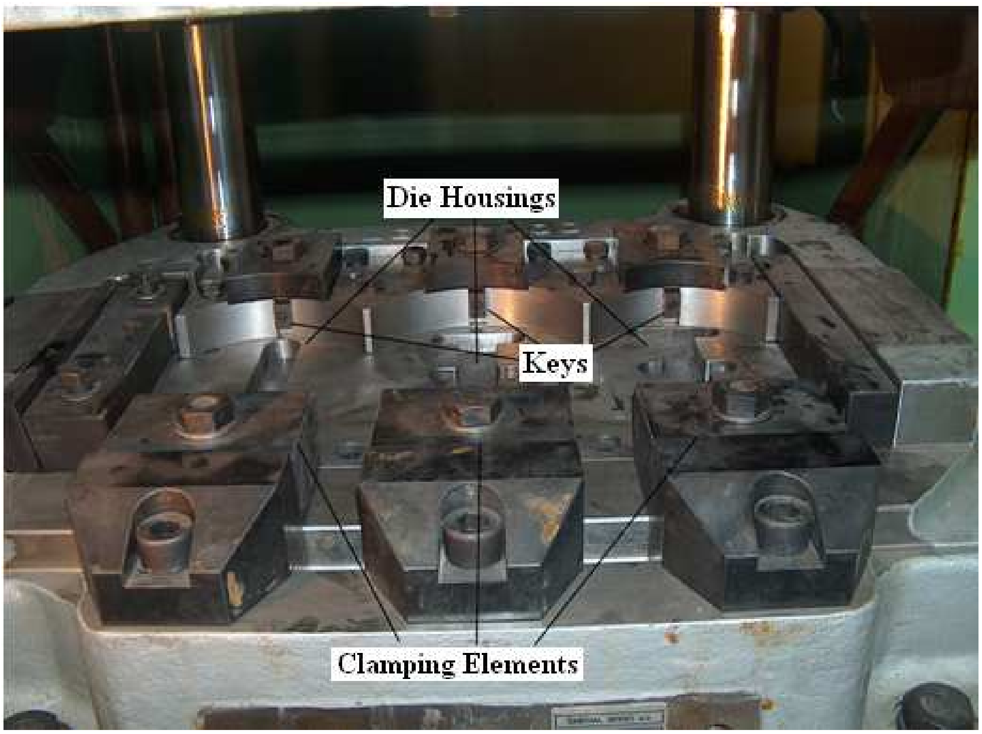

Figure 4.6 View of the Lower Die Holder on Press

In Figure 4.7 and Figure 4.8, top and front views of the die housings of die holder are given. According to forging stages, three different types of forging die can be used in this mechanical press. However, as seen from the Figure 4.7, the middle housing has the largest diameter and it is usually used for the finish forging stage. On the other hand, height of the die set is restricted to 200 mm as seen Figure 4.8 when dies are at the bottom dead center. So, in design of the dies, it should be considered that the total height of the dies does not exceed 200 mm including flash thickness. Furthermore, as seen from Figure 4.7, the key ways are specified with the tolerance H8 at the back of the die holder exist. These key ways are necessary to prevent the rotation of the dies during the forging process and should be considered. Finally, for clamping of the dies in the die holder, there are 5 degrees taper as seen in Figure 4.8 and it should be noted during die design.

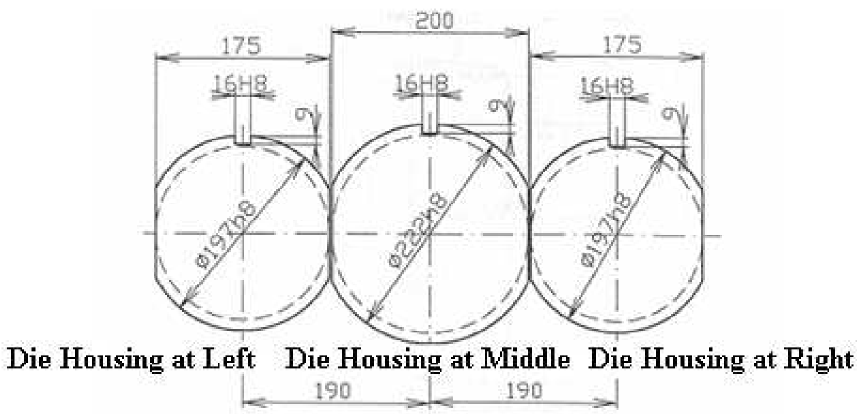

Figure 4.7 Top View of the Circular Die Housings of the Die Holder [46]

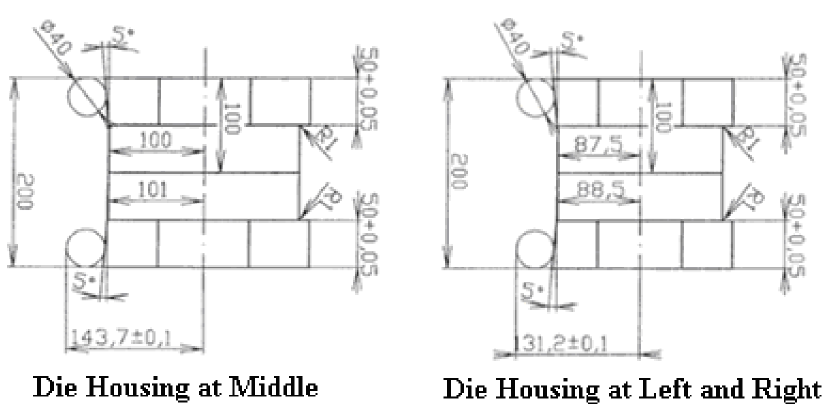

Figure 4.8 Front View of the Circular Die Housings of the Die Holder [46]

According to the constraints of the die holder, the upper and the lower dies in the finish stage are designed based on the designed part geometry. In design of the upper and lower dies, a shrinkage allowance of 1.5 % is taken since some shrinkage occurs after the forged part cools. Total height of the upper and lower die is 200 mm by considering the flash thickness when the press is at the bottom dead center. Hence, the dies are designed by considering 99.1 mm in height and by adding flash thicknesses of 1.8 mm, the total height of the dies becomes 200 mm. As seen in Figure 4.9, the flash land is provided at the circumference of the die cavity. Since the die housing at the middle is going to be used for the finish stage, the upper and lower finish dies will have an external diameter of 222 mm and outer geometry of the dies are modeled according to the dimensions given in Figures 4.7-4.8. The key ways are also modeled with 16 mm in width and 9 mm in depth to prevent the rotational motion of the dies relative to the die holder. The gutter is not designed since it is not used in the finish die. The detailed technical drawings of the finish dies are given in Appendix C.

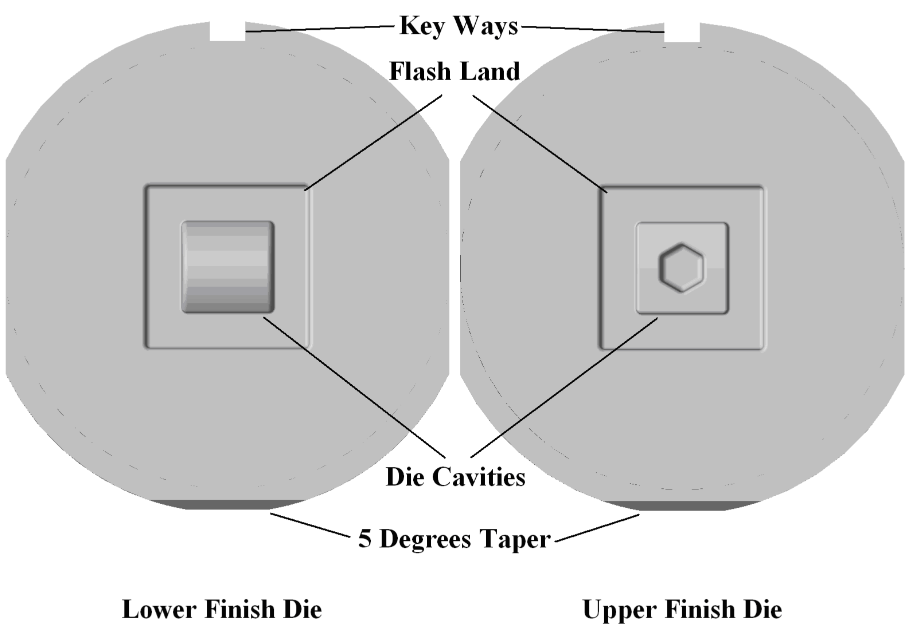

Figure 4.9 3-D Model of Lower and Upper Finish Dies

Furthermore, front view of the die assembly is shown in Figure 4.10. As seen in the figure, there is a step like structure in the dies. These types of step are required for the positioning and alignment of the upper and lower dies with respect to each other. Also, as seen in the figure, edges at the both side of the dies are cut according to die holder geometry, since generally more than one die is considered to be used for the forging operation during analysis and experiments.

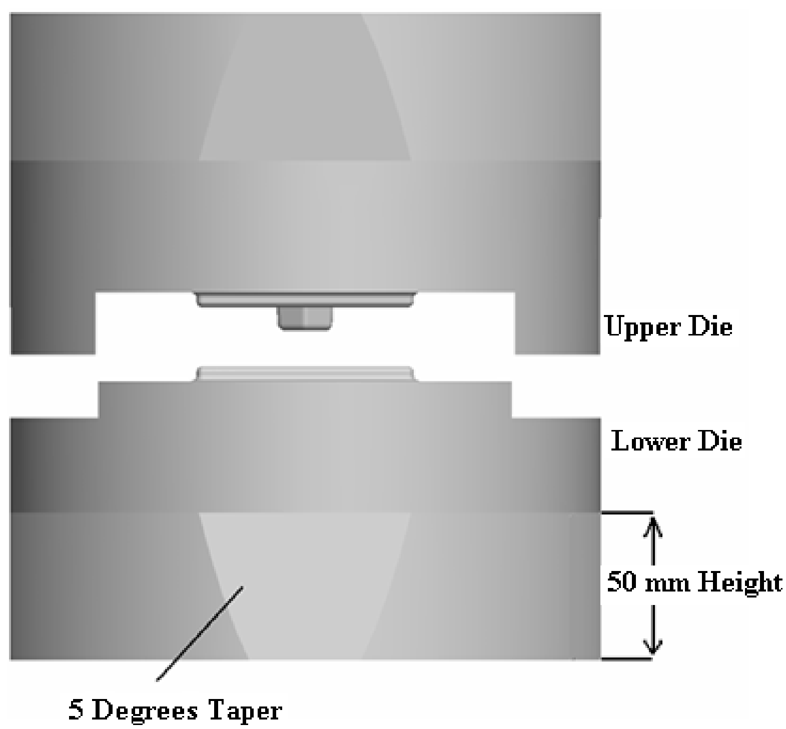

Figure 4.10 Front View of Finish Die Assembly

4.4 Simulation Process Parameters for Finite Volume Method

The finite volume method has been used for many years in analyzing the flow of materials in a liquid state. However, in recent years, some other computer simulation programs like SuperForge, i.e. SfForming 8.0 in solid state for hot metal forming operations has been established on the basis of finite volume method. In the finite volume analysis with SfForming 8.0 module of Simufact 3.0 some simulation process parameters should be defined before simulation is executed.

4.4.1 Defining the Process Type, Importing Forging Dies and Modeling of Billet

Process type may be selected as "open die" or "closed die" forging. After selecting process type, it should be noted that forging process is "hot forging", simulation is 3-D and the used solver is finite volume.

The models of upper and lower die geometries from CAD program are imported to the finite volume program in "stl" (i.e. stereo lithography) format after the process type is defined.

On the other hand, "Auto Shape" function of the program can be used for the simple parts like billet. However, initially billet dimension should be specified. Scale allowances are mostly considered in the billet geometry selection since billets are contacts with the air after heated. Most of the metals are coated with the layer of scales after heated metal contacts with the air due to the oxidation. Aluminum alloys are not scaled when heated since aluminum alloys do not oxidize considerably at the forging temperature and because of this reason, scale allowance is not considered for billet selection in this study [39]. The billet dimension is selected according to part volume with considering flash volume. By using the mass properties module of CAD program, the part volume is found as 20657 mm^3. Round cross-section aluminum billets are available in Turkey from diameter of 3 mm to 150 mm with a step of 1 mm [47]. The billet dimensions, which does not cause buckling and early flash formation, are obtained according to finite volume results and the billet dimensions are taken as seen in Table 4.1 with considering available billet diameter and required flash volume.

Table 4.1 Billet Geometry and Billet Dimension

Billet Geometry	Billet Dimension (mm)
Cylindrical Shape	30 mm in diameter 32 mm in height

4.4.2 Assigning the Material Properties of Dies and Billet

In this analysis, the dies are considered as rigid die with heat conduction. Because of this reason, the die material is not defined although different types of die material data exist in the material library of SfForming 8.0 [45].

The billet material is chosen according to recommendation of FNSS which is one of the most important defense company in Turkey and which uses the aluminum forgings in their products [48]. 7075-0 type of aluminum alloy is chosen since that type of aluminum alloys are extensively used in aerospace, automotive and defense industry with its high strength, low density, and low cost. 7075-0 type of aluminum alloy is available in material database of SfForming 8.0 [45] for the hot forging temperature range of 400-550 ^{o}C.

The flow stress-strain rate relation for the different type of hot forging temperatures is as follows [32] :

$$\overline{\sigma} = C(\dot{\bar{\varepsilon}})^{m} \tag{4.1}$$

where; $\overline{\sigma}$: flow stress

C: yield constant

$\dot{\bar{\varepsilon}}$: strain rate

m: strain rate hardening exponent

In Table 4.2, some parameters related with the Equation 4.1 are given to define flow stress for strain value of 0.115 in different forging temperatures.

According to Equation 4.1 and Table 4.2, flow stress-strain rate curves of 7075-0 for the strain of 0.115 in different temperatures are obtained as shown in Figure 4.11.

Table 4.2 Flow Stress Parameters for 7075-0 [45]

Strain Rate (1/s)	**Yield Stress according to Temperature**			
	400 ^oC	**450 ^oC**	**500 ^oC**	**550 ^oC**
0.01	45.55	22.22	13.48	9.14
0.34	62.57	35.76	22.87	16.65
0.67	66.51	39.19	25.32	18.68
1.00	68.95	41.37	26.89	20.00

Tensile yield strength and ultimate tensile strength of the aluminum alloy 7075-0 are given in Equations 4.2 and 4.3 according to the simple tension test at the room temperature [49].

$$\sigma_Y = 103 \text{ MPa} \tag{4.2}$$

$$\sigma_{UTS} = 228 \text{ MPa} \tag{4.3}$$

Also, some basic material constant and heat material constant are specified as shown in Table 4.3 [45].

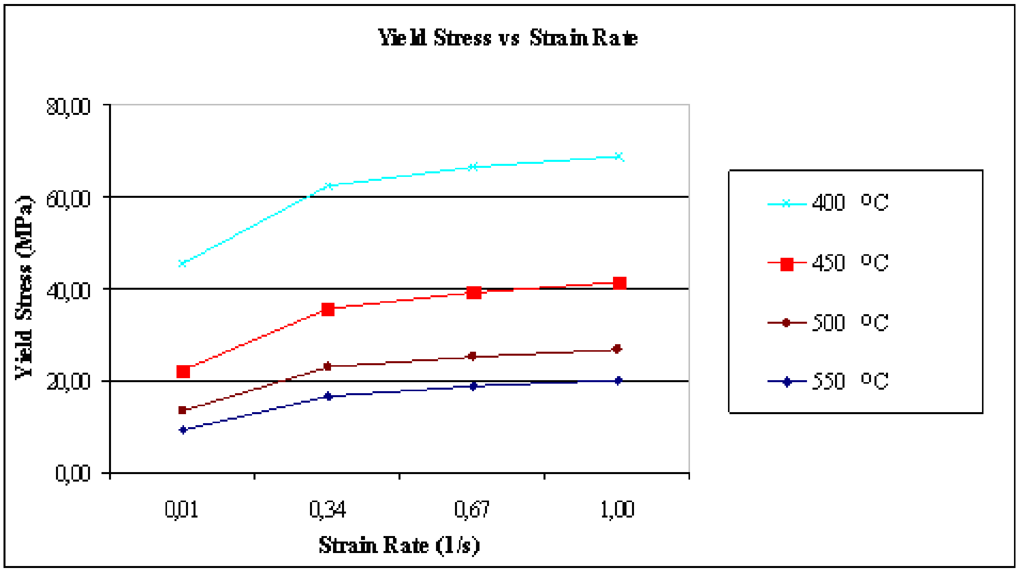

Figure 4.11 Stress-Strain Rate Curves of 7075-0 for Different Temperatures [45]

Table 4.3 Material Properties of 7075-0 [45]

Material Property	Value
Young's Modulus (GPa)	72
Poisson's Ratio	0.33
Density (kg/m^3)	2810
Thermal Conductivity (Watt/(m*K))	173
Specific Heat Constant (Joule/(kg*K))	960
Coefficient of Thermal Expansion (1/K)	2.52e-5
Solidus Point (^{o}C)	477
Melting Point (oC)	635

4.4.3 Initial Temperature of Billet and Dies

Initial temperatures of the billet are taken as 375 ^{o}C, 400 ^{o}C, 425 ^{o}C and simulation is made for these temperature values. On the other hand, temperature of the dies during the aluminum forging process is recommended as 150 °C to 260 °C for the closed die forging [36]. So, initial temperature of the dies is assumed as 200 °C during the analysis. Parameters directly used in analysis are given as follows according to SfForming 8.0 [45];

Ambient temperature:	25°C
Emissivity for heat radiation to ambient:	0.25
Heat transfer coefficient to ambient:	50 W/m^2.K
Heat transfer coefficient to workpiece:	6000 W/m^2.K

4.4.4 Defining the Coefficient of Friction

Friction between die and billet is an important consideration in a metal forming process. Such friction produces a tangential (shear) force at the interface between die and billet which restricts movement of the material and results in increased energy and press forces. The magnitude of the shear friction stress influences the deformation pattern, temperature rise, the tool deflection and total force in metal forming [50].

The friction coefficient is ranged from 0.06 to 0.24 in aluminum forging with the test previously done [32]. In this study, plastic shear friction is used with a coefficient of 0.2 since high loads are applied in forging operations.

4.4.5 Defining the Press in Finite Volume Program

Schematic illustration of the crank press is shown in Figure 4.12 and properties of it related with the available press in METU-BILTIR Center Forging Research and Application Laboratory are given in Table 4.4.

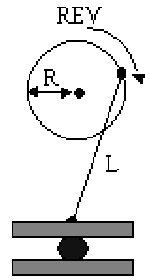

Figure 4.12 Schematic Illustration of Crank Press [45]

Table 4.4 Properties of Crank Press available in METU-BILTIR Center

Crank Radius (mm)	Rod Length (mm)	Revolution Speed (rpm)
110	750	100

4.4.6 Defining Forming Properties

Forming parameters are defined to initiate the simulation program as given in Table 4.5. Element sizes in finite volume program should be assigned for the billet. The stroke length depends on billet dimension and not shown in the table.

Table 4.5 Forming Properties in Finite Volume Analysis

Workpiece Element Size (mm)	1
Output Divisions	21
Finite Volume Ratio	0.2

In Table 4.5, output divisions is the frequency of output data storage by the program and the finite volume ratio is used to make the finite volume elements that constitute the billet, smaller compared to global elements [27].

4.5 Analysis of Aluminum Forging Process by Finite Volume Method

In this part of the study, different finite volume simulations are made to ensure to proper forging operation without any defects. Forging operation is firstly thought as single operation and analysis are made for the single operation.

4.5.1 Single Stage Forging Operation

Two types of single step forging operation are investigated according to orientation of the billet in the die as follows.

a) Billet at Perpendicular Position

In this orientation, the billet is placed in the die at the perpendicular position as shown in Figure 4.13 and the analysis is executed for this position.

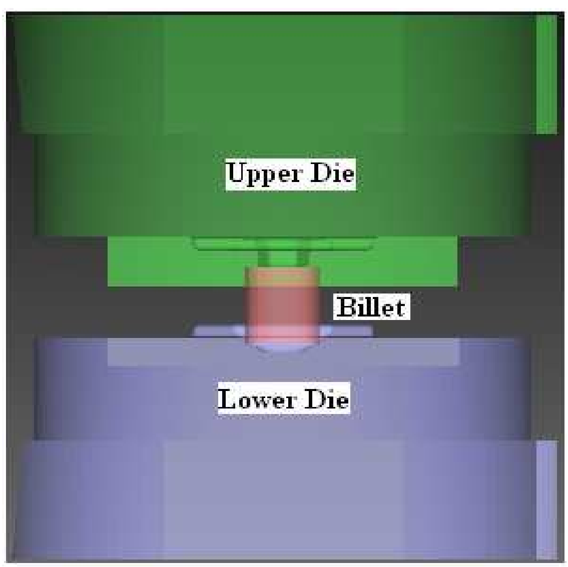

Figure 4.13 Perpendicular Orientation for Single Operation

The die and forging part contact is the important feature for the analysis since die filling is important during forging operation. In Figure 4.14, die filling of this type of orientation is given. In the Figure 4.14, blue color shows that billet does not contact with forging dies and red color shows that billet contacts with the dies. The die is completely filled as seen in Figure 4.14.

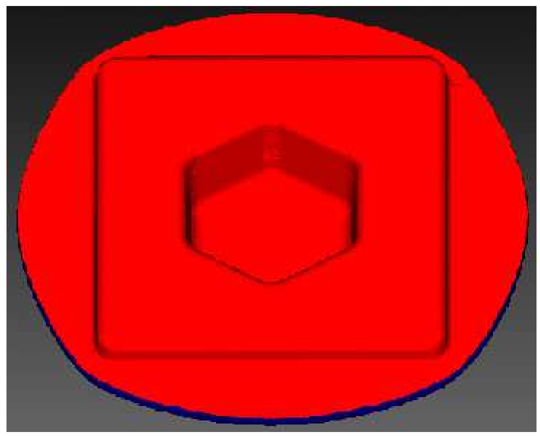

Figure 4.14 Die Filling for Perpendicular Orientation at 400 ^{o}C

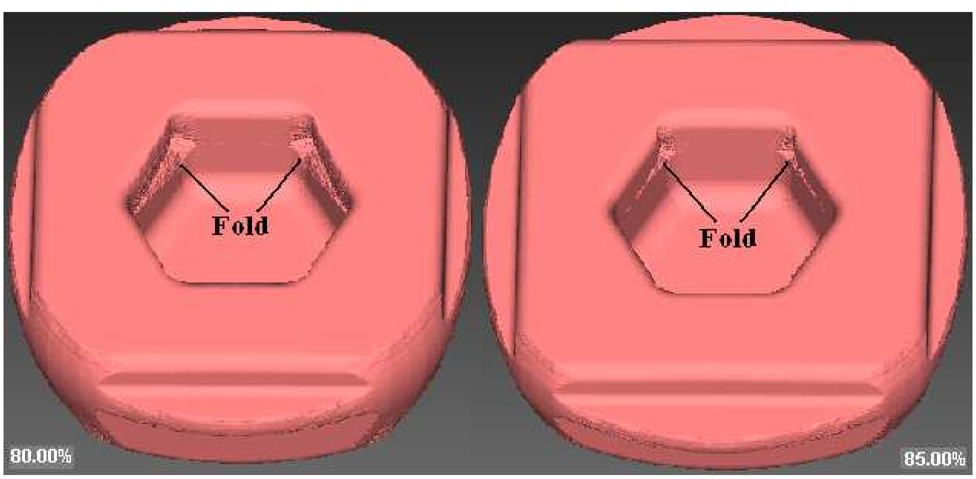

Figure 4.15 Folds in Perpendicular Orientation at 400 ^{o}C

During the forging operation some folds are observed as seen in Figure 4.15 when the operation reaches 80 % and 85 % of the stroke. Folds are the important product failure type and must be avoided.

b) Billet at Horizontal Position

In this orientation, the billet is placed in the die at the horizontal position as shown in Figure 4.16 and the analysis is made for the single stroke.

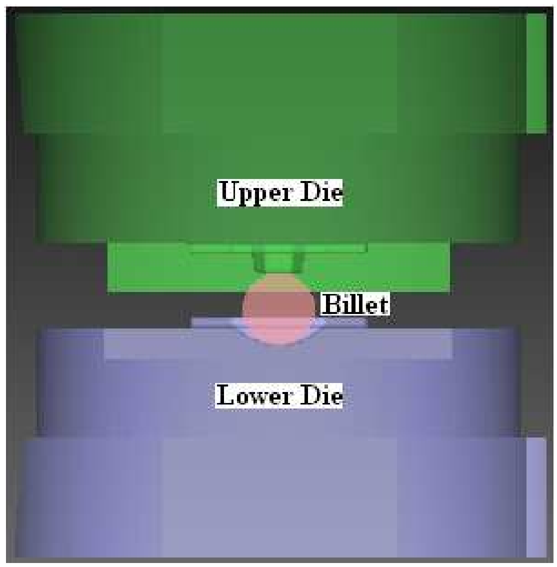

Figure 4.16 Horizontal Orientation for Single Operation

In this type of orientation, die filling and the flash distribution are obtained as in Figure 4.17. In this orientation, flash distribution is more uniform especially at the corners rather than the perpendicular orientation of the billet. However, as seen in Figure 4.18, during the forging operation, folds occur also for this type of single operation and therefore, it has been decided that at least one preform stage is required before the finish forging stage.

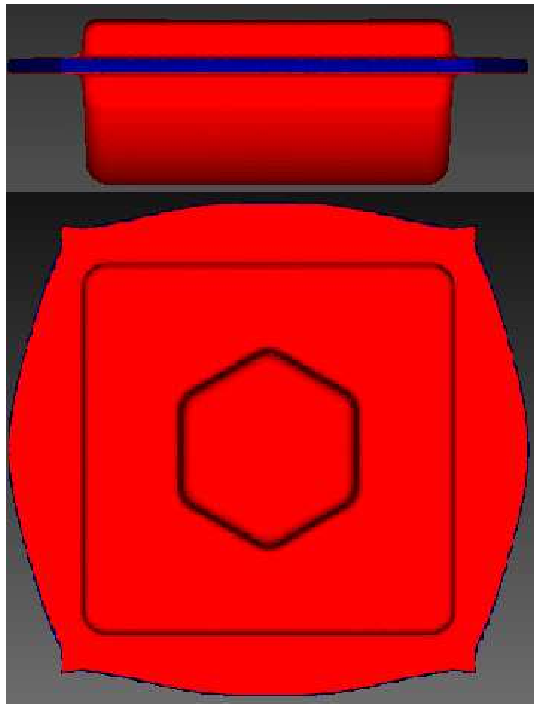

Figure 4.17 Die Filling for Horizontal Orientation at 400 ^{o}C

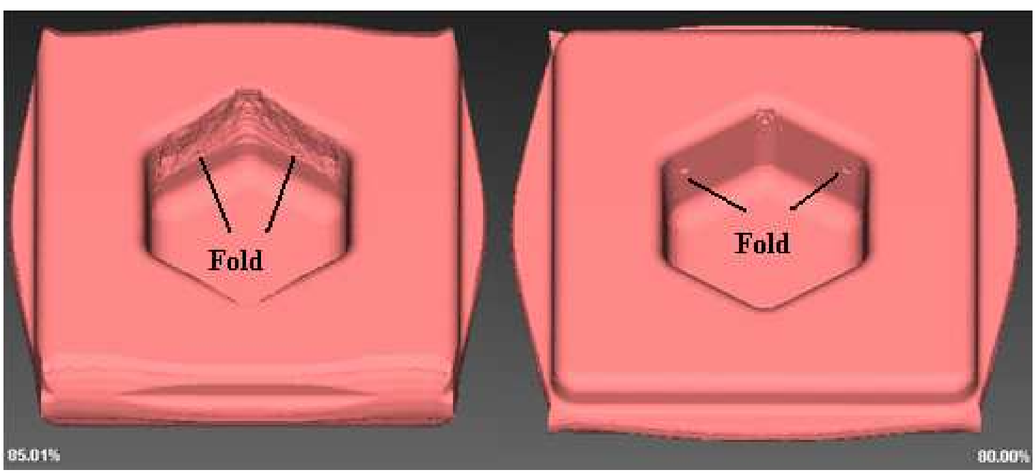

Figure 4.18 Folds in Horizontal Orientation at 400 ^{o}C

4.5.2 Two Stages Forging Operation

Open die upsetting is modeled as the preform stage for the two stages forging operation since cost of the open die used in upsetting is cheaper than the closed die. 3-D model of the upsetting dies which are the same with each other is given in Figure 4.19.

In design of the upsetting dies, it is considered that height of the upset part is more than the height of the finish part and cross-sectional area and lateral dimensions of the upset part are less than cross-sectional area and lateral dimensions of the finish part. Since, the finish part has height of 18 mm, height of the upset part is taken as 18.5 mm and dies are modeled according to this height. Because of this reason, the upper and the lower upsetting dies are taken as 90.75 mm in height and summation of die heights and gap between upper and lower upsetting dies at the bottom dead center is 200 mm. External geometry of the dies are modeled according to die holder geometry given in Figure 4.7 and Figure 4.8. Detailed technical drawing of upsetting dies are given in Appendix C.

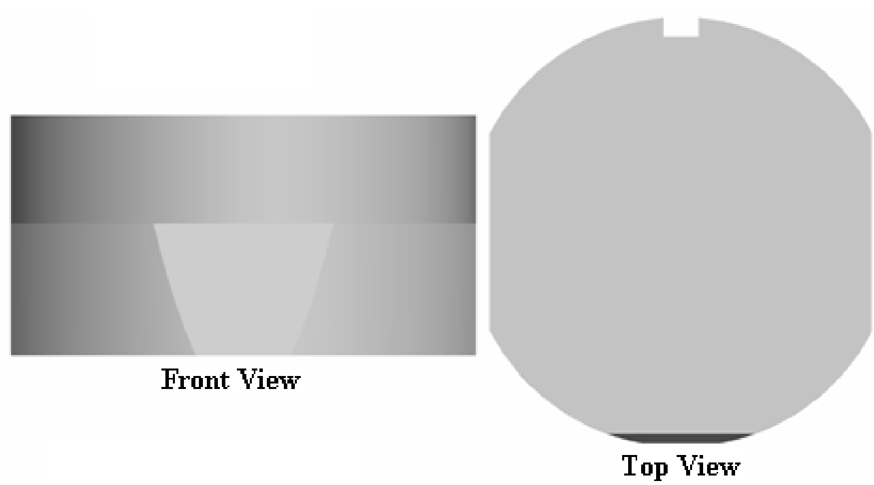

Figure 4.19 3-D Model of Upsetting Dies

Finite volume analysis of the two stages forging process is performed since the folds are observed during the single stage forging process. In two stages forging operation, again two different orientations of the billet are thought and the analysis are made.

a) Billet at Perpendicular Position on the Upsetting Die

In this orientation of billet, the billet is firstly placed on the upsetting die at the perpendicular position and upsetting operation is made and then the finish forging operation is performed in the finish die. Position of the billet on the upsetting die and the finish die are shown in Figure 4.20.

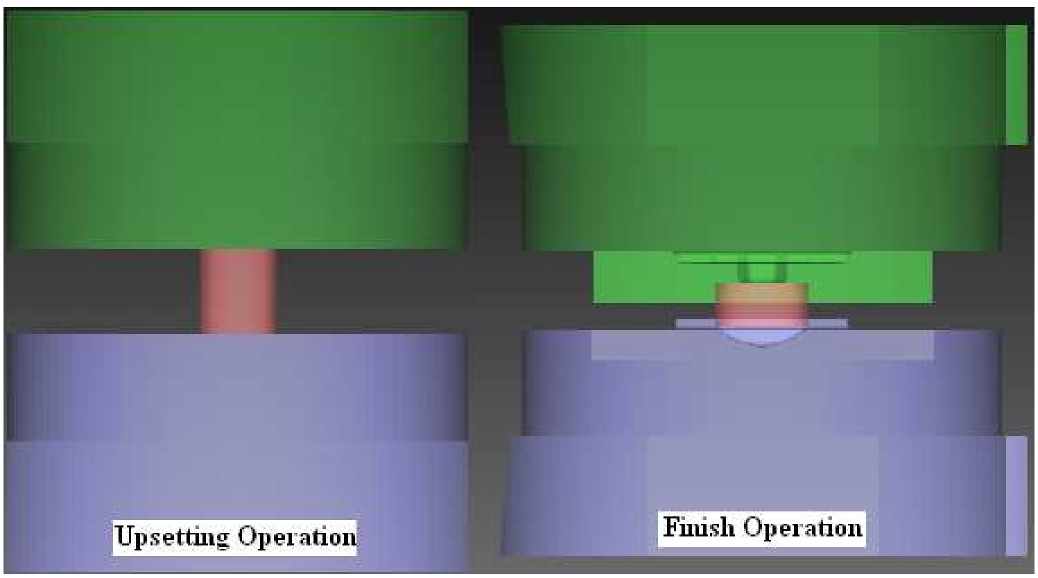

Figure 4.20 Perpendicular Orientation for Two Stages Operation

In this orientation, the billet is firstly upset to 18.5 mm in height and the maximum diameter become almost 40 mm at the middle of the upset part since barreling occurs in upsetting as shown in Figure 4.21.

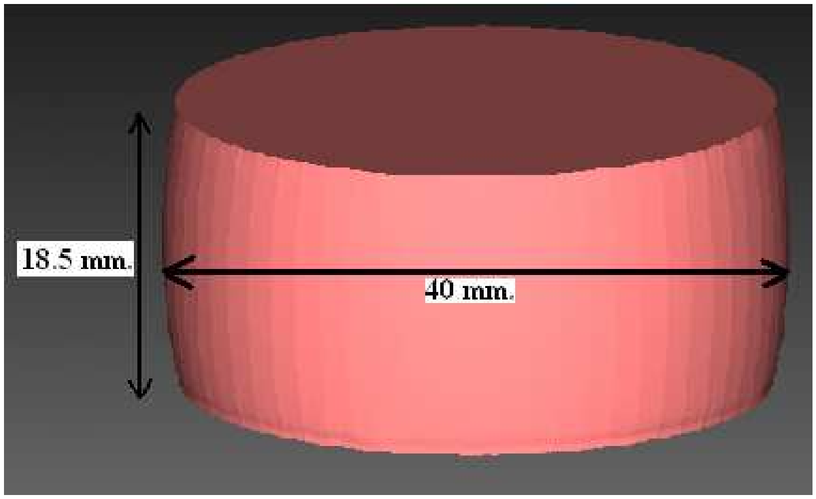

Figure 4.21 Billet Dimension after Upsetting Operation for Perpendicular Position

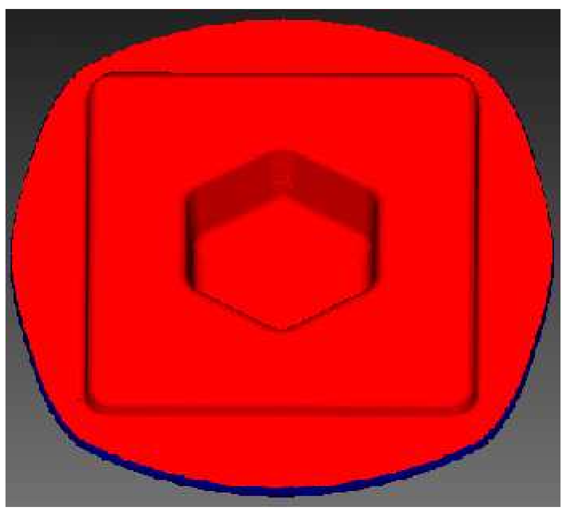

Figure 4.22 Die Filling for Perpendicular Orientation in Two Stages Forging Operation 400 ^{o}C

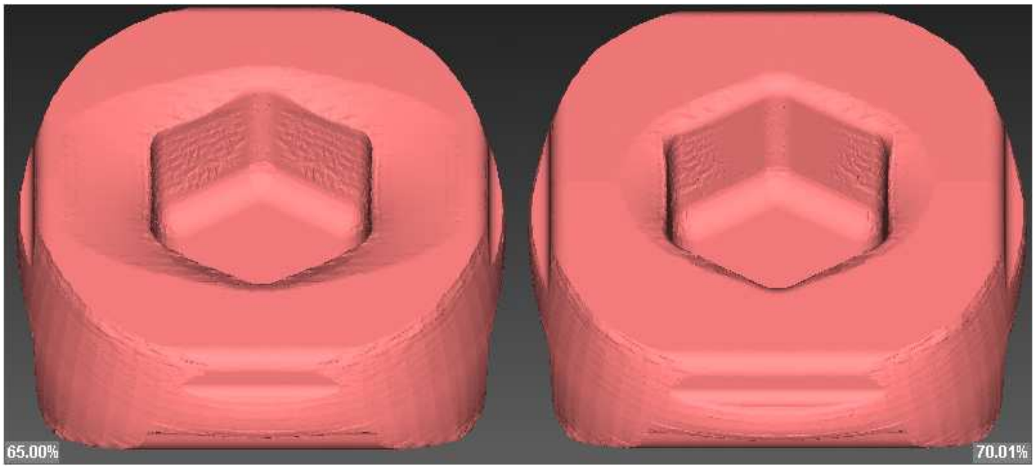

Figure 4.23 Observation of No Folds in Perpendicular Orientation in Two Stages Forging Operation at 400 ^{o}C

After the upsetting operation is completed, the preform is forged in the finish dies. The finish die is completely filled as seen in Figure 4.22 and there is not any folds in this two stages operation as shown in Figure 4.23. However, as mentioned previously, in this type of orientation, the flash formation at the corners are not uniform. Also, the maximum diameter of upset part after upsetting operation is nearly same as the width of the finish part and this violates the rule of preform design. For these reasons, the horizontal orientation in two stages forging operation is also performed.

b) Billet at Horizontal Position on the Upsetting Die

In this orientation, the billet is firstly placed on the upsetting die at the horizontal position and the upsetting operation is applied and then the finish forging operation is performed in the finish die. Position of the billet on the upsetting die and the finish die are shown in Figure 4.24. In this orientation, the billet is firstly upset to 18.5 mm in height and width of the part in x-direction becomes 37.4 mm and width of the part in y-direction becomes 38.5 mm as shown in Figure 4.25.

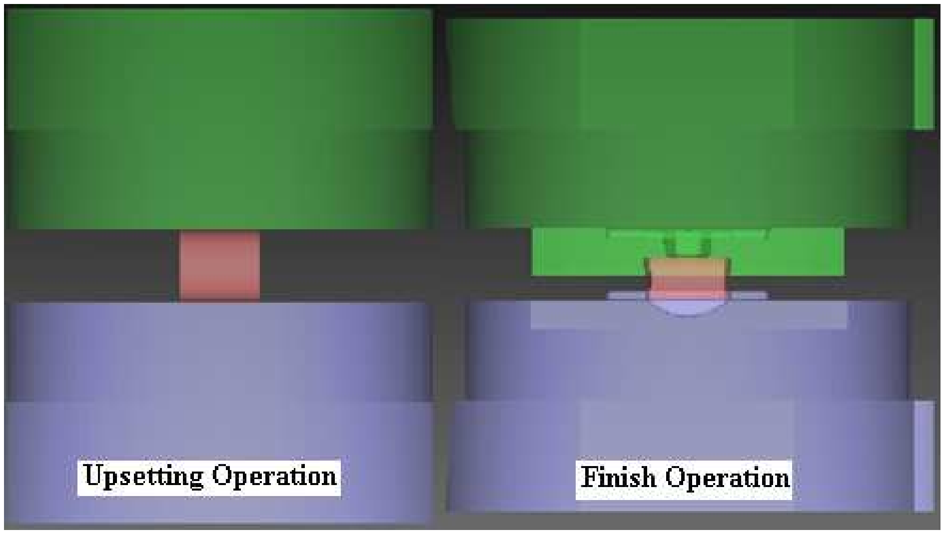

Figure 4.24 Horizontal Orientation for Two Stages Operation

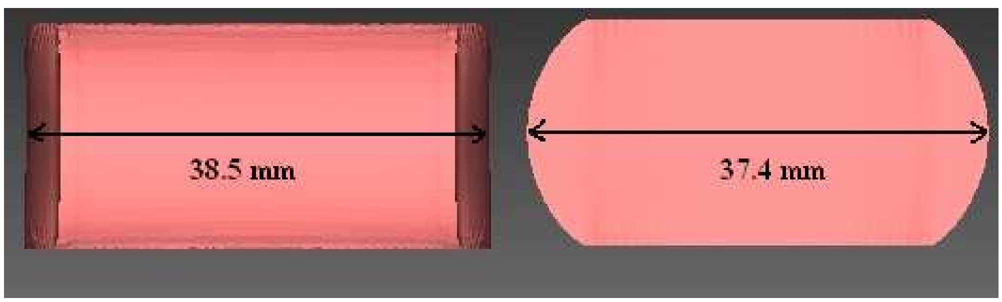

Figure 4.25 Billet Dimension after Upsetting Operation for Horizontal Position

The die is completely filled in the finish operation as seen in Figure 4.26 and the flash distribution is more uniform than the perpendicular position mentioned previously. Also, the upset part dimensions are more suitable in horizontal orientation for the rule of the preform design than the perpendicular orientation. Meanwhile, from Figure 4.27, no fold is observed during the forging operation. Although both two stages are suitable for the forging operation, the horizontal orientation of the billet is chosen as the forging operation and the experiments are done according to the horizontal orientation of the billet for the reasons stated above.

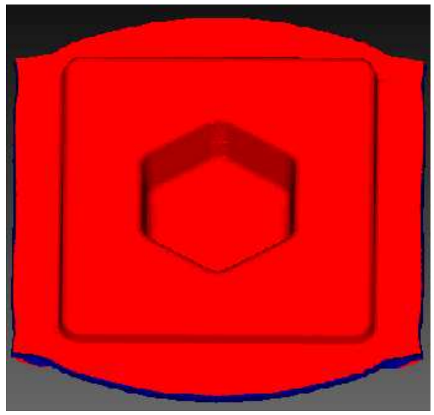

Figure 4.26 Die Filling for Horizontal Orientation in Two Stages Forging Operation at 400 ^oC

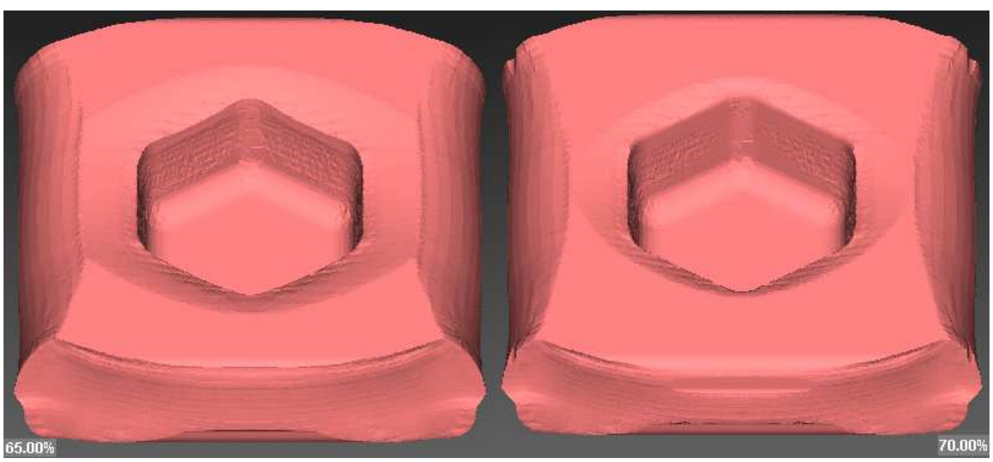

Figure 4.27 Observation of No Folds in Horizontal Orientation in Two Stages Forging Operation at 400 ^oC

4.5.3 Simulation Results

In the simulations, 25512 finite volume elements are created for the upsetting operation while 24997 finite volume elements are created for the finish operation and the simulation time is measured nearly 3 hours 15 minutes for the upsetting operation while the simulation time is nearly 10 hours for the finish operations for a workstation with 3 GHz (x2) processor and 4 GB RAM.

After simulation of the forging operation, the force requirement, stress values and part temperature after the upsetting and the finish forging operations can be obtained by the finite volume program. As stated previously, the simulations have been made for the forging temperatures of 375 ^{o}C, 400 ^{o}C and 425 ^{o}C and simulation results are given in Figure 4.28-4.45.

In the die force diagrams, the force is given as a function of time. For the finish operation, the force slightly increases initially since at the beginning of the finish operation upsetting occurs and after that point, the force increases dramatically and reaches the maximum value to complete the forming. However, for the upsetting operation, force increases almost linearly. The maximum force values are lower in upsetting as seen from the force diagrams.

In the effective stress distribution figures, the red color always represents the higher effective stress values and the blue the lowest value. As seen from the effective stress distribution figures, the maximum effective stress occurs in the loading regions where the lower and the upper die contact with the workpiece at first time as expected. The maximum effective stress values are relatively higher in finish operation since deformation is much more in finish operation.

In the temperature distribution figures, it is seen that the maximum temperature occurs at the zones where the maximum deformation happens throughout the forging operation. The temperature values at the end of the upsetting process is directly transfered to the finish operation as seen in the figures. In Table 4.6 and Table 4.7, simulation results are tabulated for the initial billet temperatures of 375 ^{o}C, 400 ^{o}C and 425 ^{o}C. As seen from the given tables as the temperature of the initial billet increases, the maximum die forces and the maximum effective stress values decreases as expected. However, the maximum temperature of the forged part increases when the initial temperature of the billet increases as given in Table 4.7. However, temperature raise during the upsetting and the finish operations are in the desired range and melting of alumnium due to the temperature raise is not expected during the experiments.

Table 4.6 Maximum Die Force and Effective Stress for Different Forging Temperatures of Al 7075

Temperature of the Billet (^oC)	Maximum Die Force for Upsetting (Ton)	Maximum Die Force for Finish (Ton)	Maximum Effective Stress for Upsetting (MPa)	Maximum Effective Stress for Finish (MPa)
375	7.6	31.9	101.4	112.0
400	7.4	29.2	100.2	108.7
425	6.2	26.8	88.4	94.7

Table 4.7 Maximum Part Temperatures for Different Forging Temperatures of Al 7075

Temperature of the Billet (^oC)	Maximum Part Temperature for Upsetting (^oC)	Maximum Part Temperature for Finish (^oC)
375	392.9	429.1
400	417.2	447.1
425	439.1	464.0

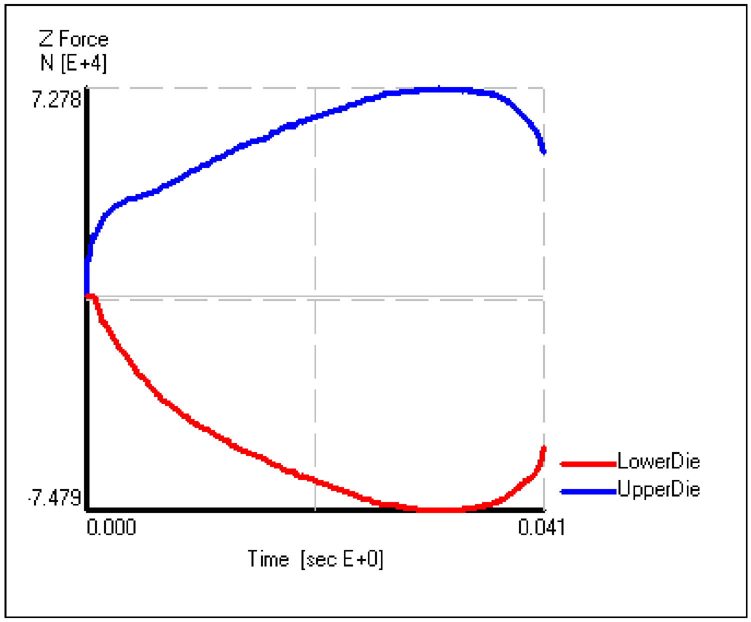

Figure 4.28 Die Force for Upsetting Operation of Aluminum Alloy 7075 at 375 ^{o}C

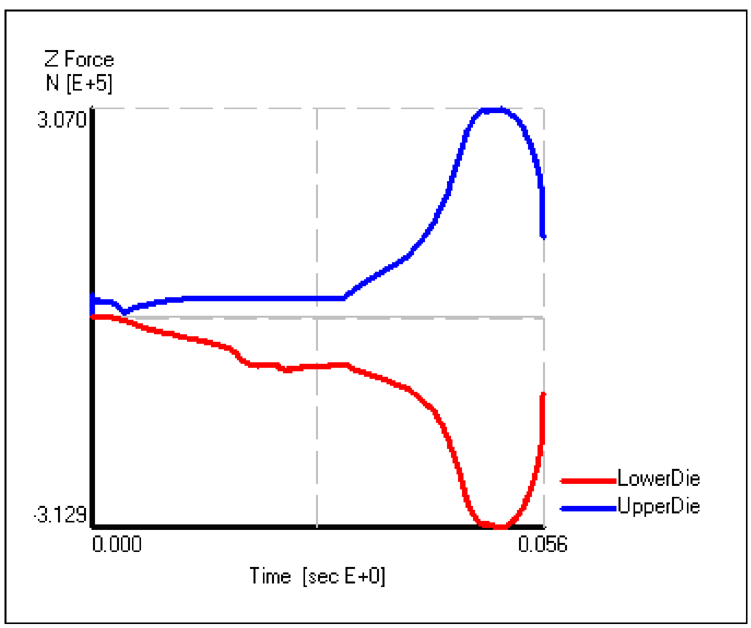

Figure 4.29 Die Force for Finish Operation of Aluminum Alloy 7075 at 375 ^{o}C

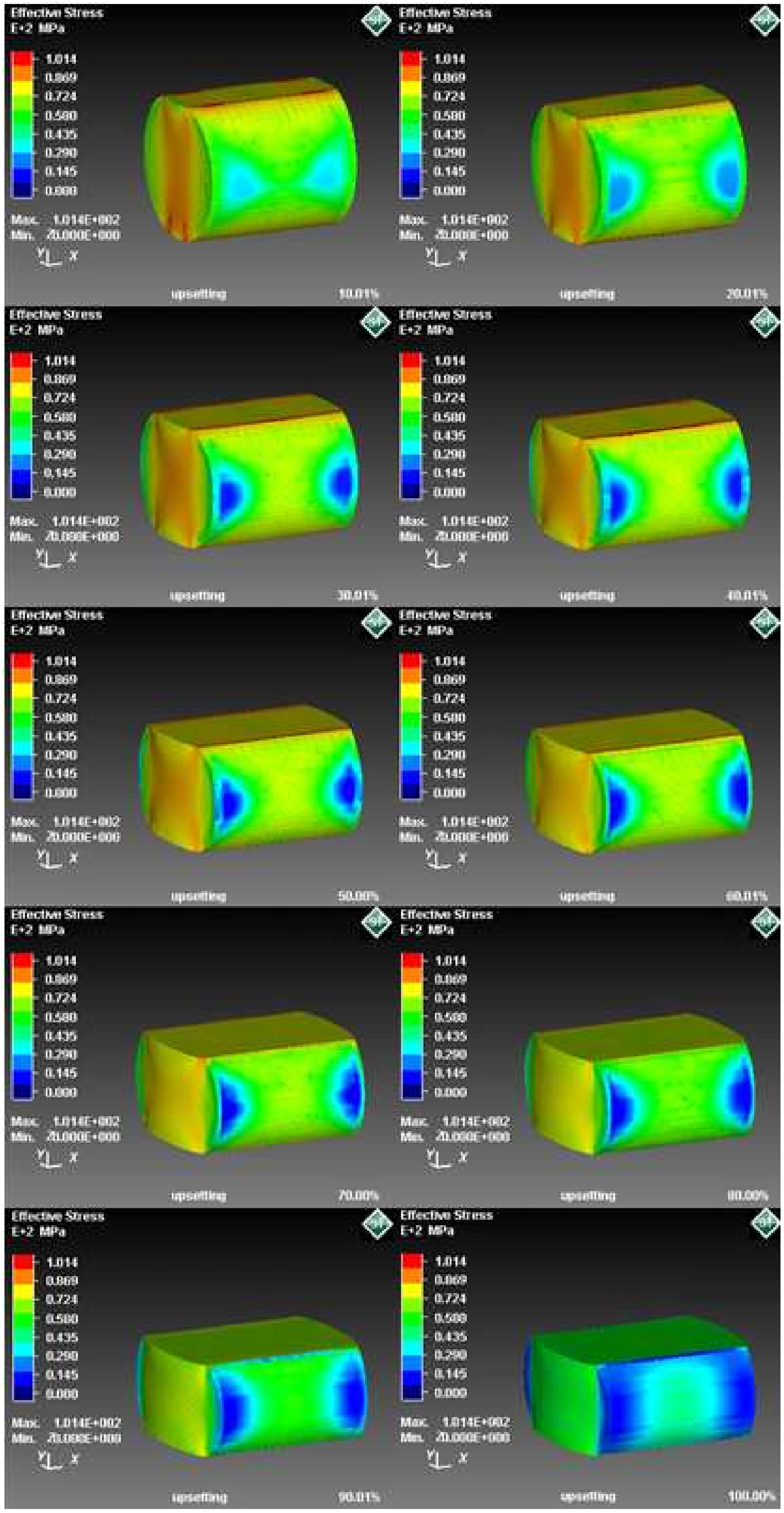

Figure 4.30 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 7075 at 375 ^{o}C

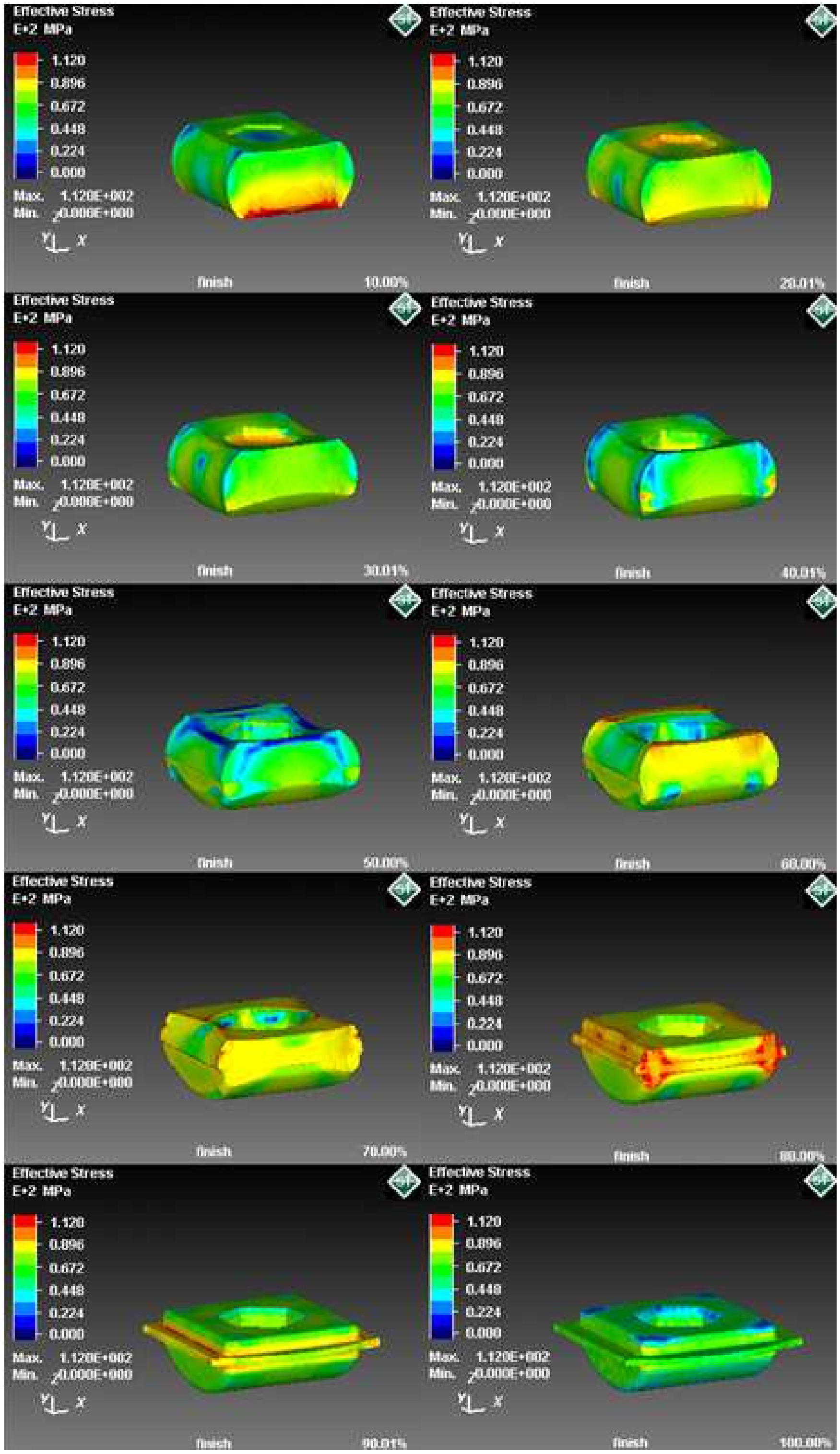

Figure 4.31 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 7075 at 375 ^{o}C

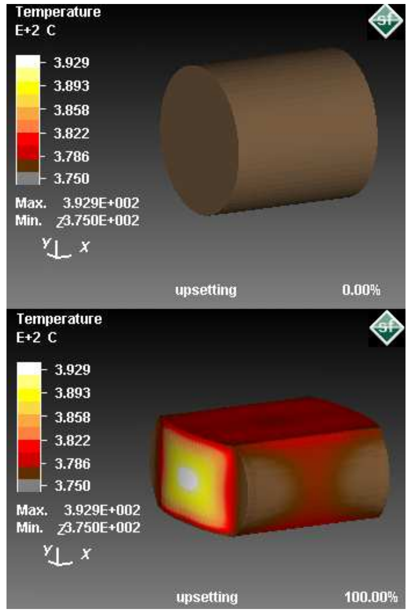

Figure 4.32 Temperature Distribution for Upsetting Operation of Aluminum Alloy 7075 at 375 ^{o}C

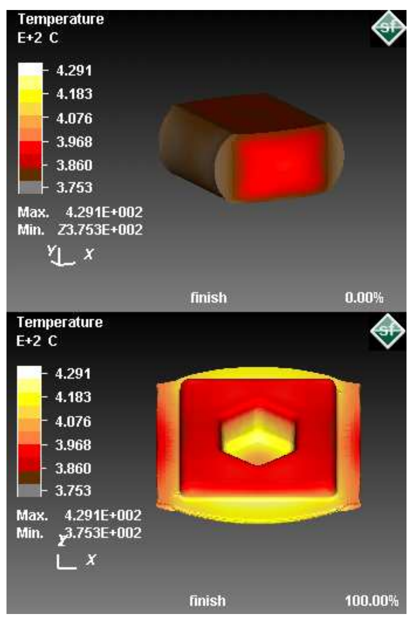

Figure 4.33 Temperature Distribution for Finish Operation of Aluminum Alloy 7075 at 375 ^{o}C

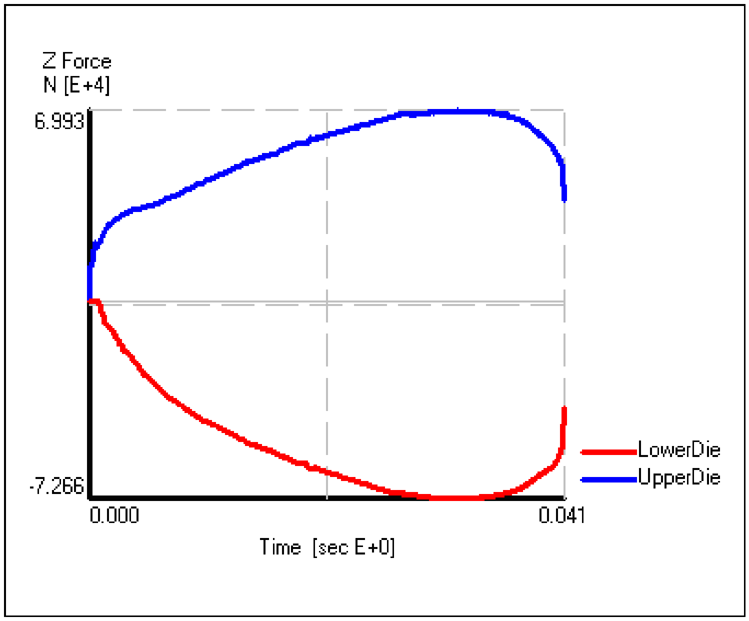

Figure 4.34 Die Force for Upsetting Operation of Aluminum Alloy 7075 at 400 ^{o}C

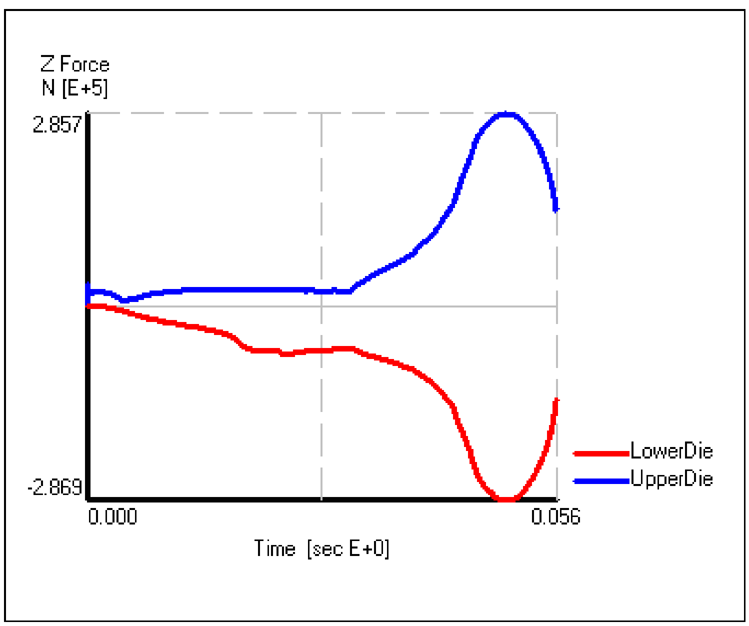

Figure 4.35 Die Force for Finish Operation of Aluminum Alloy 7075 at 400 ^{o}C

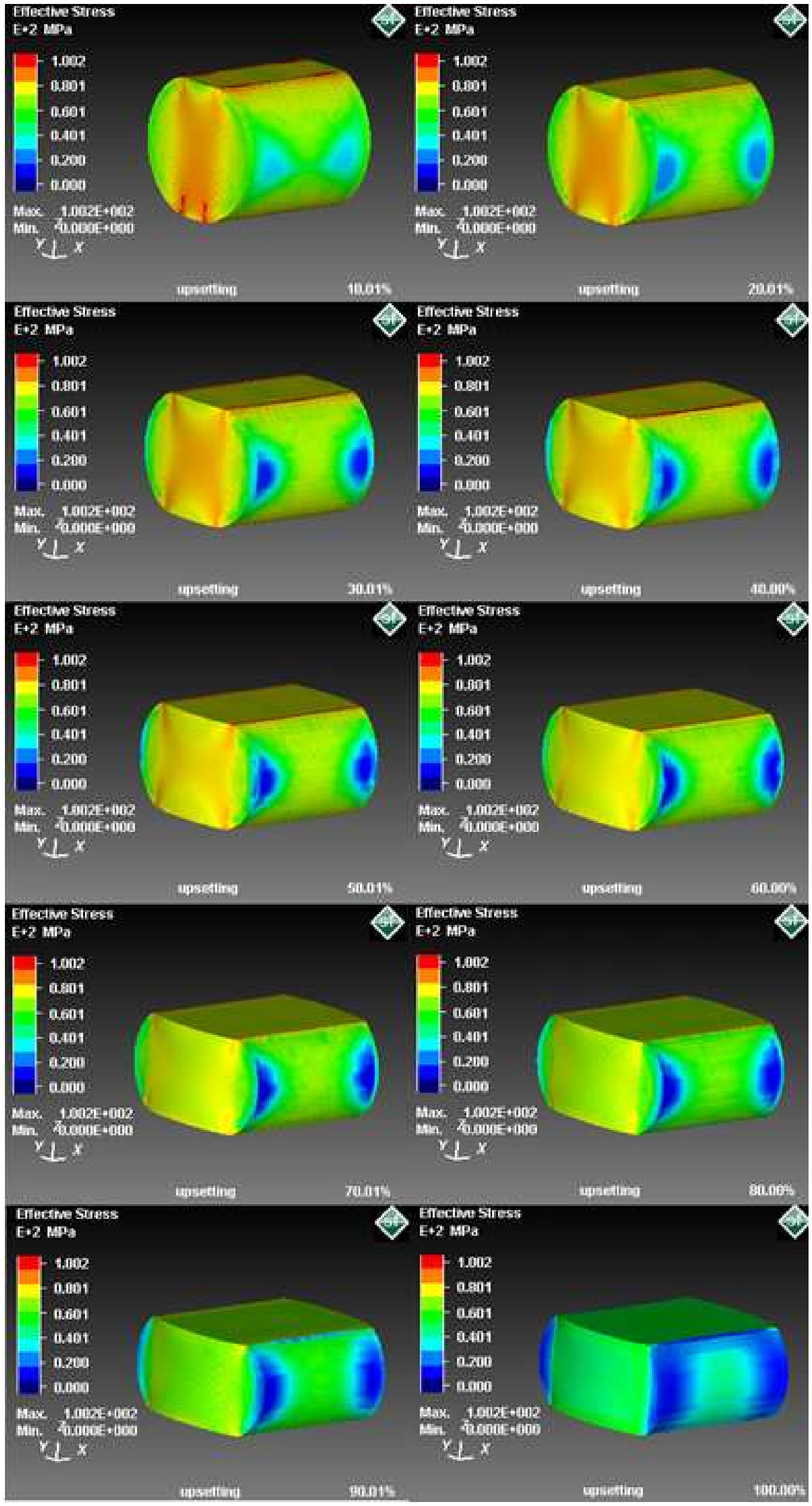

Figure 4.36 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 7075 at 400 ^{o}C

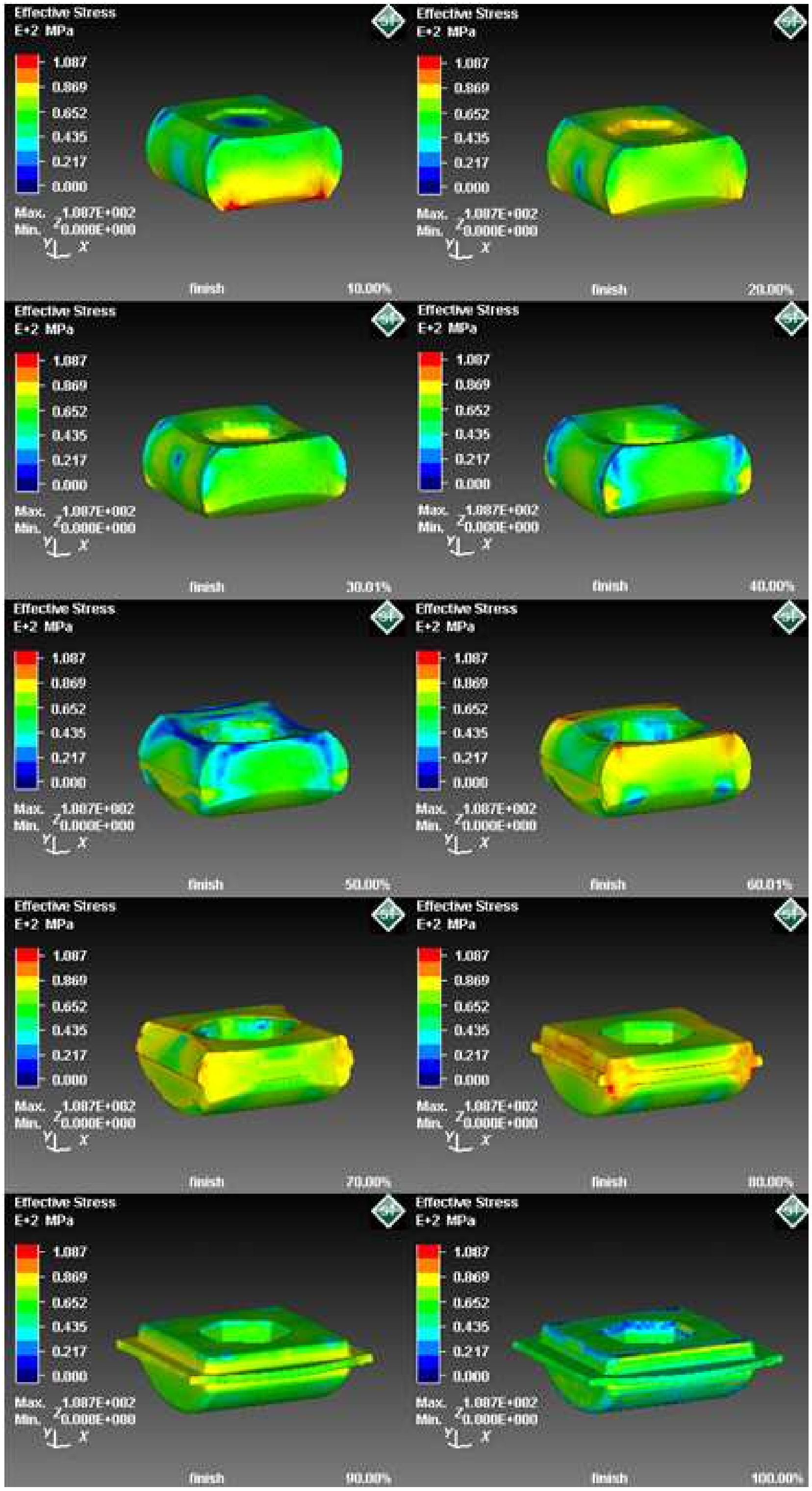

Figure 4.37 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 7075 at 400 ^{o}C

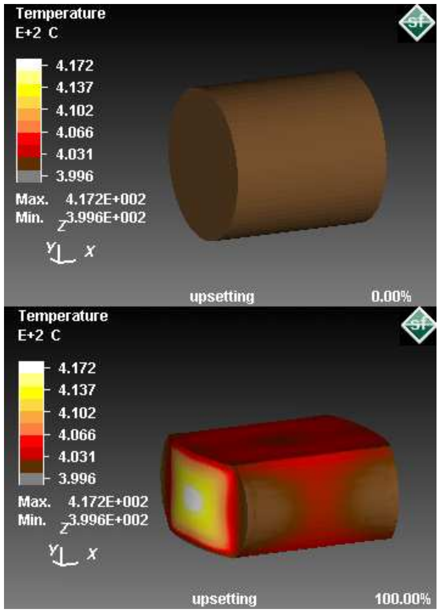

Figure 4.38 Temperature Distribution for Upsetting Operation of Aluminum Alloy 7075 at 400 ^{o}C

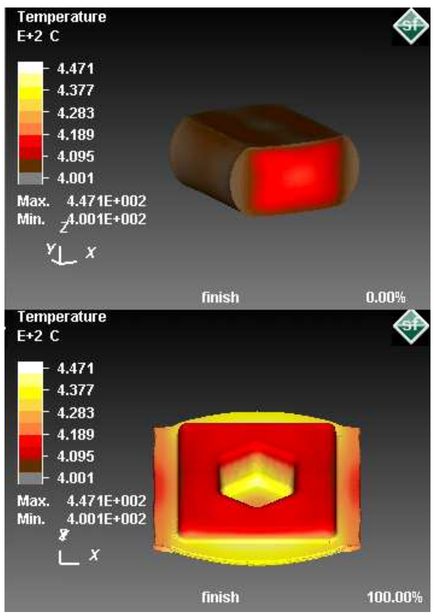

Figure 4.39 Temperature Distribution for Finish Operation of Aluminum Alloy 7075 at 400 ^{o}C

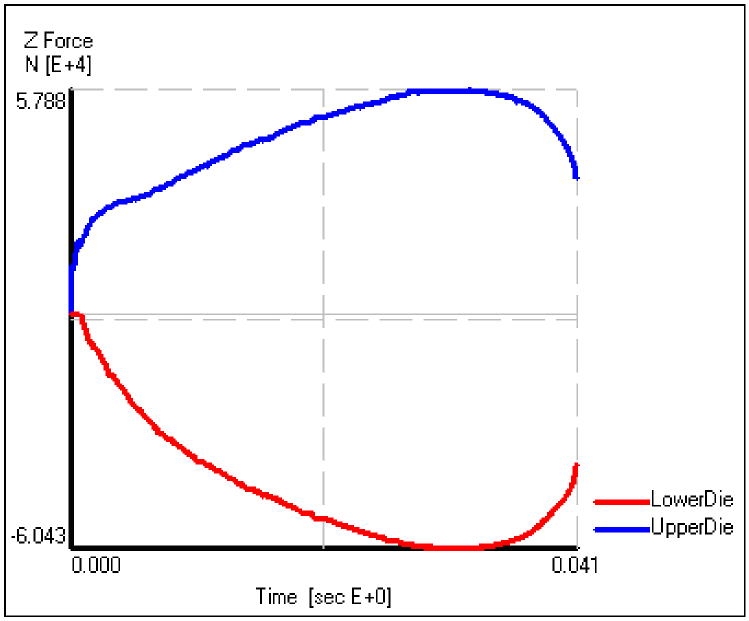

Figure 4.40 Die Force for Upsetting Operation of Aluminum Alloy 7075 at 425 ^{o}C

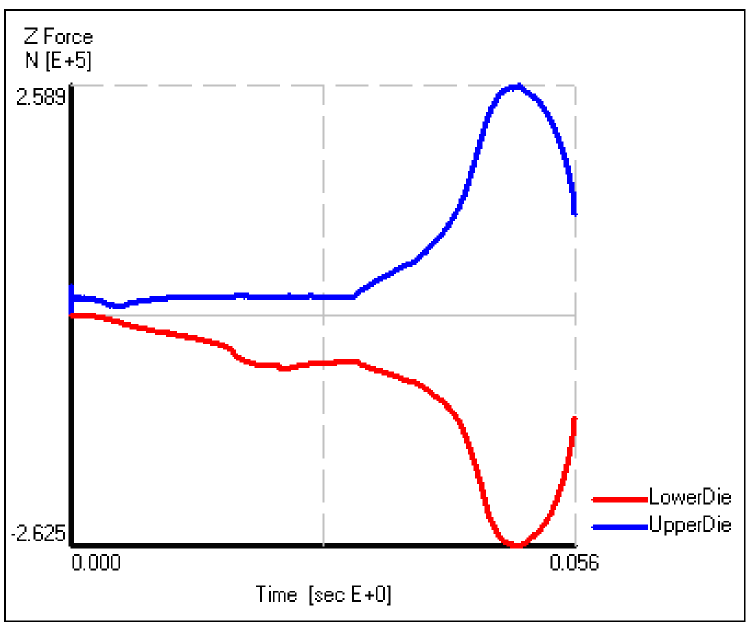

Figure 4.41 Die Force for Finish Operation of Aluminum Alloy 7075 at 425 ^{o}C

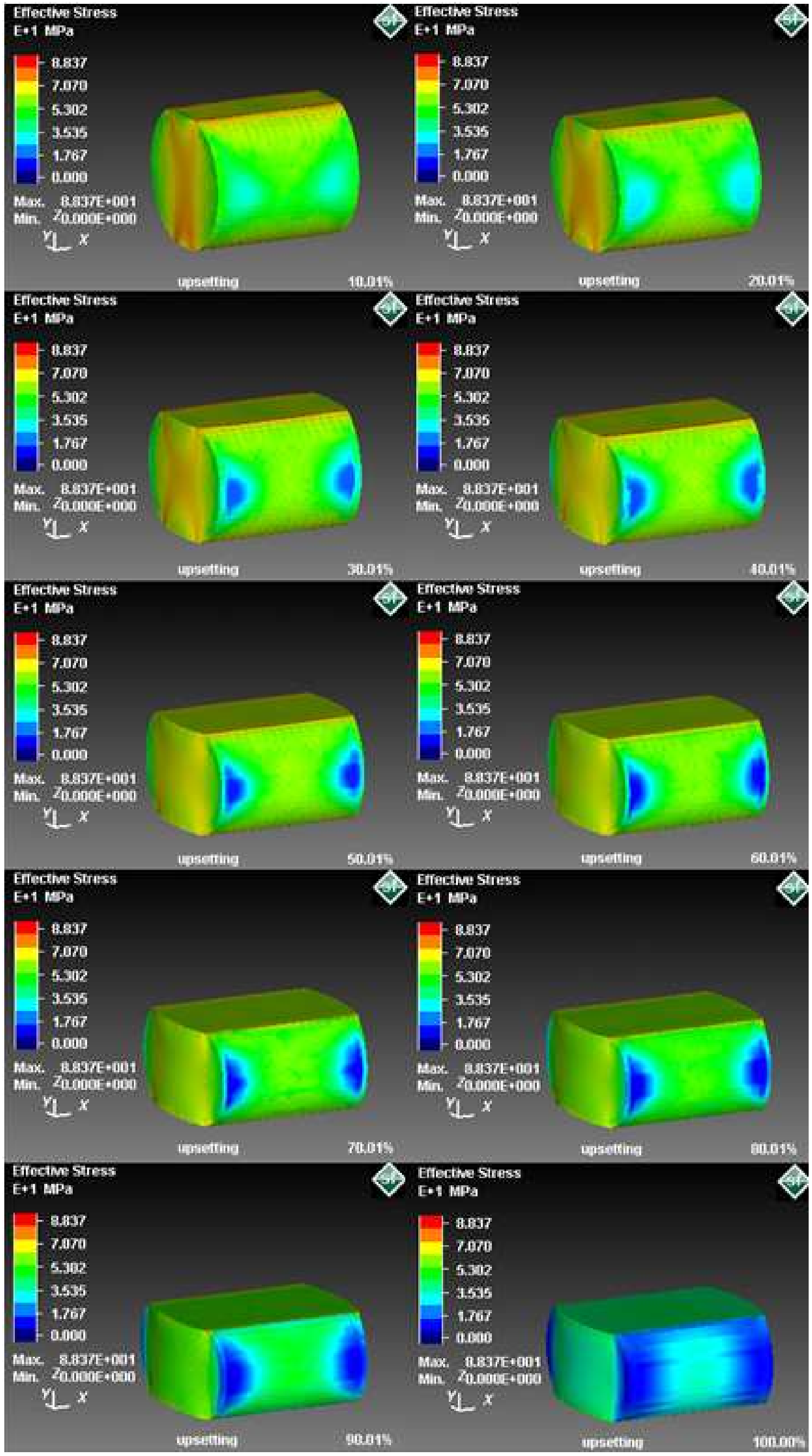

Figure 4.42 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 7075 at 425 ^{o}C

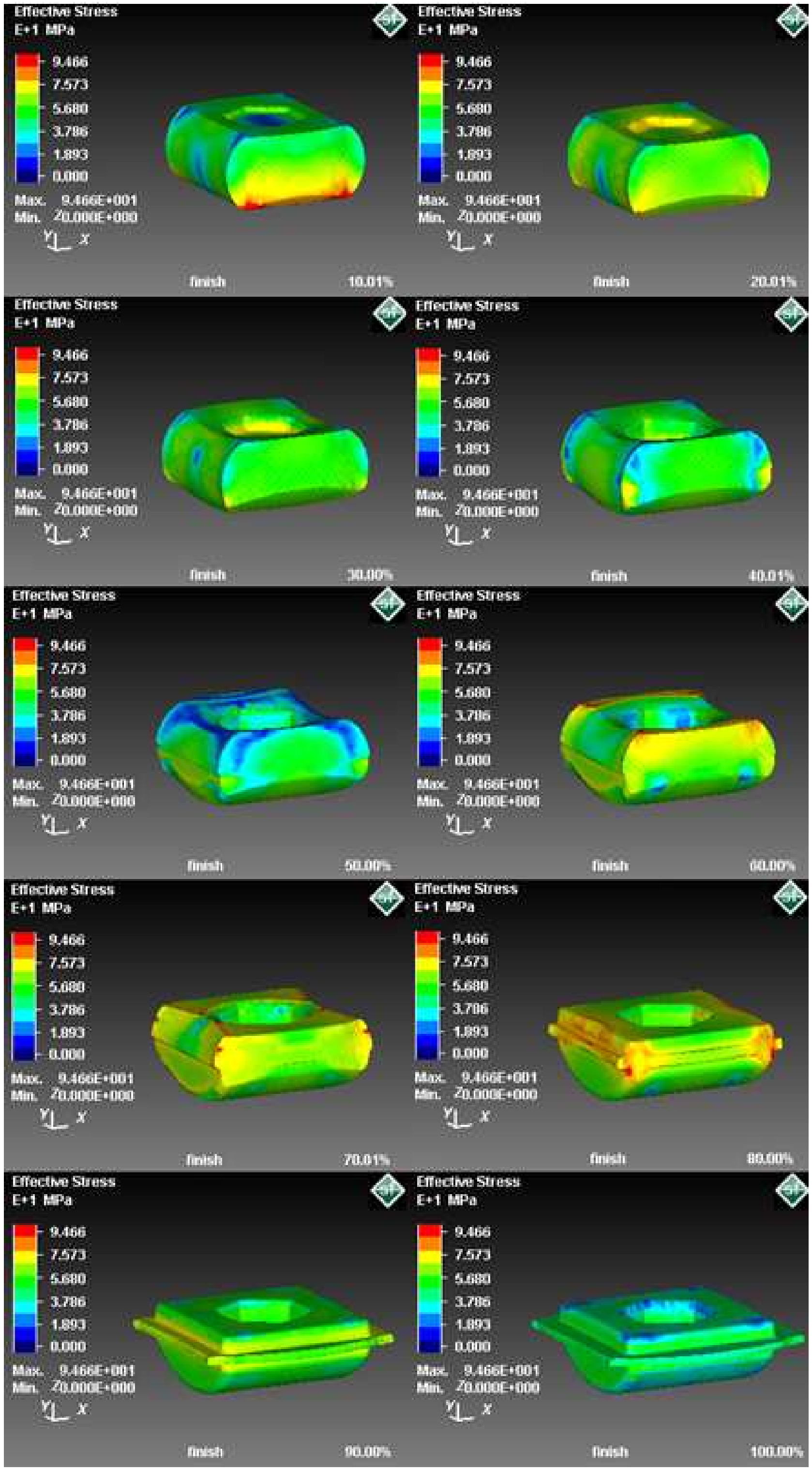

Figure 4.43 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 7075 at 425 °C

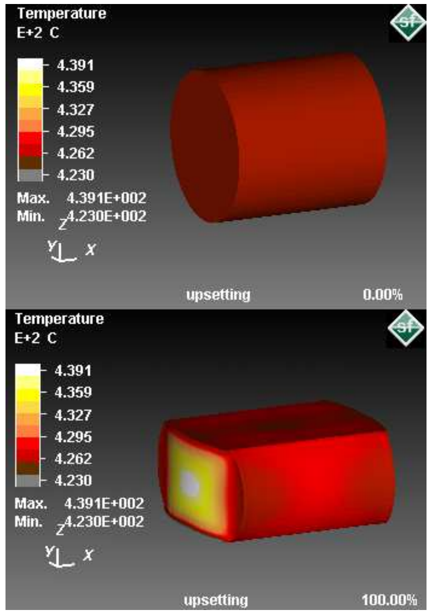

Figure 4.44 Temperature Distribution for Upsetting Operation of Aluminum Alloy 7075 at 425 ^{o}C

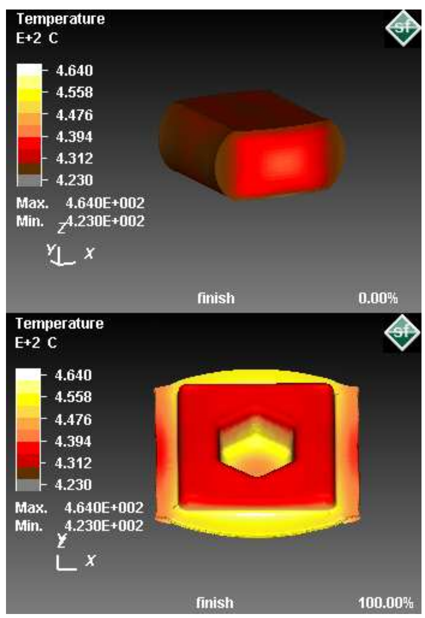

Figure 4.45 Temperature Distribution for Finish Operation of Aluminum Alloy 7075 at 425 ^{o}C

CHAPTER 5

MANUFACTURING OF THE FORGING DIES AND EXPERIMENTS OF ALUMINUM FORGING PROCESS

Design of the upsetting and the finish dies has been described in detailed according to the 10 MN SMERAL mechanical press die holder geometry and; the finite volume simulation and their results have been given in Chapter 4. In this chapter, initially manufacturing of the upsetting and the finish dies will be mentioned and then the experiments based on the simulation results for the 7075-0 type of aluminum alloy will be explained with the forging equipment used during experiments.

5.1 Manufacturing of the Forging Dies

The upsetting and finish dies have been manufactured in METU-BILTIR Center CAD/CAM Laboratory with the proper CAD/CAM approach. For the manufacturing of the dies, "Dievar" is selected as the die material [51]. Detailed properties of the "Dievar" are given in Appendix D. After selecting the die material, raw die materials are turned according to the die holder dimensions and the die after the turning operation is given in Figure 5.1.

After the turning process, MAZAK Variaxis 630-5X high-speed vertical milling machine are used for the production of the forging dies. NC codes, e.g. G-codes, for manufacturing of the dies are obtained by using the manufacturing module of the PRO/ENGINEER Wildfire 3.0 [44] and then these codes are loaded to MAZAK Variaxis 630-5X through the computer interface. After the codes are loaded to machining center, dies are produced according G-codes and the die in the machining process in the high-speed vertical milling machine can be seen in Figure 5.2.

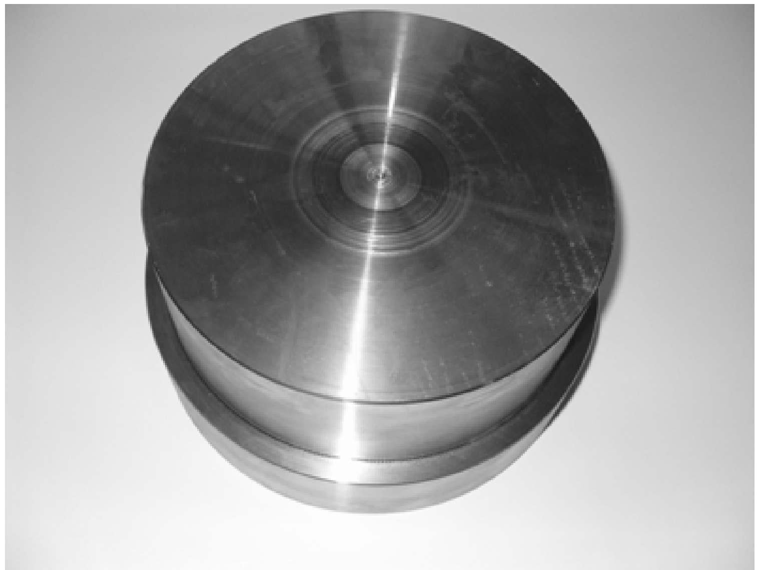

Figure 5.1 Die after Turning Operation

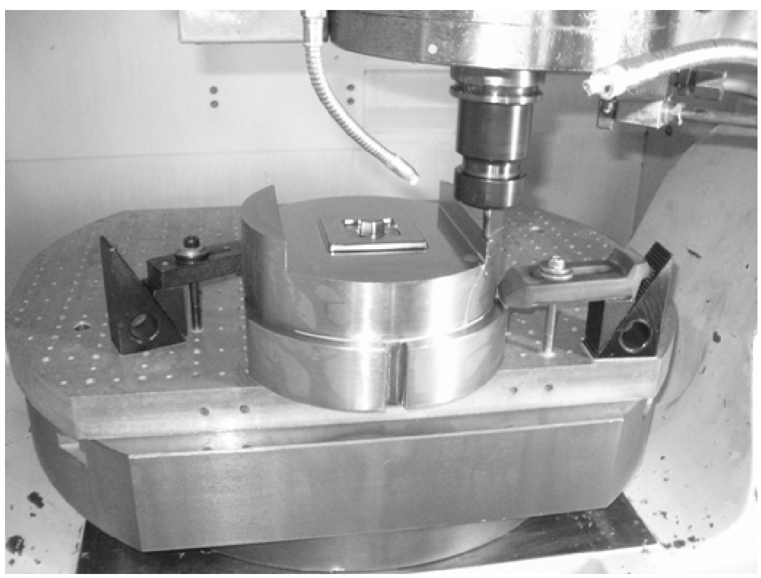

Figure 5.2 Machining of Dies in MAZAK Variaxis 630-5X

Views of lower finish die, upper finish die and upsetting die after machining processes are given in Figure 5.3, Figure 5.4 and Figure 5.5 respectively.

After the production of the dies has been completed, they are sent for heat treatment. Heat treatment should be done since high loads are applied on the die during the forging operation and soft raw die material without heat treatment may cause failure. Details of the heat treatment process, hardness value obtained by using the portable hardness measuring instrument in METU-BILTIR Center Forging Research and Application Laboratory and true stress-true strain curves for different temperatures for the Dievar tool steel obtained after the creep experiment in the METU Central Laboratory are given in Appendix D.

Figure 5.3 Photograph of Upper Die

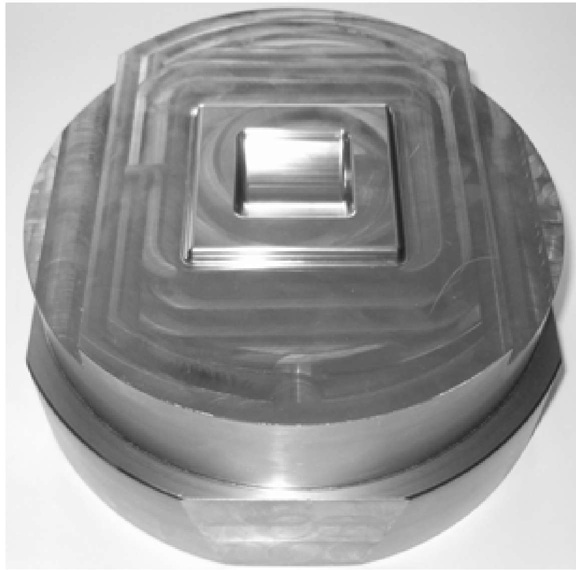

Figure 5.4 Photograph of Lower Die

Figure 5.5 Photograph of Upsetting Die

5.2 Preparation for the Experiments

Before the experiments, some preparations are made both for the experiment setup and the initial billets. Billets are cut to the desired length in the sawing machine and their dimensions are measured by the digital calipers and weighed by using precision balance with the tolerance of the ± 0.01 gram as can be shown in Figure 5.6.

Figure 5.6 Photograph of Billet on Precision Balance

Dimensions of the billets and their weights before the forging process are given in Table 5.1. In Table 5.1, some variations in the dimensions of the billet can be observed and because of these variations also weights of the billets show variations. Reasons of these variations are basically cutting condition of the sawing machine and diameter variation of bought aluminum products.

The set up begins with the upper upsetting and the upper finish dies with the aid of the hydraulic jack. The upper dies are raised to the desired height with the hydraulic jack and then the upper die is aligned that the key on the die holder housing will fit into the key way on the upper die to prevent the rotational motion. After that, the upper dies are fastened from the front taper and back side of the die with clamping elements and bolts. The hydraulic jack is downed and the set up of upper dies is completed. The lower dies are also set up with the same way of the upper dies. Lower dies are again initially aligned that the key on the die holder housing will fit into the key way on the lower die and then mounted from the front taper and back side of the die by using the clamping elements and bolts as can be seen from Figure 5.7. After the dies are properly set up, experimentation process begins.

Figure 5.7 Clamping of Lower Finish Die in Die Holder

Table 5.1 Billet Dimensions and Billet Weights

Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
1	30.03	32.06	63.30
2	29.99	32.12	63.38
3	30.06	32.21	63.70
4	30.06	32.19	63.62
5	29.99	32.12	63.38
6	30.00	32.09	62.97
7	30.05	32.01	63.07
8	30.06	32.05	63.45
9	30.10	32.20	64.19
10	30.10	32.15	63.80
11	29.95	32.40	64.29
12	29.96	32.20	63.84
13	30.00	32.01	63.20
14	30.02	32.01	63.37
15	30.02	32.10	63.46
16	29.95	32.36	64.31
17	30.05	32.16	63.95
18	30.02	32.45	64.15
19	30.04	32.15	63.76
20	30.07	32.21	64.05
21	30.04	32.39	64.39
22	30.02	32.03	63.66
23	29.96	32.25	63.88
24	30.00	32.07	62.94
25	30.03	32.10	63.48
26	30.10	32.15	63.80

Table 5.1 Billet Dimensions and Billet Weights (Continued)

Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
27	30.05	32.18	64.12
28	30.00	32.05	63.55
29	30.03	32.10	62.82
30	30.06	32.17	64.20
31	30.06	32.41	64.62
32	30.05	32.20	63.85
33	30.12	32.23	64.53
34	30.14	32.09	64.22
35	30.08	32.16	63.73
36	30.12	31.98	63.60
37	30.06	32.12	64.02
38	30.03	32.00	63.47
39	30.10	32.15	64.31
40	30.14	32.00	63.95
41	30.12	32.18	64.51
42	30.04	32.00	63.47
43	30.00	32.06	63.45
44	30.00	32.03	63.51
45	30.14	32.04	64.24
46	30.03	32.65	65.05
47	30.05	32.22	64.18
48	30.14	32.23	64.67
49	30.06	32.70	65.21
50	30.09	32.15	64.27

5.3 Experimentation of the Aluminum Forging Process

In the experiments, firstly billets are heated. Since melting point of the aluminum is low, it is difficult to control the temperature in the heaters like induction heater and the careful handling is required during the heating of billets. In heating stage, 125 KVA- 3000 Hz induction heater, which is available in METU-BILTIR Center Forging Research and Application Laboratory, is considered to use for heating and it was asked to the producer if this heater is suitable for the heating of aluminum billets or not. They suggested an additional induction heater with a hot frequency range of 500-1000 Hz although small diameter of aluminum billets can be heated at 3000 Hz frequency according to results of the heating experiments [52]. Due to small diameter of billets is used in this study; numerous heating operations are realized to see if the desired billet temperature is achieved or not. However, during the heating process, the aluminum billets reached its melting temperature before steady-state is achieved. Due to these difficulties, although it is not suitable for mass production, electrical box type furnace is used during the experiment. Illustration of the heated billet at the induction heater exit and pyrometer which measures the exit temperature of the billet is shown in Figure 5.8.

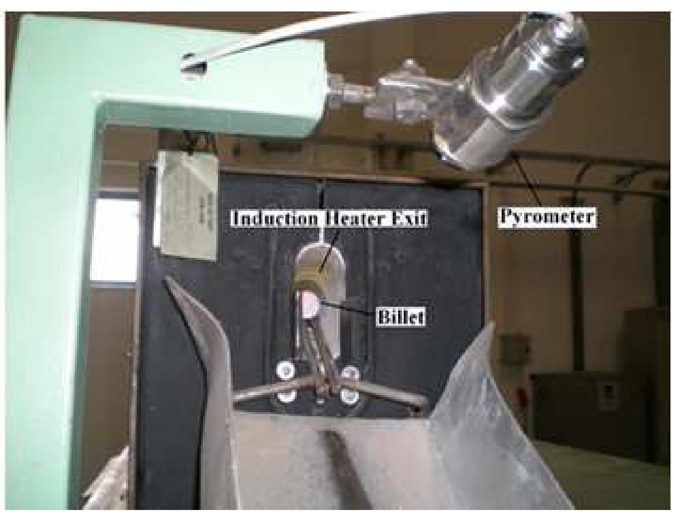

Figure 5.8 Heated Billet at the Induction Heater Exit

The billets are put into the Protherm chamber furnace and temperature of the furnace is set to the 450 ^{o}C. 450 ^{o}C is selected for the furnace temperature after the some test to achieve the desired temperature in press before forging. Photograph of the Protherm chamber furnace is given in Figure 5.9.

Figure 5.9 Photograph of the Protherm Chamber Furnace

While billets are put and waited in the furnace, heating of the dies is performed. Heating of the dies is critical in aluminum forging process since temperature ranges are low for aluminum forging and heating of the dies is required to prevent to cooling of the aluminum billet rapidly. Heating of the dies is realized by two LPG heater flame guns as shown in Figure 5.10. Temperatures of the dies are measured with a portable optical pyrometer every 15 minutes during the heating stage. There are three different optical pyrometers in METU-BILTIR Center Forging Research and Application Laboratory to measure the temperature in the experiments. But, during the experiments, only two of them have been used. The first one is a fixed pyrometer at the induction heater exit as can be pointed previously. The second one is the portable optical pyrometer with the temperature range -32 ^oC to 600 ^oC. The dies are heated to temperature value between 200 ^oC to 250 ^oC for 1.5 hours and during the experiment, temperatures of the dies are checked by the portable pyrometer after every 5 parts forged. Since the part is small when compared to the dies, dies cool during the forging process and if the die temperatures are below the desired range at the check points, dies are reheated to increase to their temperatures. Since the furnace is used during experiment, it is easy to reheat the dies without cooling of the billets and to control the desired die temperatures.

Figure 5.10 Heating of Dies by Using LPG Heater Flame Guns

Before the experimentation is begun, lubricant is sprayed to the dies with the aid of the air through the lubrication gun. In this experiment, colorless water soluble lubricant suitable for aluminum forging operation is used. Technical specification of this lubricant is given in Appendix E.

During the experiments, firstly single stage forging process is realized to verify the folds formation for single stroke operation in the finite volume simulations. In Figure 5.11, the fold formation obtained during experiment for the single stroke operation is shown. As seen from the figure, fold is at the half of the hexagonal hole like a line while at the corner of the hexagonal hole, it grows in volume. The fold formation in Figure 5.11 shows that it is necessary the make two stage operations. As a result, finite volume simulation gives very similar result with the experiments and finite volume programs are very suitable to predict the forging stages and forging behavior of the required operations.

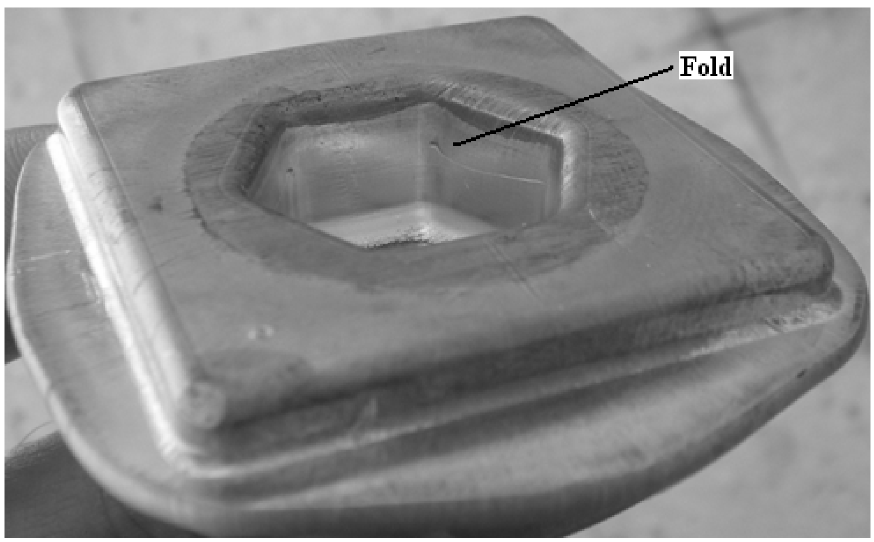

Figure 5.11 Fold Formation for Single Stroke Forging Operation

From Figure 5.12 to Figure 5.16, forging stages of the parts are given for the two stages forging operations. Billet is taken from the furnace and placed onto the upsetting die and after upsetting is completed, the finish operation is applied and finally parts are obtained as given in Figure 5.16.

Figure 5.12 A View of Heated Billet in the Furnace

Figure 5.13 A View of Heated Billet on the Upsetting Die

Figure 5.14 A View of the Part after Upsetting on the Finish Die

Figure 5.15 A View of Finish Part on the Finish Die

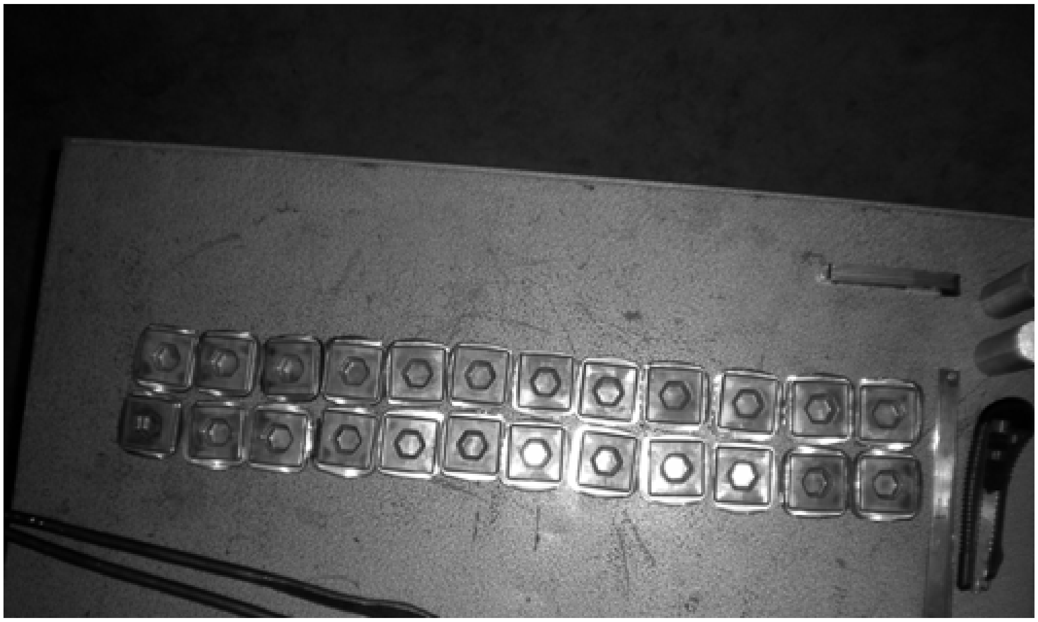

Figure 5.16 Views of Finish Parts

5.4 Results for the Experiment

During the experiments, the billet temperature before upsetting, part temperature after upsetting that is before finish and part temperature after finish are measured and tabulated. The die temperatures are also measured for every 5 parts to keep the die temperatures within the desired range. The data recorded during the experiment is given in Table 5.2. Furthermore, the forging part mass measured by precision balance to see if there is any scale formation or not after forging is cleaned, its dimensions and flash thickness are measured by using the digital calipers after the forging operation and its values are tabulated in Table 5.3.

Table 5.2 Experimental Data Recorded during Forging Process

Billet No	Billet Temperature Before Upsetting (^oC)	Part Temperature After Upsetting (^oC)	Part Temperature After Finish Forging (^oC)
1	390	420	441
2	395	430	460
3	404	425	434
4	408	435	450
5	392	420	467
6	375	402	436
7	393	420	436
8	385	420	435
9	405	433	445
10	410	425	435
11	370	392	401
12	365	384	391
13	383	409	454
14	415	422	467
15	402	427	448
16	383	417	445
17	387	417	440
18	389	402	437
19	401	421	434
20	370	385	410
21	405	420	445
22	396	409	440
23	375	390	415
24	402	415	440
25	396	420	455

Table 5.2 Experimental Data Recorded during Forging Process (Continued)

Billet No	Billet Temperature Before Upsetting (^oC)	Part Temperature After Upsetting (^oC)	Part Temperature After Finish Forging (^oC)
26	380	413	423
27	370	392	420
28	407	425	440
29	405	420	447
30	405	425	456
31	396	424	460
32	397	429	455
33	391	425	463
34	408	421	439
35	397	410	426
36	396	412	430
37	402	416	430
38	395	405	435
39	393	407	442
40	412	427	438
41	382	396	425
42	410	425	460
43	403	417	455
44	401	411	463
45	389	401	439
46	403	417	443
47	410	416	435
48	396	410	429
49	404	414	422
50	400	423	445

Table 5.3 Experimental Data Measured after the Forging Process

Billet No	Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexagonal Cavity Height (mm)	Hexagonal Cavity Length (mm)	Flash Thickness (mm)
1	63.29	18.05	40.07	40.07	11.98	18.97	1.86
2	63.36	18.04	40.09	40.08	11.97	19.05	1.82
3	63.70	18.05	39.98	39.97	11.97	19.04	1.81
4	63.62	18.17	40.08	40.08	12.00	18.98	1.90
5	63.36	18.12	40.20	40.18	12.04	19.08	1.88
6	62.97	18.01	40.07	40.07	12.02	19.08	1.80
7	63.06	18.15	40.12	40.12	11.98	19.13	1.88
8	63.44	18.00	39.98	39.98	12.01	19.01	1.82
9	64.15	18.19	40.09	40.09	11.98	19.14	1.88
10	63.80	18.33	40.22	40.22	12.07	19.07	1.95
11	64.27	18.09	40.05	40.05	11.98	19.02	1.81
12	63.84	18.05	40.09	40.09	11.97	19.05	1.84
13	63.19	17.95	40.05	40.05	12.03	19.01	1.76
14	63.37	18.05	40.07	40.07	11.90	19.10	1.85
15	63.44	18.07	40.06	40.07	11.96	19.05	1.86
16	64.31	18.05	40.04	40.01	12.01	19.02	1.83
17	63.90	18.07	39.97	39.99	11.95	18.95	1.85
18	64.12	18.12	40.04	40.08	12.07	19.05	1.87
19	63.75	18.25	40.00	40.00	11.94	19.03	1.94
20	64.03	18.01	39.98	39.98	11.99	19.01	1.79
21	64.36	18.18	40.11	40.11	12.03	19.12	1.96
22	63.66	18.09	40.07	40.07	12.05	19.07	1.88
23	63.88	18.04	40.01	40.01	11.95	19.01	1.82
24	62.93	18.31	40.03	40.03	12.07	18.95	2.01
25	63.48	17.99	40.02	40.02	12.01	18.99	1.79

Table 5.3 Experimental Data Measured after the Forging Process (Continued)

Billet No	Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexagonal Cavity Height (mm)	Hexagonal Cavity Length (mm)	Flash Thickness (mm)
26	63.80	18.02	40.07	40.07	11.98	19.03	1.85
27	64.12	18.04	39.99	40.00	12.01	19.01	1.86
28	63.55	18.09	40.03	40.03	12.05	19.04	1.87
29	62.81	18.00	40.01	40.01	11.99	19.04	1.80
30	64.20	18.02	40.05	40.05	11.98	19.04	1.78
31	64.62	18.03	39.88	39.88	11.97	19.01	1.75
32	63.83	18.02	39.98	39.98	11.99	19.03	1.78
33	64.53	18.05	40.06	40.09	12.02	18.97	1.85
34	64.21	18.06	40.12	40.14	12.06	19.02	1.87
35	63.73	18.10	40.08	40.08	11.96	19.09	1.89
36	63.64	18.13	40.05	40.05	12.06	19.07	1.91
37	64.02	18.08	40.13	40.13	12.00	19.10	1.85
38	63.47	18.14	40.07	40.07	11.95	19.02	1.93
39	64.31	18.21	40.01	40.01	12.06	19.09	1.96
40	63.97	18.19	40.02	40.01	11.99	19.07	1.96
41	64.51	18.25	39.98	39.98	12.06	19.07	2.04
42	63.48	18.03	40.02	40.02	12.01	19.05	1.81
43	63.45	18.01	40.01	40.01	11.98	19.03	1.79
44	63.50	18.01	40.02	40.02	12.03	18.98	1.80
45	64.22	18.01	39.99	39.99	11.96	19.01	1.81
46	65.02	18.05	40.05	40.07	12.08	18.98	1.86
47	64.17	18.08	40.01	40.04	11.96	18.99	1.86
48	64.57	18.04	40.08	40.09	11.97	19.03	1.85
49	65.20	18.09	40.12	40.12	12.09	19.07	1.87
50	64.28	18.11	40.13	40.15	12.06	19.10	1.90

5.5 Discussion of the Results

Table 5.2 gives the temperature of the forging part during the forging process. In the table, the maximum part temperature before upsetting is 415 ^{o}C while the minimum part temperature is 365 ^{o}C although billets are waited in the furnace at the 450 ^{o}C. These temperature differences arise from the heat loss of the billet to the ambient while carrying it and the temperature of the dies during the forging operation since aluminum losses heat very rapidly if the die temperature is below the desired temperature. Temperature can also be measured below the desired temperature due to time delay in measuring the temperature of the billet. However, results are mostly suitable with the finite element result which is listed in Table 4.7 although it is very difficult to control the temperature of the forging during the experiments. Average value of the temperature raise after upsetting is obtained as 16.5 ^{o}C in the finite volume simulation from Table 4.7 while average value of the temperature raise after upsetting during the experiments is obtained as 20 ^{o}C from Table 5.2. Also, average value of the temperature raise after finish operation is obtained as 46.5 ^{o}C in finite volume simulation while average value of the temperature raise after finish operation during the experiments is obtained as 44.5 ^{o}C. In addition, since the forging part temperature did not exceed the solidus temperature of 477 ^{o}C, there are no thermal defects observed during forging operations. As seen from the results, there are slight discrepancies between the numerical results and the experimental results due to the experimental setup such as heating of the dies, heating of the billets and the sensitivity of the pyrometer used during the forging operations. However, temperature values obtained during experiments are still within the temperature ranges obtained from the finite volume simulations mentioned above. Closer temperature values can be also obtained by measuring the temperature from the maximum temperature zones although it is difficult.

Furthermore, in Table 5.3, dimensions of the forging part and the forging part mass after the forging operation are given. When mass values of the Table 5.1 which gives mass of the billet before forging and Table 5.3 which gives mass of the part after the forging completed, it is easily seen that mass of the billet before forging and after forging are the same for the majority of the part. From the result of the mass of the billet before forging and part mass after forging, it can be concluded that there is no scale formation for the aluminum forging.

Figure 5.17 Forged Part Obtained in the Experiment

Additionally, dimensions of the forged part shown in Figure 5.17 according to Figure 5.18 are given in Table 5.3. Dimensions of the part are given as 40 mm for the length and width and 18 mm for the height with the ± 0.5 mm tolerances from the technical drawing of the part in Appendix A. From Table 5.3, the maximum width and length are measured as 40.22 mm while the minimum value is 39.88 mm and part height is between 18.33 mm and 17.95 mm. These dimensions are within the recommended tolerance limits. Also, hexagonal cavity height and length are 12 mm and 19 mm from the technical drawing of the part in Appendix A, respectively. During the experiments, the hexagonal cavity height is obtained between 11.90 mm and 12.09 mm and hexagonal length is obtained between 18.95 mm and 19.14 mm in the required tolerance values. On the other hand, the flash thickness is measured between the 1.75 mm and 2.04 mm although flash thickness value is taken as 1.8 mm during the finite volume analysis.

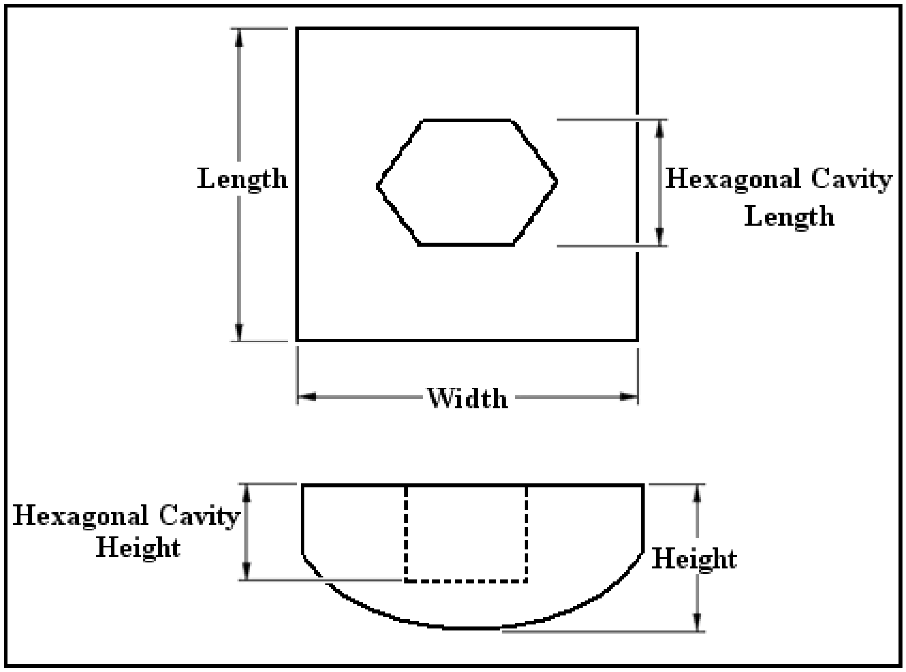

Figure 5.18 Forged Part Dimension Representation

5.6 Effect of Forging Temperature on the Part

During the experiments, temperature of the initial billet was decreased to see the effect of the forging temperature on the forged part and as a result of this to see if the forging defects occur or not. Hence, as seen in Figure 5.19, four different forging temperatures 200 ^{o}C, 250 ^{o}C, 300 ^{o}C and 350 ^{o}C was studied in additon to 400 ^{o}C which have been described previously in this chapter. The experimental setup and die temperatures are the same as the previous forging experiment. In the experiments, ten billets were forged for each of the four different forging temperatures; and the experimental data recorded before the forging operation and after the forging operation are provided in Appendix F.

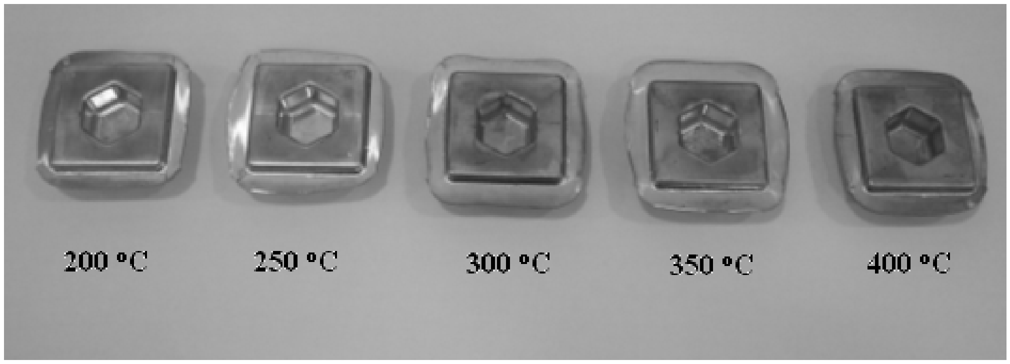

Figure 5.19 Forged Part Obtained in the Experiment for Different Forging Temperatures

In the experiments, the forging temperature was firstly decreased to the 350 ^{o}C and there was no forging defects observed at this temperature for the ten different part forged. Thus, the forging temperature was decreased to the 300 ^{o}C and forging operation was completed at this temperature and at the end of the forging operation crack formation were seen in the two forgings. The crack were occured in the flash zone as seen in Figure 5.20. Therefore, the billet temperature of 300 ^{o}C can be practically applicable for this particular part geometry. The forging temperature was decreased to the 250 ^{o}C and it was observed that defected part numbers became three and the cracks were observed in the flash zone of the forgings. Although at this time the cracks observed were greater in length than as in the 300 ^{o}C as seen in Figure 5.21, the billet temperature of 250 ^{o}C can still be applicable for this particular part geometry. Finally, the experiments were realized in 200 ^{o}C and four parts had defects. As seen in Figure 5.22, the cracks were formed increasingly also in the flash zone of the forgings in this temperature.

Figure 5.20 Crack Observation in the Flash Zone for the Forging Temperature of 300 ^{o}C

Figure 5.21 Crack Observation in the Flash Zone for the Forging Temperature of 250 ^{o}C

Figure 5.22 Crack Observation in the Flash Zone for the Forging Temperature of 200 ^{o}C

The cracks were occurred in the flash zones of the forgings for the forging temperatures of 200 ^{o}C, 250 ^{o}C and 300 ^{o}C as seen in the results. Although these temperatures can be suitable for this particular part geometry, they can be critical for the different part geometries,and careful handling can be required during forging process for the different part geometries.

CHAPTER 6

FINITE VOLUME SIMULATIONS AND EXPERIMENTS OF ALUMINUM ALLOY 6061

6.1 Introduction

Aluminum alloy 6061 is one of the most important aluminum alloy used in different application areas such as aircraft fittings, couplings, marines fittings, electrical fittings, brake pistons, hydraulic pistons and valves [49].

6061 type of aluminum alloy forging products have been used widely in aerospace, automotive and defense industry like 7075 type of aluminum alloys. In this chapter, finite volume simulation of the suggested forging operation for the particular part described in Chapter 4 will be performed for the 6061-0 type of aluminum alloy; and the experiments will be realized. Results of the finite volume simulations and experiments for 6061-0 type of aluminum will be compared with the simulation results and the experimental results for the 7075-0 type of aluminum alloy, which have been given in Chapter 4 and 5.

6.2 Finite Volume Simulation of Aluminum Alloy 6061

In the simulation of 6061-0 type of aluminum alloy, two stages forging process has been investigated similar to that described in Chapter 4. The billet material was chosen as 6061-0 which is presented in material database of SfForming 8.0 [45] for the temperature range of 250-500 ^{o}C. Yield stress-strain rate curves of aluminum alloy 6061-0 are given in Figure 6.1 for the strain of 0.115 for the different temperatures according to Table 6.1 and its material properties are given in Table 6.2.

The tensile yield strength and the ultimate tensile strength of the aluminum alloy 6061-0 are given in Equation 6.1 and Equation 6.2 according to the simple tension test at the room temperature [49]. These values are fairly below the tensile yield strength and the ultimate tensile strength values of aluminum alloy 7075-0 given in Chapter 4.

$$\sigma_Y = 55.2 \text{ MPa} \tag{6.1}$$

$$\sigma_{UTS} = 124 \text{ MPa} \tag{6.2}$$

In the simulation process, forging dies, the billet dimensions and the forming properties were used same as in Chapter 4. Initial temperature of the billet is taken as 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC. Initial temperature of the dies is assumed as 200 °C and the plastic shear friction is 0.2.

Table 6.1 Flow Stress Parameters for 6061-0 [45]

Strain Rate (1/s)	**Yield Stress according to Temperature**					
	250 ^oC	**300 ^oC**	**350 ^oC**	**400 ^oC**	**450 ^oC**	**500 ^oC**
0.01	60.24	47.75	37.85	29.99	23.77	18.84
0.34	89.77	71.16	56.41	44.70	35.42	28.08
0.67	96.95	76.84	60.90	48.27	38.26	30.32
1.00	101.44	80.39	63.73	50.50	40.04	31.72

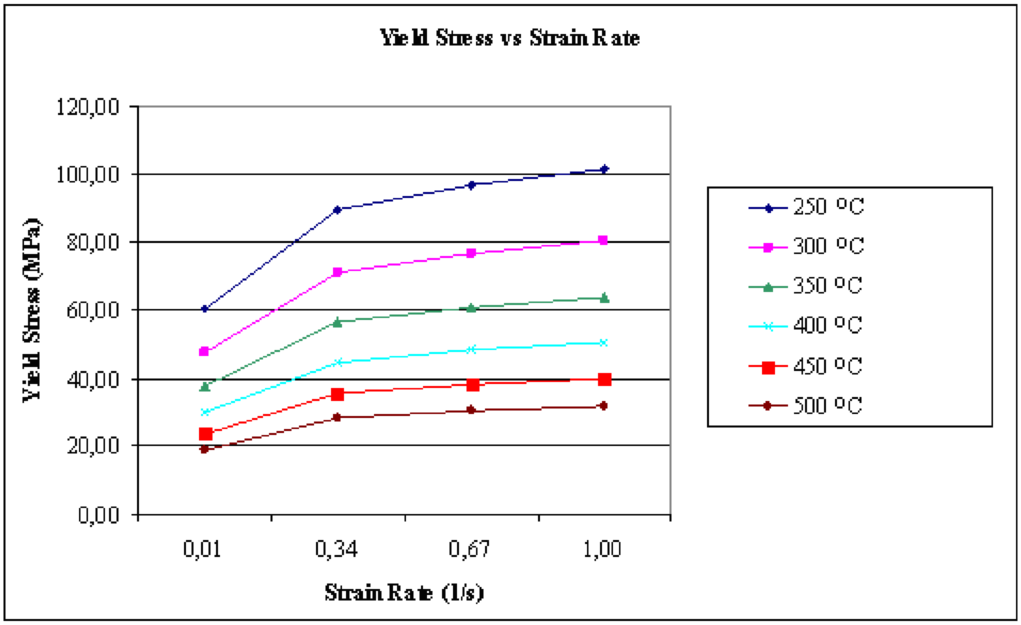

Figure 6.1 Stress-Strain Rate Curves of 6061-0 for Different Temperatures [45]

Table 6.2 Material Properties of 6061-0 [45]

Material Property	Value
Young's Modulus (GPa)	36.81
Poisson's Ratio	0.333
Density (kg/m^3)	2640
Thermal Conductivity (Watt/(m*K))	193
Specific Heat Constant (Joule/(kg*K))	1132
Coefficient of Thermal Expansion (1/K)	2.8e-5
Solidus Point (^oC)	582
Melting Point (^oC)	652

In the simulations, 25512 and 24977 finite volume elements are created for the upsetting operation and the finish operation respectively as in Chapter 4 for the defined wokpiece element size of 1 mm. However, the finite volume element numbers changes during the simulation since new meshes are created.

Although it changes for each analysis, the simulation time is measured as nearly 3 hours for the upsetting operation while the simulation time is nearly 9.5 hours for the finish operation for a workstation with 3 GHz (x2) processor and 4 GB RAM.

6.2.1 Simulation Results of Aluminum Alloy 6061 for the Particular Part

The force requirement, the effective stress distribution and the temperature distribution obtained from the finite volume program are given in Figures 6.2-6.31 and their maximum values are given in Tables 6.3-6.4 for the initial billet temperatures of 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC.

In Figure 6.2 and 6.3, the die forces for 6061-0 type of aluminum alloy are given for the billet temperature of 200 ^oC for the upsetting and the finish operations respectively. In Figure 6.4 and 6.5, the effective stress distributions are presented in ten steps for the billet temperature of 200 ^oC for the upsetting and the finish operations respectively. The temperature distributions are given in two steps in Figure 6.6 for the upsetting operation and in Figure 6.7 for the finish operation for the billet temperature of 200 ^oC. Similarly, the die forces, the effective stress and the temperature distributions are given in Figures 6.8-6.13, Figures 6.14-6.19, Figures 6.20-6.25 and Figures 6.26-6.31 for the billet temperature of 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC respectively.

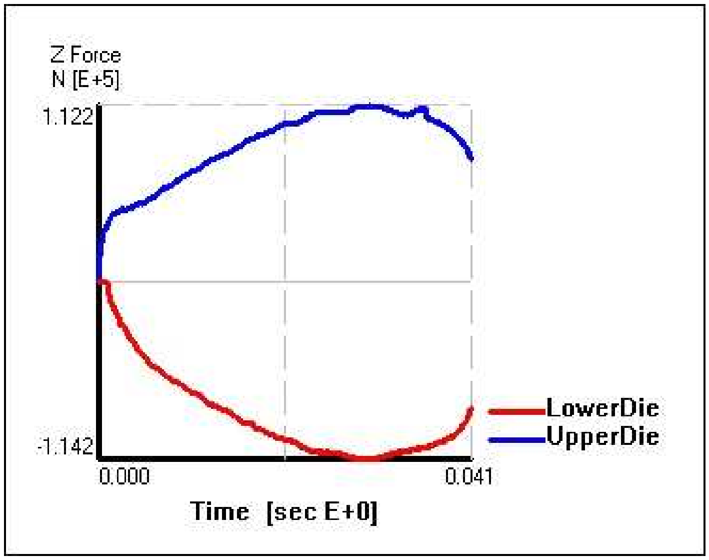

Figure 6.2 Die Force for Upsetting Operation of Aluminum Alloy 6061 at 200 ^{o}C

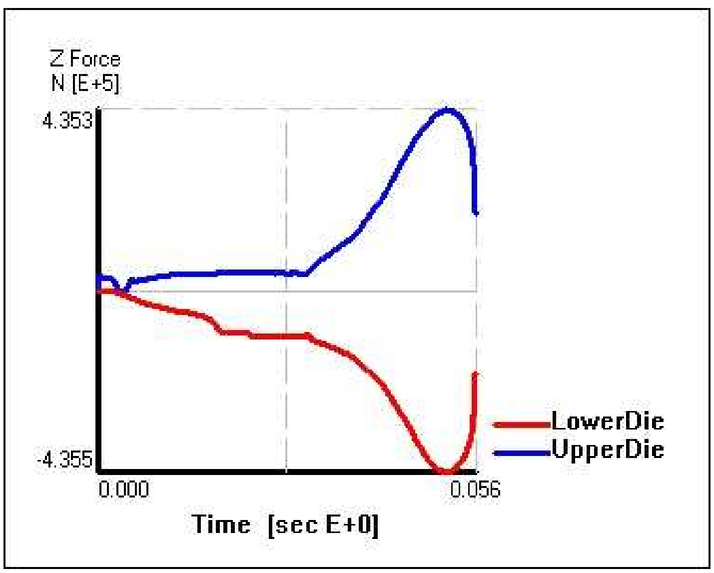

Figure 6.3 Die Force for Finish Operation of Aluminum Alloy 6061 at 200 ^{o}C

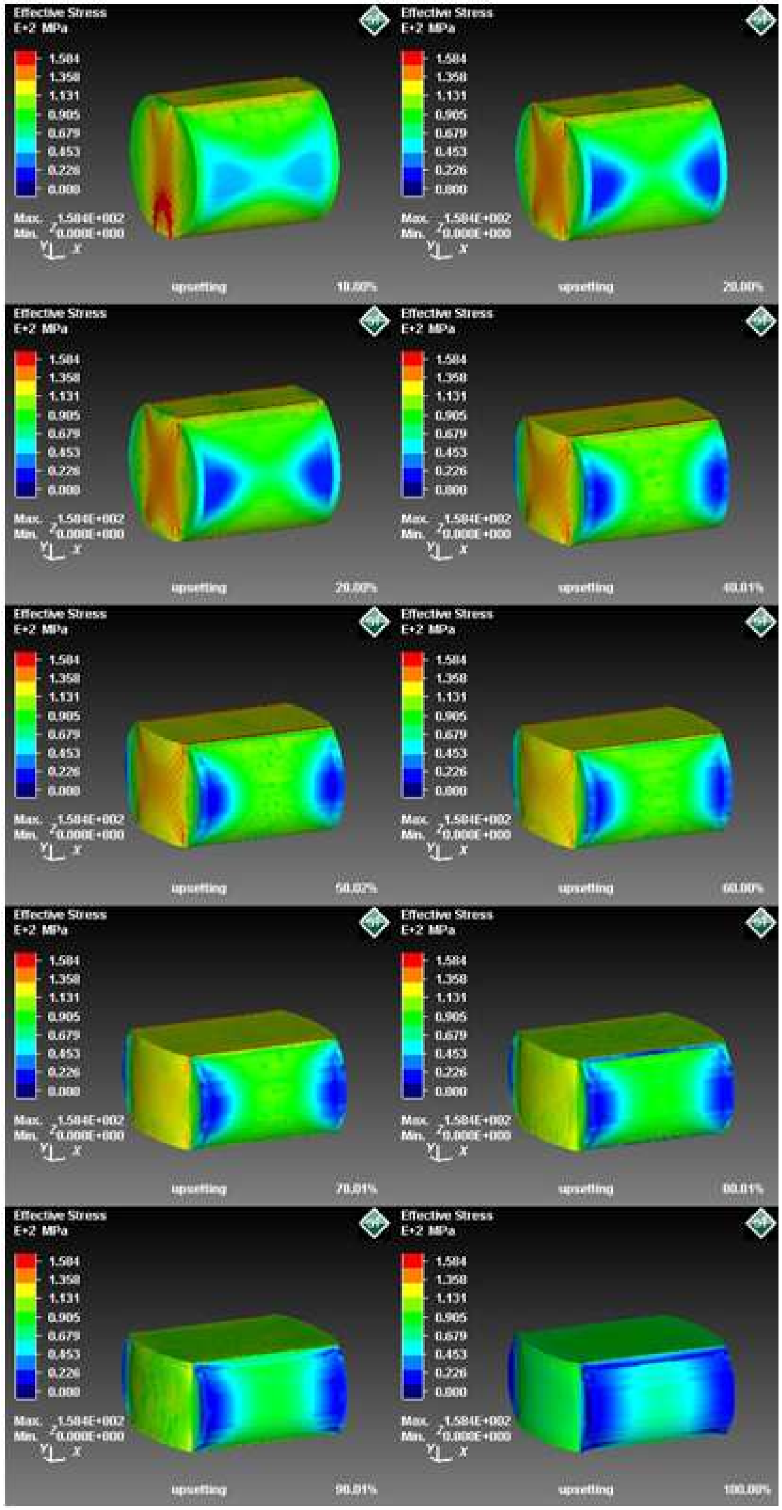

Figure 6.4 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 6061 at 200 ^{o}C

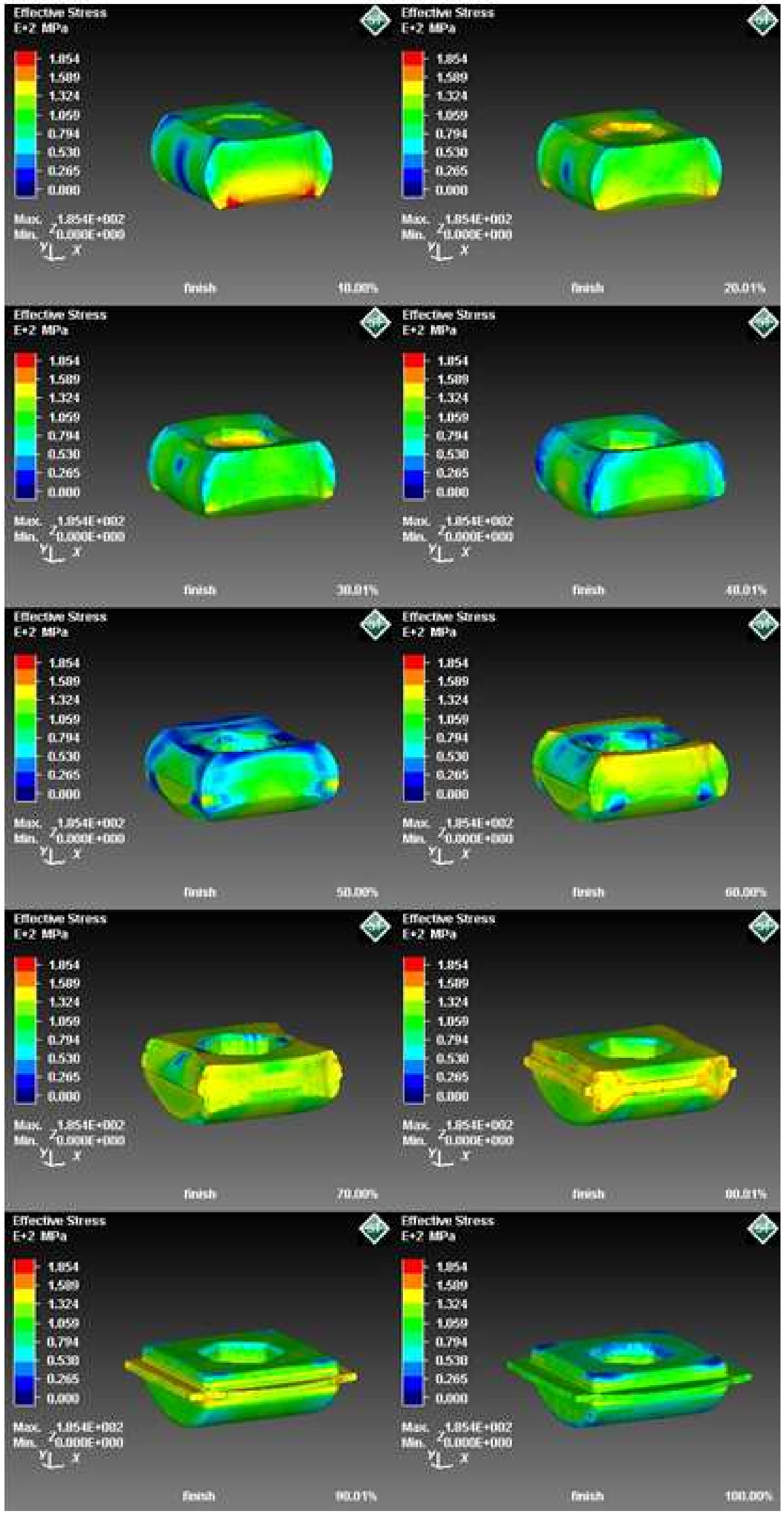

Figure 6.5 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 6061 at 200 ^{o}C

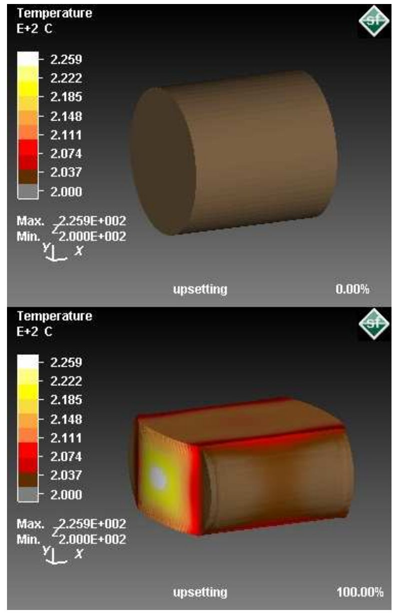

Figure 6.6 Temperature Distribution for Upsetting Operation of Aluminum Alloy 6061 at 200 ^{o}C

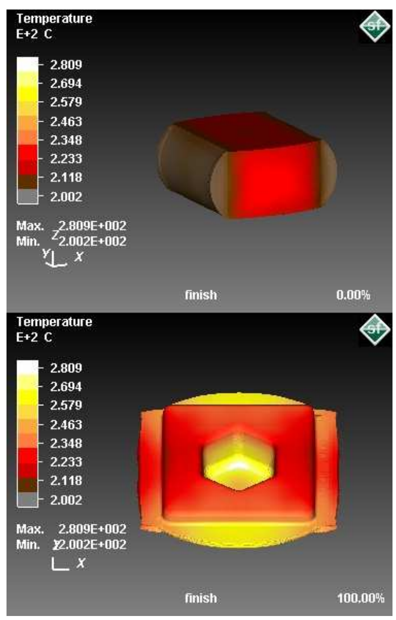

Figure 6.7 Temperature Distribution for Finish Operation of Aluminum Alloy 6061 at 200 ^{o}C

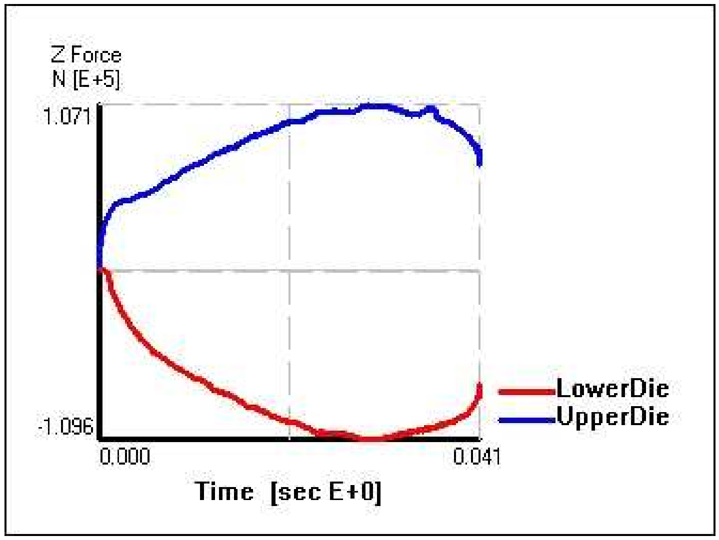

Figure 6.8 Die Force for Upsetting Operation of Aluminum Alloy 6061 at 250 ^{o}C

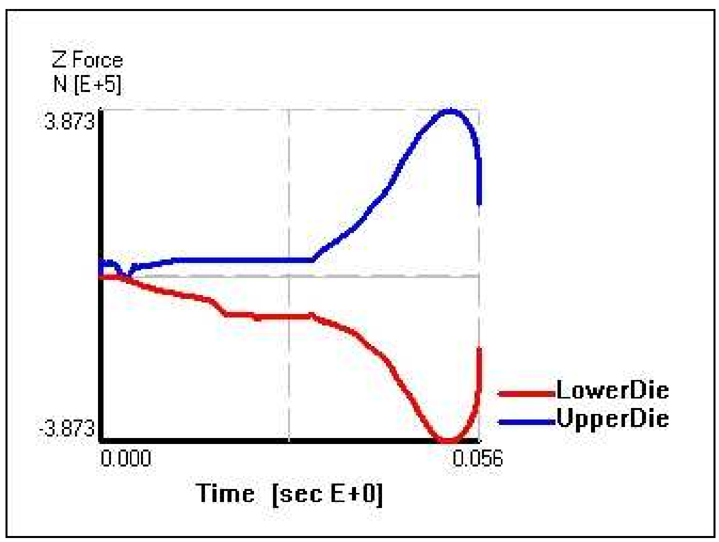

Figure 6.9 Die Force for Finish Operation of Aluminum Alloy 6061 at 250 ^{o}C

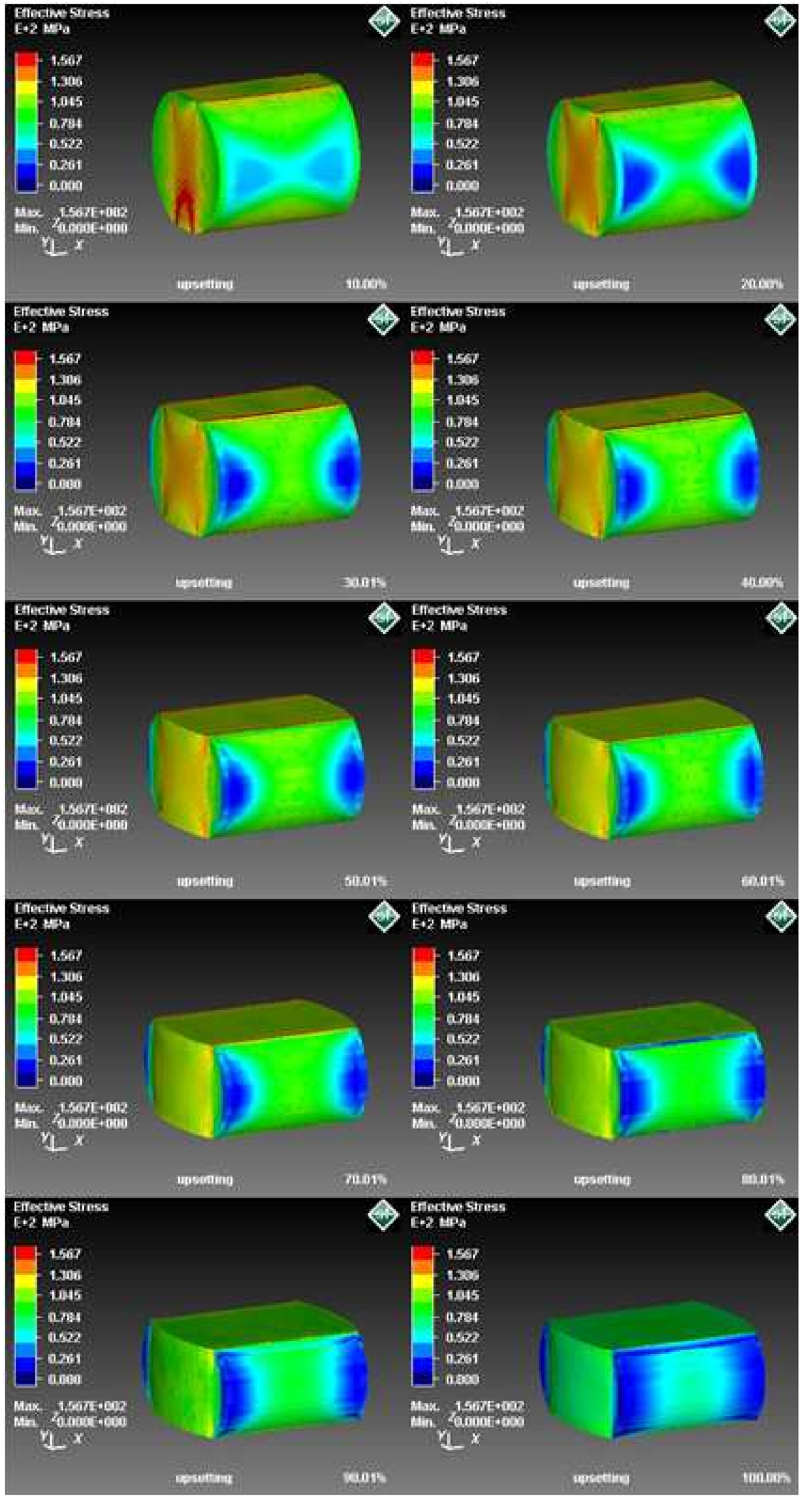

Figure 6.10 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 6061 at 250 ^oC

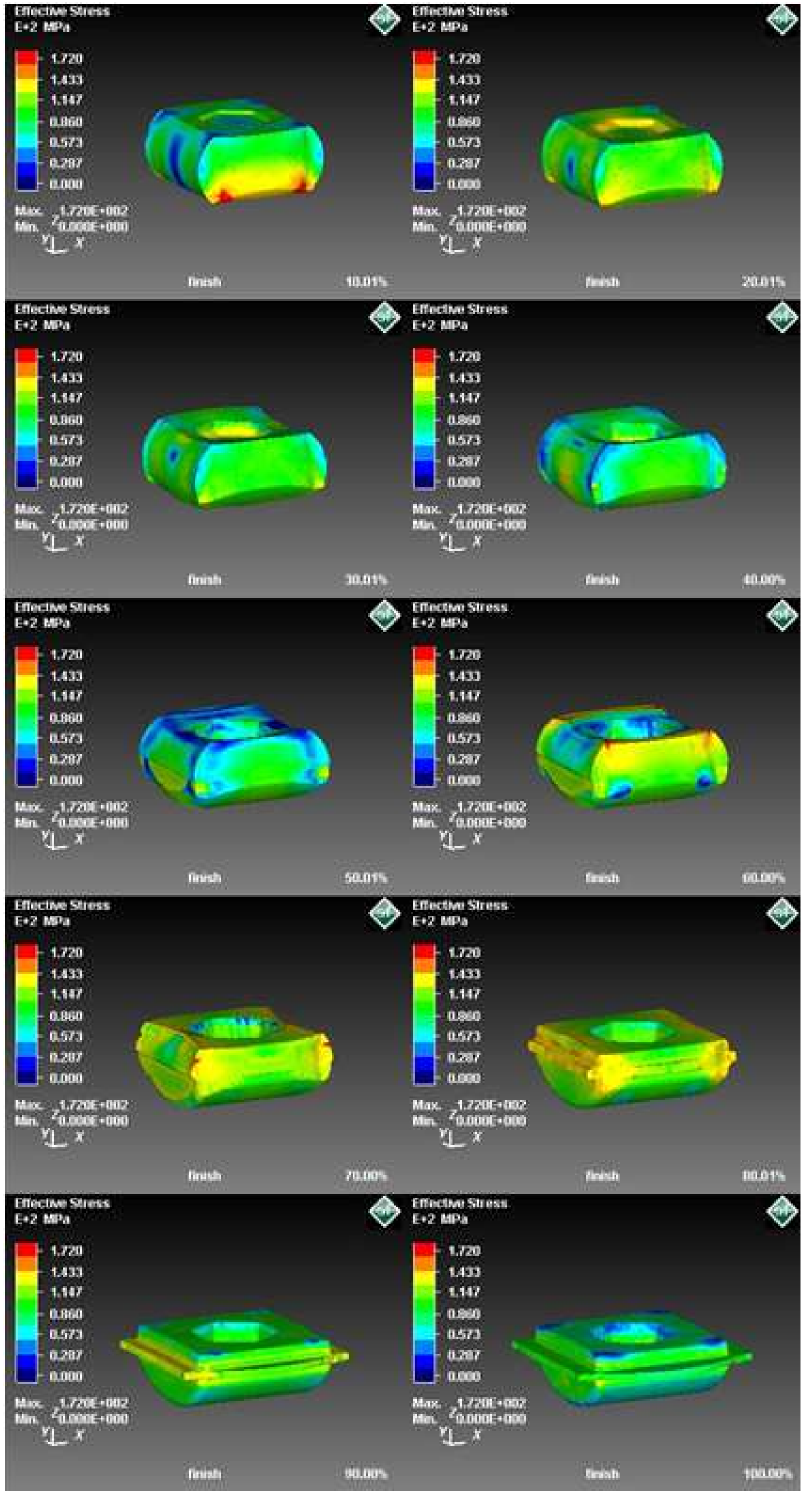

Figure 6.11 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 6061 at 250 ^oC

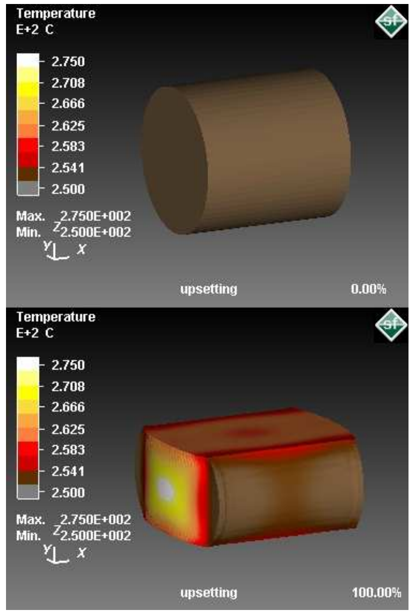

Figure 6.12 Temperature Distribution for Upsetting Operation of Aluminum Alloy 6061 at 250 ^{o}C

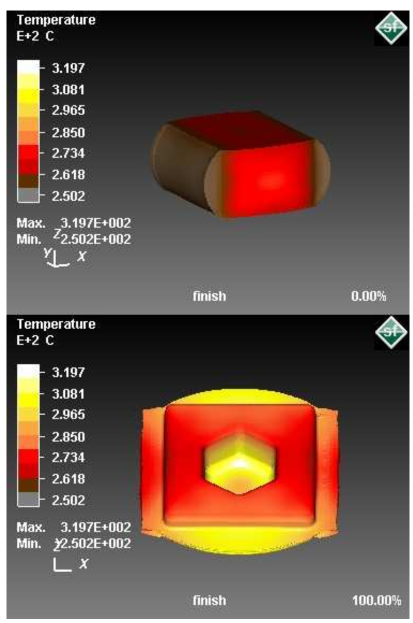

Figure 6.13 Temperature Distribution for Finish Operation of Aluminum Alloy 6061 at 250 ^{o}C

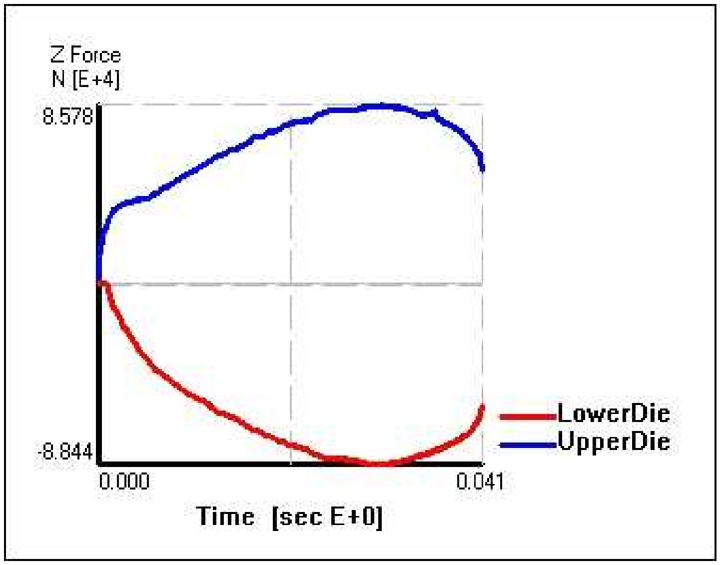

Figure 6.14 Die Force for Upsetting Operation of Aluminum Alloy 6061 at 300 ^{o}C

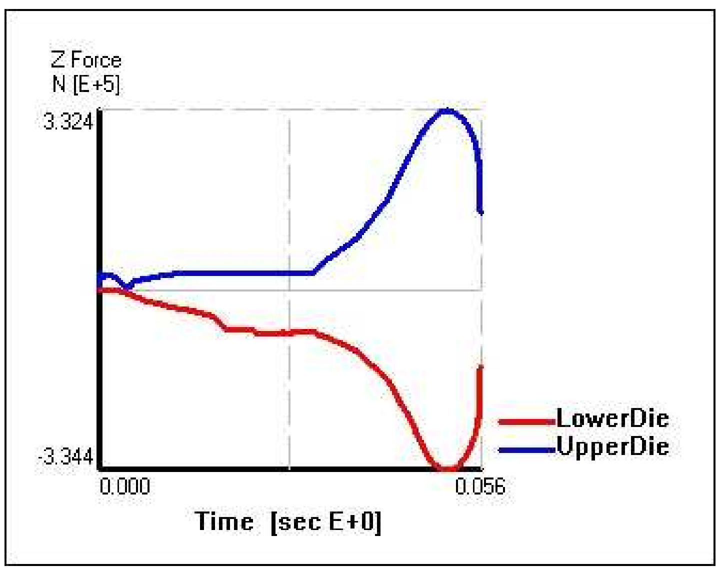

Figure 6.15 Die Force for Finish Operation of Aluminum Alloy 6061 at 300 ^{o}C

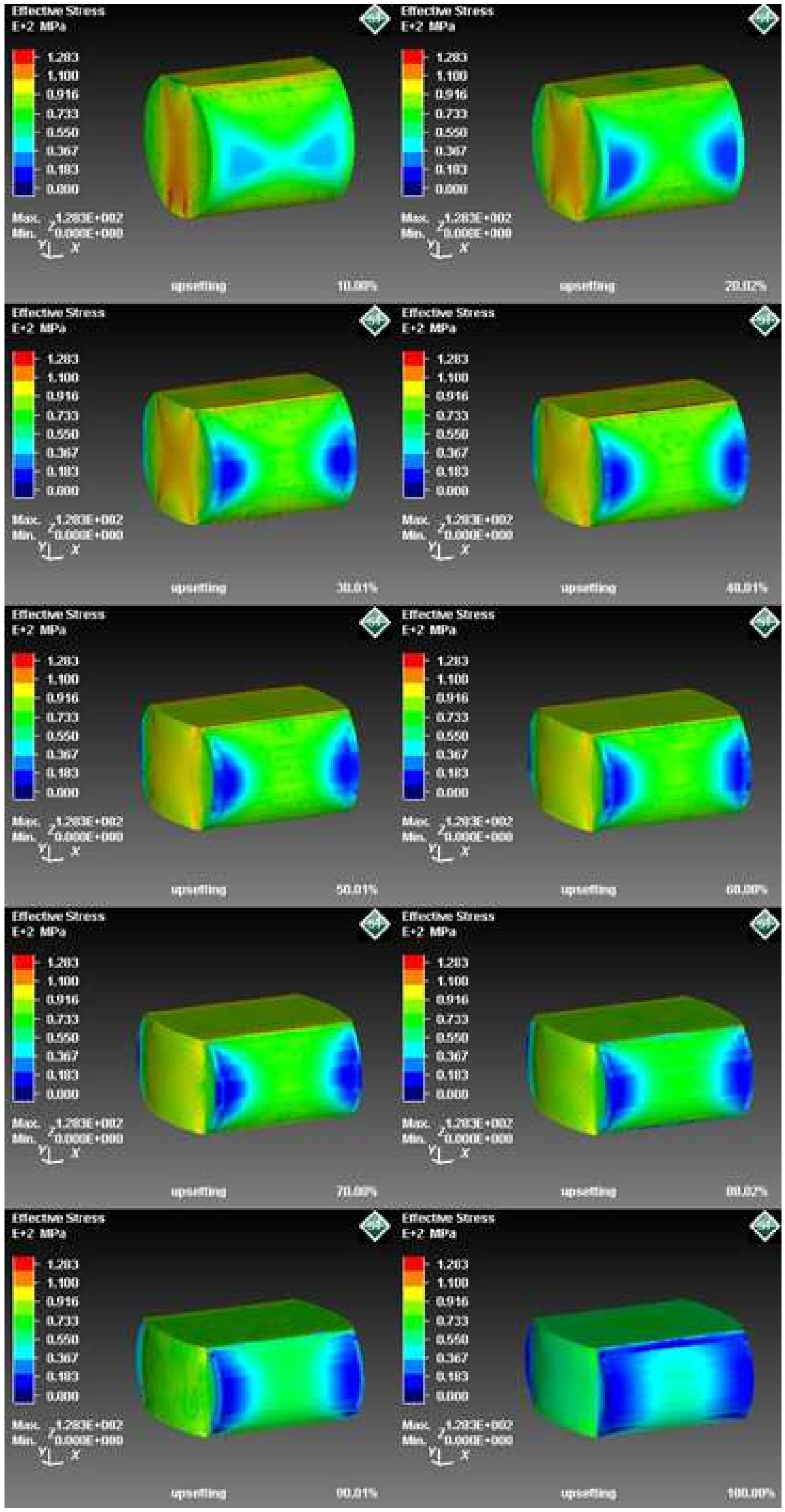

Figure 6.16 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 6061 at 300 ^{o}C

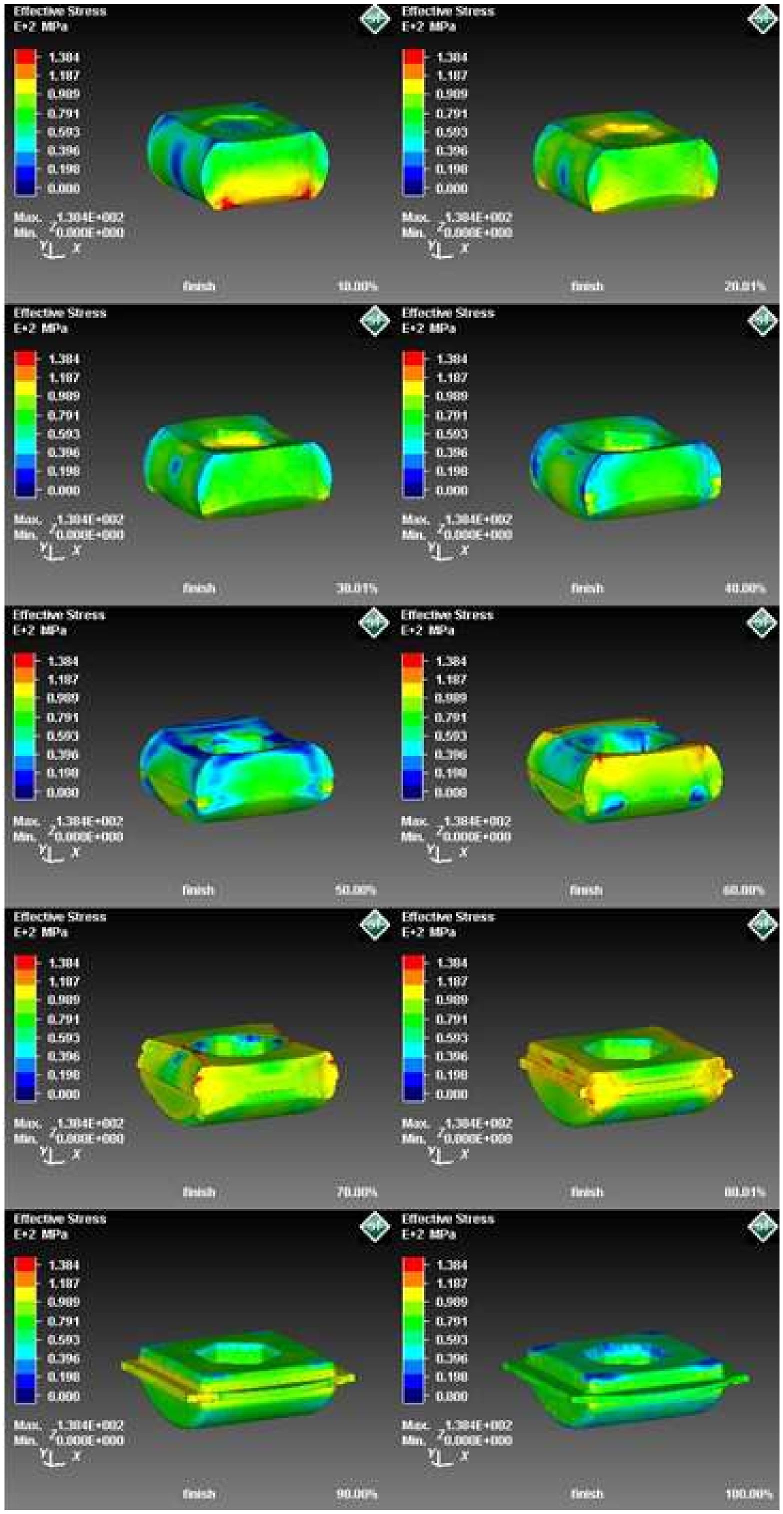

Figure 6.17 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 6061 at 300 ^{o}C

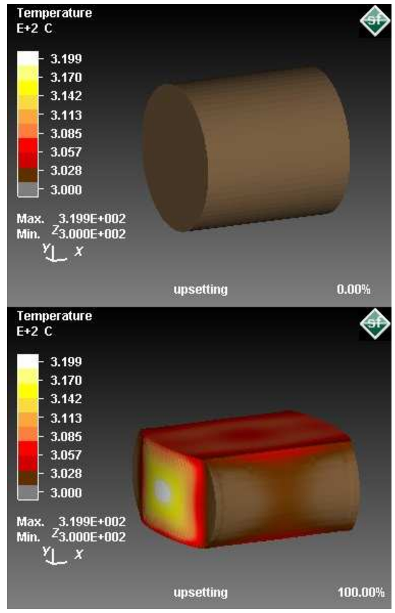

Figure 6.18 Temperature Distribution for Upsetting Operation of Aluminum Alloy 6061 at 300 ^{o}C

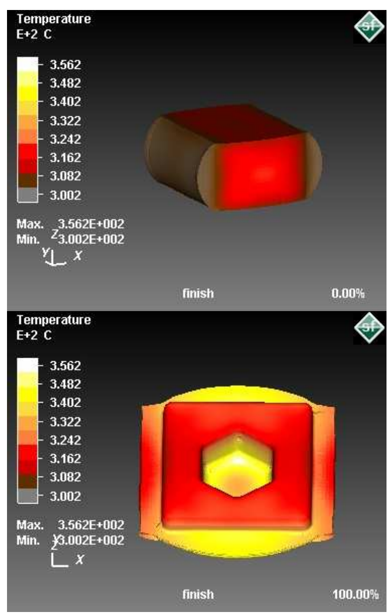

Figure 6.19 Temperature Distribution for Finish Operation of Aluminum Alloy 6061 at 300 ^{o}C

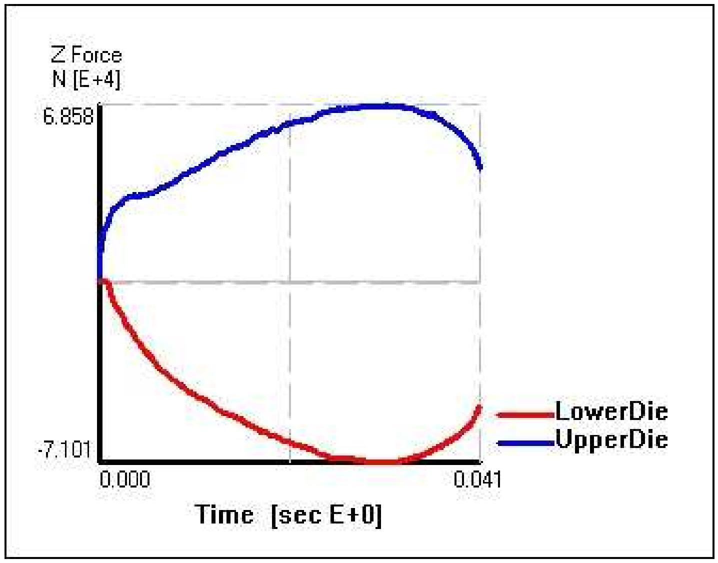

Figure 6.20 Die Force for Upsetting Operation of Alloy Aluminum 6061 at 350 ^{o}C

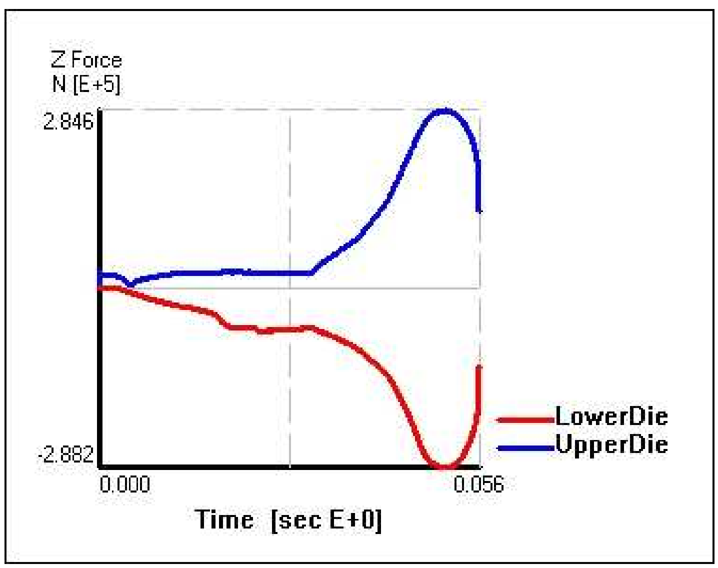

Figure 6.21 Die Force for Finish Operation of Aluminum Alloy 6061 at 350 ^{o}C

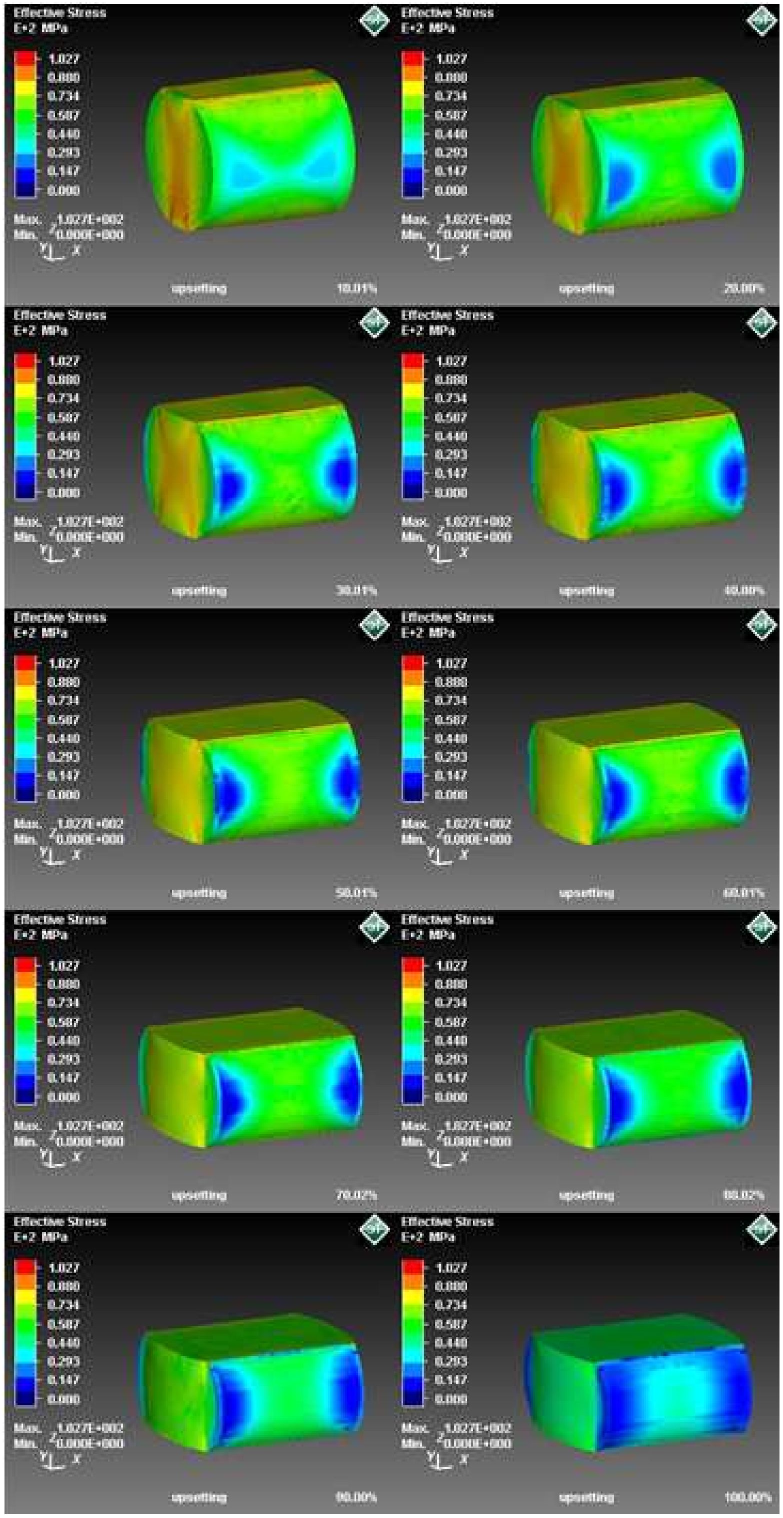

Figure 6.22 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 6061 at 350 ^{o}C

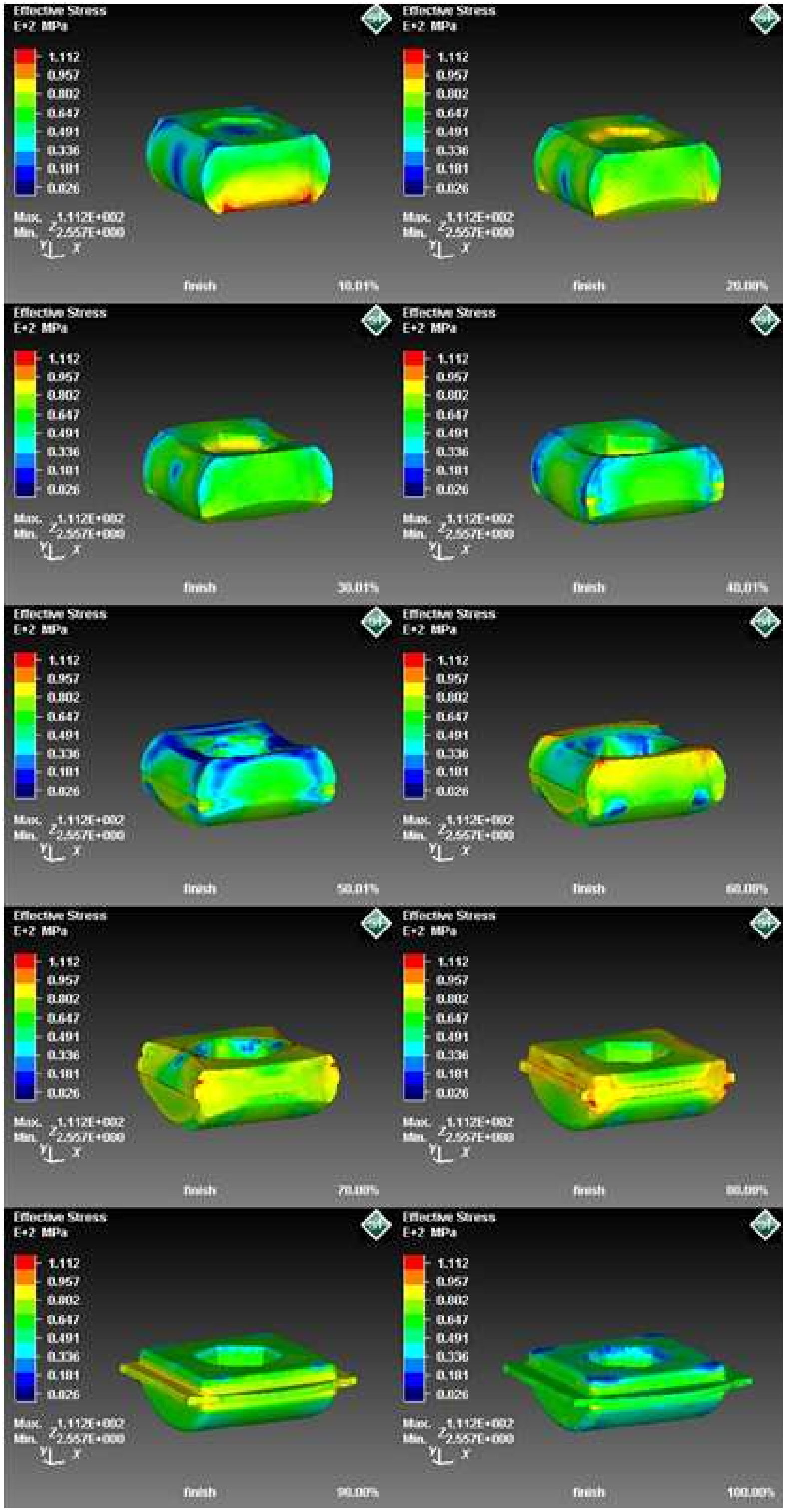

Figure 6.23 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 6061 at 350 ^{o}C

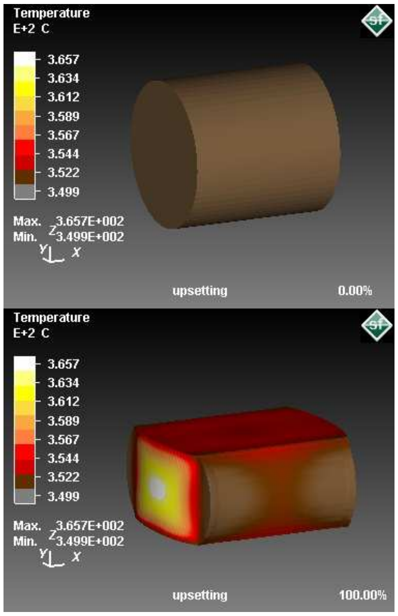

Figure 6.24 Temperature Distribution for Upsetting Operation of Aluminum Alloy 6061 at 350 ^{o}C

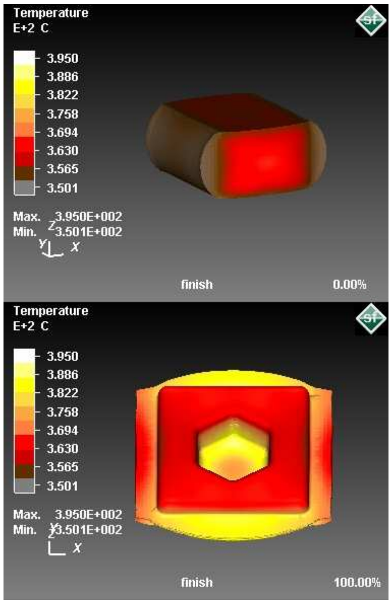

Figure 6.25 Temperature Distribution for Finish Operation of Aluminum Alloy 6061 at 350 ^{o}C

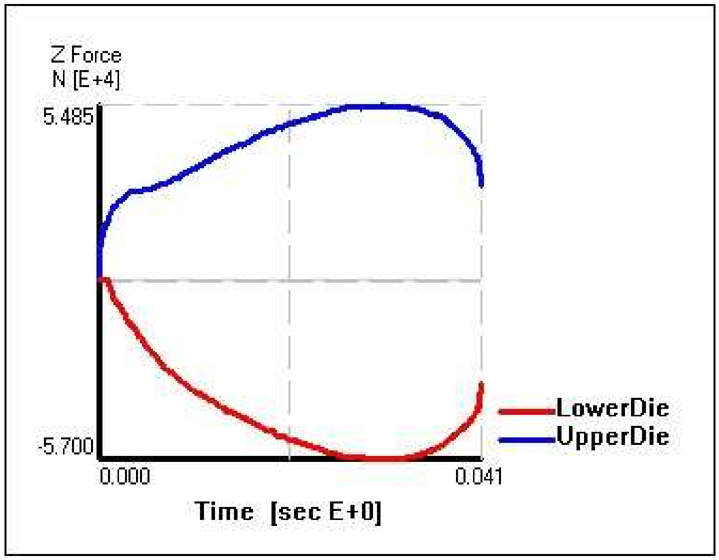

Figure 6.26 Die Force for Upsetting Operation of Aluminum Alloy 6061 at 400 ^{o}C

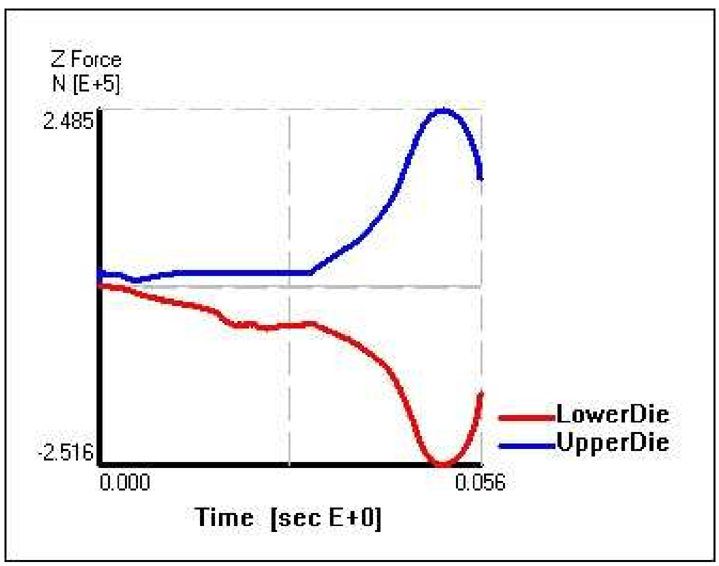

Figure 6.27 Die Force for Finish Operation of Aluminum Alloy 6061 at 400 ^{o}C

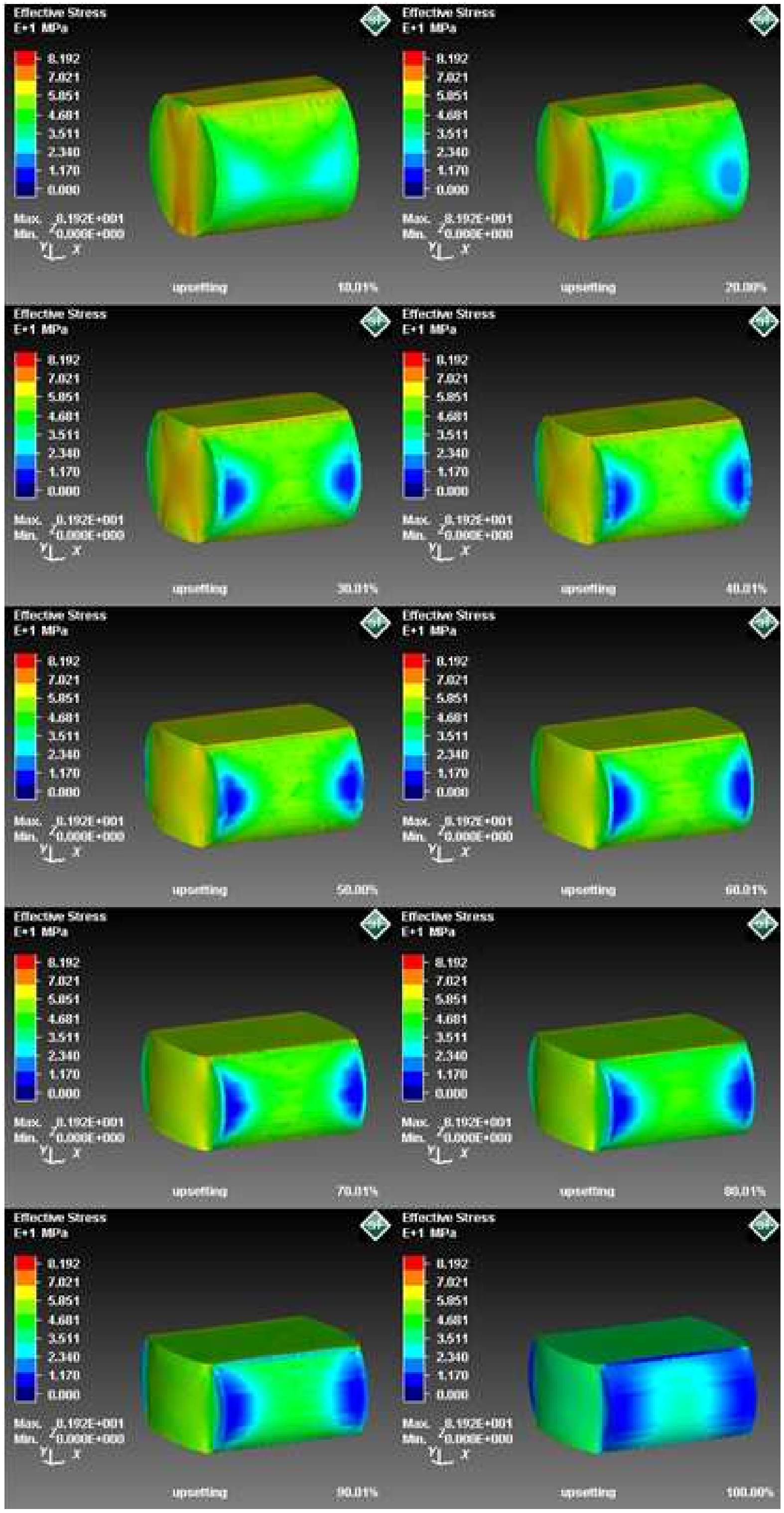

Figure 6.28 Effective Stress Distribution for the Upsetting Operation of Aluminum Alloy 6061 at 400 ^{o}C

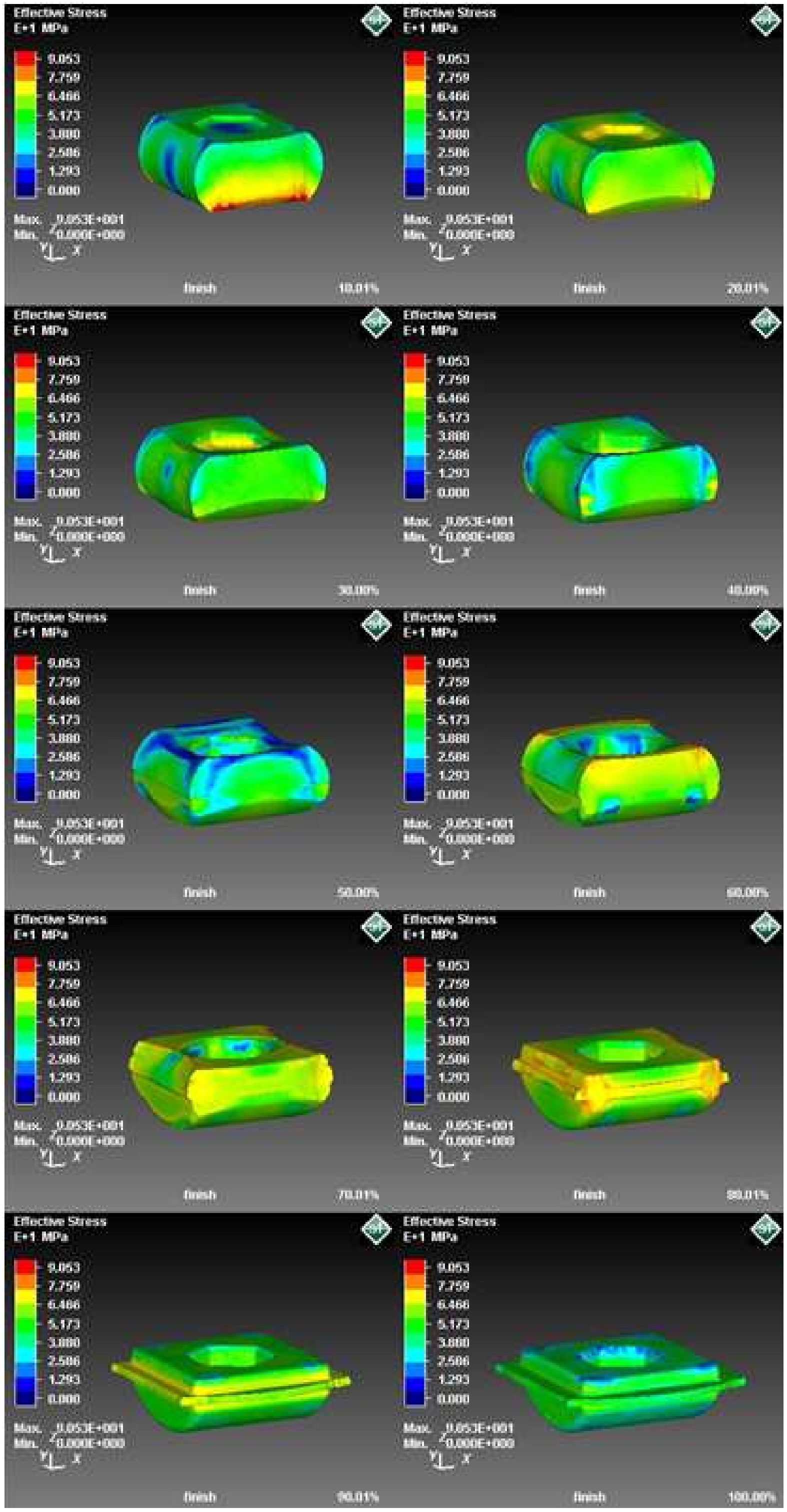

Figure 6.29 Effective Stress Distribution for the Finish Operation of Aluminum Alloy 6061 at 400 °C

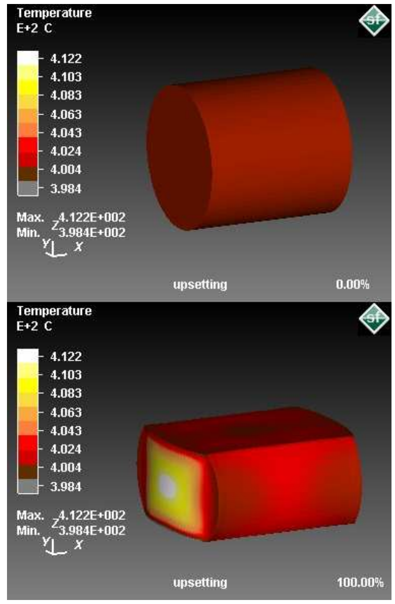

Figure 6.30 Temperature Distribution for Upsetting Operation of Aluminum Alloy 6061 at 400 ^{o}C

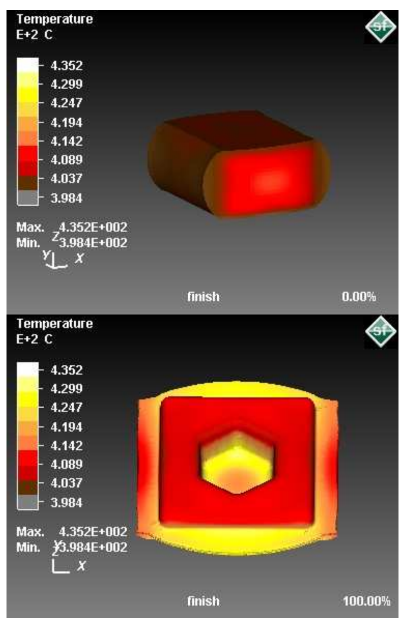

Figure 6.31 Temperature Distribution for Finish Operation of Aluminum Alloy 6061 at 400 ^{o}C

Table 6.3 Maximum Die Force and Effective Stress for Different Forging Temperatures of Al 6061

Billet Temperature (^oC)	Maximum Die Force for Upsetting (Ton)	Maximum Die Force for Finish (Ton)	Maximum Effective Stress for Upsetting (MPa)	Maximum Effective Stress for Finish (MPa)
200	11.6	44.4	158.4	185.4
250	11.2	39.5	156.7	172.0
300	9.0	34.1	128.3	138.4
350	7.2	29.4	102.7	111.2
400	5.8	25.7	81.9	90.5

Table 6.4 Maximum Part Temperatures for Different Forging Temperatures of Al 6061

Billet Temperature (^oC)	Maximum Part Temperature for Upsetting (^oC)	Maximum Part Temperature for Finish (^oC)
200	225.9	280.9
250	275.0	319.7
300	319.9	356.2
350	365.7	395.0
400	412.2	435.2

Table 6.5 Comparison of the Finite Volume Simulation Results of Al 6061 and Al 7075 for 400 ^{o}C

Simulation Results	Al 7075	Al 6061
Maximum Die Force for Upsetting (Ton)	7.4	5.8
Maximum Die Force for Finish (Ton)	29.2	25.7
Maximum Effective Stress for Upsetting (MPa)	100.2	81.9
Maximum Effective Stress for Finish (MPa)	108.7	90.5
Maximum Part Temperature for Upsetting (^{o}C)	417.2	412.2
Maximum Part Temperature for Finish (^{o}C)	447.1	435.2

As seen in Table 6.3, the maximum die force for the initial billet temperature of 200 ^{o}C is about two times greater than the maximum die force for the initial billet temperature of 400 ^{o}C for the upsetting and the finish operations. The maximum die force increases as the initial billet temperature decreases as expected as given in Table 6.3. However, when the maximum die force values of this type of aluminum alloy are compared to the maximum die force values of the 7075-0 type of aluminum alloy in Table 6.5, it is seen that the maximum die force requirements are less in forging of 6061-0 type of aluminum alloy.

The maximum effective stress values are also given in Table 6.3. As seen in the table, the maximum effective stress values are 158.4 MPa and 185.4 MPa for the initial billet temperature of 200 ^{o}C for the upsetting and the finish forging operation, respectively while the maximum effective stress values are 81.9 MPa and 90.5 MPa for the initial billet temperature of 400 ^{o}C for the upsetting and the finish forging operation, respectively. On the other hand, the maximum effective stress values are less in forging of 6061-0 type of aluminum alloy when compared to the 7075-0 type of aluminum alloy for the initial billet temperature of 400 ^{o}C from Table 6.5. Since lower stresses are achieved in the finite volume simulations of 6061-0 type aluminum alloy, it can be said that flow stresses of this type of aluminum alloy is lower than the 7075-0 type of aluminum alloy.

As seen in Table 6.4, at the low billet temperatures, the effect of temperature during forging are greater while the effect of temperature decreases as the billet temperature increases. For example, temperature difference between the maximum part temperature in the finish operation and the billet temperature of 200 ^oC is 80.9 ^oC while it is 69.7 ^oC, 56.2 ^oC, 45.0 ^oC and 35.2 ^oC for the billet temperatures of 250 ^oC, 300 ^oC, 350 ^oC, 400 ^oC respectively. One of the most important reason of this effect is the die temperatures since the die temperatures are close to the billet temperatures for the low forging temperatures and heat transfer between the part and the billet is less for the low billet temperatures. . However, the maximum temperature rise is 447.1 ^oC in finish operation for 7075-0 type of aluminum alloy for the 400 ^oC billet temperature while the maximum temperature rise is 435.2 ^oC for the 6061-0 type of aluminum alloy in same temperature as given in Table 6.5. The temperature rise effect is less critical in forging of 6061-0 type of aluminum alloy when compared to the 7075-0 type of aluminum alloy as seen from the simulation results of these two aluminum alloy groups.

6.3 Experiments of Aluminum Alloy 6061

In the experiments, effect of the temperature on the forging part has been performed and the results of the experiments of 6061-0 type of aluminum alloy have been compared with the experiments of 7075-0 type of aluminum alloy for the forging temperatures of 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC.

During the experiments the same forging dies were used and the same experimental procedure was applied as explained in Chapter 5. The dies were heated to the temperature between the 200 ^oC and 250 ^oC by using the LPG flame gun heaters and the billets were heated by using electrical box type furnace. The temperature of the furnace was decreased after each set of ten forgings and when the furnace reached to the steady state condition, the experiments were carried on for that temperature. The temperature of the dies and the billets were controlled by using the optical pyrometer during the forging process. The set with ten billets were forged for the billet temperatures of 200 °C, 250 °C, 300 °C, 350 °C and 400 °C and therefore fifty forgings were produced at the end of the experiments. The billets were weighed with using the precision balance and their diameters and lengths were measured with using the digital calipers before the experiments; and their tabulated values are given in Table 6.6 according to five different billet temperatures. The experimental data recorded during the forging operation (i.e. temperature rise values) is given and the experimental data recorded after forging operation such as dimensions and weights of the forged parts are given in Table 6.7 and Table 6.8 respectively according to the initial billet temperatures. There are no forging defects such as cracks observed especially at the flash zone for the all forging temperatures during the experiments of 6061-0 type of aluminum alloy although the cracks were observed in the experiments of 7075-0 type of aluminum alloy for some billet temperatures in Chapter 5 and the forging parts for the different forging temperature are given Figure 6.32.

In Table 6.7, the temperature rise during the forging experiments of 6061-0 are seen for the different initial billet temperatures. As seen in the table, the maximum temperatures before the forging operation are measured as 208 °C, 261 °C, 312 °C, 360 °C and 409 °C while the minimum part temperature is measured as 195 °C, 245 °C, 292 °C, 342 °C and 398 °C for the billet temperatures of 200 °C, 250 °C, 300 °C, 350 °C and 400 °C respectively.

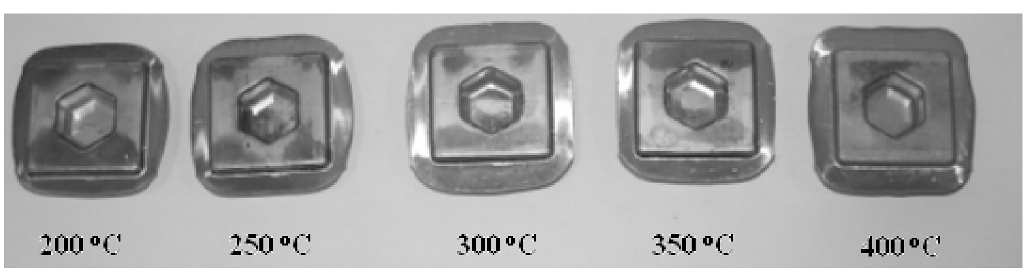

Figure 6.32 Final Forgings of 6061-0 for Different Billet Temperatures

The average values of the temperature rise during the experiments are obtained as 23.8 ^{o}C, 19.1 ^{o}C, 18.9 ^{o}C, 14.6 ^{o}C and 10.7 ^{o}C in the upsetting operation while average values of the temperature rise during the simulations are obtained as 25.9 ^{o}C, 25.0 ^{o}C, 19.9 ^{o}C, 15.7 ^{o}C and 12.2 ^{o}C in the upsetting operation for the initial billet temperatures of 200 ^{o}C, 250 ^{o}C, 300 ^{o}C, 350 ^{o}C and 400 ^{o}C respectively. For the finish operation, the average values of the temperature rise during the experiments are obtained as 81.4 ^{o}C, 66.4 ^{o}C, 50.3 ^{o}C, 47.4 ^{o}C and 34.7 ^{o}C while average values of the temperature rise during the simulations are obtained as 80.9 ^{o}C, 69.7 ^{o}C, 56.2 ^{o}C, 45.0 ^{o}C and 35.2 ^{o}C in the finish operation for the initial billet temperatures of 200 ^{o}C, 250 ^{o}C, 300 ^{o}C, 350 ^{o}C and 400 ^{o}C respectively. As seen from the temperature rise results, the experimental results are generally consistent with the finite volume simulation results and there are small differences due to similar reasons discussed in Chapter 5. Also, as seen from the temperature rise results of the experiments, when the temperature of the initial billet increases, the temperature rise during the upsetting and finish operation decreases. Although the temperature rise effect is greater in low initial billet temperature, it is not critical since it does not exceed the melting temperature of the 6061-0 type of aluminum alloy. For the initial billet temperature of 400 ^{o}C, the maximum temperature during the forging operation reaches to 450 ^{o}C and it is fairly below the melting temperatures of 6061-0 type of auminum alloy.

Moreover, when the billet mass values before forging operation and the forged part mass after the forging operation were measured as given in Table 6.6 and Table 6.8 respectively, it was seen that the weight values change within the tolerance limit of precision balance. Due to this reason, there are no scale formation observed also in forging of 6061-0 type of aluminum alloy. As seen in the Table 6.8, the dimensions of the forgings height, forgings width and length, hexagonal cavity height, hexagonal cavity length and the flash thickness are within the recommended tolerance values with ± 0.5 mm from the technical drawing of the part in Appendix A. Also, the forged part dimensions are small for the low billet temperatures since forging dies were manufactured with considering the thermal expansion of the forged part for the billet temperature of 400 ^{o}C and used for all temperatures.

Table 6.6 Billet Dimensions and Billet Weights of the Aluminum Alloy 6061 for Different Temperatures

Billet Temp. (^oC)	Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
200	1	30.09	32.17	61.09
	2	30.21	32.23	62.12
	3	29.96	32.19	60.71
	4	30.00	32.10	60.59
	5	30.03	32.56	61.68
	6	30.20	32.21	62.01
	7	29.93	32.52	61.88
	8	30.00	32.08	60.48
	9	30.10	32.04	61.13
	10	30.09	32.07	61.13
250	1	30.09	32.67	62.35
	2	30.08	32.00	60.55
	3	29.93	32.01	60.14
	4	30.03	32.12	61.25
	5	30.03	32.18	60.86
	6	30.03	32.88	62.78
	7	30.02	32.17	60.83
	8	30.13	32.08	61.08
	9	30.18	32.27	62.11
	10	30.02	32.18	61.00
300	1	29.97	32.24	61.09
	2	30.01	32.38	61.65
	3	29.97	32.50	61.28
	4	30.03	32.41	61.47
	5	30.20	32.12	62.09

Table 6.6 Billet Dimensions and Billet Weights of the Aluminum Alloy 6061 for Different Temperatures (Continued)

Billet Temp. (^{o}C)	Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
300	6	30.16	32.11	61.60
	7	29.95	32.37	61.77
	8	29.92	32.47	61.76
	9	30.01	32.07	60.95
	10	30.01	32.03	60.23
350	1	30.24	32.44	62.77
	2	30.18	32.40	61.93
	3	29.96	32.15	60.64
	4	30.02	32.45	62.42
	5	29.98	32.61	61.76
	6	30.03	32.25	61.25
	7	30.18	32.36	61.87
	8	29.90	32.20	61.25
	9	30.17	32.32	62.39
	10	30.01	32.17	61.48
400	1	30.23	32.10	61.37
	2	30.00	32.67	61.62
	3	29.94	32.21	60.60
	4	29.90	32.40	61.00
	5	29.89	32.04	60.48
	6	30.09	32.56	61.79
	7	30.28	32.22	62.30
	8	30.04	32.24	61.35
	9	30.10	32.2	61.94
	10	30.01	32.15	60.69

Table 6.7 Experimental Data Recorded during Forging Process for the Aluminum Alloy 6061 for Different Temperatures

Billet Temp. (^oC)	Billet No	Part Temperature Before Upsetting (^oC)	Part Temperature After Upsetting (^oC)	Part Temperature After Finish (^oC)
200	1	198	223	276
	2	202	224	277
	3	201	227	282
	4	199	221	284
	5	208	228	279
	6	197	219	278
	7	195	219	280
	8	200	226	282
	9	204	226	290
	10	195	224	285
250	1	259	282	325
	2	254	278	317
	3	251	280	320
	4	261	278	316
	5	258	275	318
	6	254	265	322
	7	245	261	312
	8	246	261	315
	9	250	267	328
	10	261	283	330
300	1	303	320	355
	2	306	323	350
	3	308	323	355
	4	302	322	354
	5	312	331	368

Table 6.7 Experimental Data Recorded during Forging Process for the Aluminum Alloy 6061 for Different Temperatures (Continued)

Billet Temp. (°C)	Billet No	Part Temperature Before Upsetting (°C)	Part Temperature After Upsetting (°C)	Part Temperature After Finish (°C)
300	6	306	320	348
	7	307	329	351
	8	298	321	355
	9	292	312	347
	10	298	320	352
350	1	348	363	400
	2	351	367	408
	3	354	369	404
	4	342	350	390
	5	345	362	393
	6	351	368	399
	7	360	375	397
	8	354	363	394
	9	351	368	397
	10	354	371	402
400	1	398	414	450
	2	402	413	441
	3	403	415	437
	4	405	412	430
	5	409	417	442
	6	402	412	438
	7	401	410	434
	8	405	413	431
	9	400	415	436
	10	407	418	440

Table 6.8 Experimental Data for Forging of Aluminum Alloy 6061

Billet Temp. (^{o}C)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)
200	1	61.09	18.13	40.20	40.21	12.08	19.12	1.85
	2	62.12	18.10	40.19	40.19	12.05	19.07	1.83
	3	60.72	18.06	40.13	40.11	12.04	19.03	1.79
	4	60.59	18.08	40.14	40.14	12.04	19.04	1.81
	5	61.68	18.05	40.15	40.14	12.05	19.06	1.80
	6	62.02	17.95	40.04	40.05	12.04	19.03	1.70
	7	61.88	18.07	40.12	40.15	12.07	19.04	1.80
	8	60.48	18.02	40.14	40.13	12.01	19.04	1.77
	9	61.12	18.07	40.15	40.15	12.04	19.05	1.81
	10	61.10	18.07	40.18	40.16	12.10	19.08	1.82
250	1	62.35	18.05	40.11	40.09	12.04	19.05	1.80
	2	60.56	18.07	40.10	40.11	12.03	19.03	1.81
	3	60.13	18.10	40.08	40.08	12.08	19.03	1.84
	4	61.25	18.02	40.13	40.15	12.03	19.01	1.79
	5	60.86	18.03	40.10	40.10	12.03	19.04	1.81
	6	62.77	18.04	40.10	40.09	12.06	19.04	1.81
	7	60.81	18.04	40.09	40.09	12.05	19.06	1.81
	8	61.08	18.29	39.95	39.90	11.87	18.96	2.12
	9	62.11	18.21	40.05	40.02	11.92	18.99	2.02
	10	60.99	18.19	39.98	39.95	11.91	18.97	2.07
300	1	61.10	18.05	40.03	40.03	12.04	19.00	1.83
	2	61.66	18.01	40.04	40.05	12.01	19.02	1.80
	3	61.27	18.11	40.01	39.99	12.10	18.96	1.88
	4	61.49	18.12	39.97	39.98	12.11	18.90	1.90
	5	62.09	17.98	40.03	40.02	12.01	19.02	1.75

Table 6.8 Experimental Data for Forging of Aluminum Alloy 6061 (Continued)

Billet Temp. (^oC)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)
300	6	61.59	18.01	40.04	40.04	12.01	19.01	1.81
	7	61.77	18.06	40.02	40.05	12.04	19.05	1.85
	8	61.76	18.00	40.05	40.04	12.01	19.02	1.80
	9	60.94	18.01	40.04	40.04	12.01	18.99	1.80
	10	60.22	18.02	40.04	40.06	12.00	19.03	1.80
350	1	62.78	18.02	40.01	40.03	11.95	18.97	1.84
	2	61.92	18.00	39.98	39.98	11.99	18.99	1.80
	3	60.65	18.01	39.99	39.97	11.95	18.97	1.82
	4	62.42	18.04	40.03	40.02	11.97	18.98	1.84
	5	61.76	18.25	39.87	39.85	11.83	18.81	1.96
	6	61.24	17.96	39.98	39.98	12.01	19.00	1.77
	7	61.86	18.07	39.91	39.90	11.90	18.86	1.89
	8	61.25	18.00	39.97	39.97	11.98	18.99	1.81
	9	62.40	18.00	39.98	39.98	12.00	18.98	1.81
	10	61.48	17.98	39.95	39.97	11.98	18.99	1.80
400	1	61.36	18.20	39.84	39.84	11.75	18.85	2.05
	2	61.63	17.93	39.91	39.91	11.99	18.97	1.75
	3	60.60	18.16	39.85	39.86	11.81	18.88	1.97
	4	61.00	18.03	39.87	39.87	11.92	18.91	1.87
	5	60.49	18.00	39.92	39.92	11.98	18.96	1.79
	6	61.78	17.91	39.93	39.93	11.97	18.95	1.70
	7	62.31	18.00	39.91	39.91	11.98	18.96	1.79
	8	61.35	18.01	39.92	39.92	11.98	18.96	1.80
	9	61.93	17.99	39.92	39.92	11.95	18.95	1.77
	10	60.69	18.00	39.91	39.91	11.97	18.97	1.80

CHAPTER 7

CONCLUSIONS

7.1 Discussion of the Results

In this study, aluminum forging process of a particular part has been realized. The forging part and dies are designed according to the aluminum forging design parameters as explained in Chapter 3. The proposed forging process was simulated for the initial billet temperatures of 375 ^oC, 400 ^oC and 425 ^oC for the 7075-0 type of aluminum alloy; and for the initial temperatures of 200 ^oC, 250 ^oC, 300 ^oC, 350 ^oC and 400 ^oC for the 6061-0 type aluminum alloy by a commercially available finite volume program. Forging dies were produced in METU-BILTIR Center CAD/CAM Laboratory and the experimental study was performed for the two different aluminum alloy groups (Al 7075 and Al 6061) and five different forging temperatures in METU-BILTIR Center Forging Research and Application Laboratory. Results of the numerical and the experimental studies are compared and conclusions are given as follows:

- To minimize the forging cost and forging time, firstly the process with single stage operation has been considered by the finite volume simulation process. However, it was seen that folds occur during single stage operation. In the computer analysis, the forging process with two stages was found as successful.

- The effective stress on the part decreases as the initial temperature of the billet increases. The maximum effective stress occurs during the initial contact of the lower and the upper die with the workpiece. The maximum effective stress on the part during the open upsetting forging stage is lower than that during the finish forging stage.

- The maximum effective stresses are relatively lower for the 6061-0 type of aluminum alloy when compared to the 7075-0 type of aluminum alloy.

- The maximum die force increases as the initial temperature of the billet decreases. The die forces slightly increase at the beginning of the finish forging stage and then the die forces increases rapidly to fill the die cavity completely. Moreover, the die forces are relatively lower for the forging of 6061-0 type of aluminum alloys when compared to the forging of 7075-0 type of aluminum alloys as seen from the finite volume simulation results.

- The part temperatures increase during the upsetting and finish forging operations and the maximum temperatures occur at the zones where the deformation on the part is high. Although the temperature rise seems to be within the desired temperature range during aluminum forging simulations, control of the temperature during experiments is critical to prevent the melting of the aluminum billets during forging operations as discussed in Chapter 4.

- The temperature rise is much higher in low forging temperatures which can be attributed to close die and billet temperatures at the low forging temperatures. As a result of this, there is less heat loss to the dies from the part.

- The temperature rise is less in forging of 6061-0 type of aluminum alloy when compared to the 7075-0 type of aluminum alloy as seen from the simulation results of these two aluminum alloy groups.

- In the experiments, the forged parts were controlled by visual inspection to find out if there is any unfilled region, surface crack or fold and it has been observed that there are no such forging defects as seen in the finite volume simulations. However, the cracks have been observed at the flash zone during the forging of 7075-0 type of aluminum alloy for the forging temperatures of 200 ^{o}C, 250 ^{o}C, and 300 ^{o}C. Since, the flash is trimmed after the forging operation, the crack formations at the flash are not critical. In addition, there are no crack formations observed during the forging of 6061-0 type of aluminum alloy for all forging temperatures. This shows that the forging of the aluminum alloy 6061-0 is less severe compare to the forging of the aluminum alloys 7075-0.

- During the experiments, it has been observed that heating of the aluminum billets is not easy in the available induction heater due to low melting temperature of the aluminum alloys. The electrical box type furnace available in the METU-BILTIR Center was used however it is not suitable for mass production.

- During the experiments, it has been observed that control of the aluminum billet temperatures is very difficult since aluminum looses heat very rapidly when it contacts with other metals. Also, aluminum looses heat quickly by radiation while carrying of the aluminum billets from the furnace to the forging press. Because of this reason, careful handling with the experienced technician is required during the forging. Temperature of the forging dies should be within the desired temperature range during the experiments to achieve the similar results with the finite volume simulation results.

- The temperature values tabulated during the experiment are mostly consistent with the finite volume simulation results. However, there are slight discrepancy between the results due to the experimental setup such as heating of the dies, heating of the billets and the sensitivity of the pyrometer used during the forging operations.

- The billet masses before forging process and part masses after forging process were weighed by using a precision balance for the two different aluminum alloy groups (Al 7075 and Al 6061) and it has been seen that there is no weight loss during the forging process. Therefore, it can be concluded that there is no scale formation in aluminum forging. It has been also observed during the visual inspection.

- The dimensions of the forging parts were measured by using the digital calipers and it has been observed that the part dimensions are at the desired tolerance which is ± 0.5 mm.

7.2 Future Works

Future works can be suggested as follows;

- Different types of aluminum alloys can be analyzed and experimentally tested for different part geometries.

- The finite element analysis can be performed to see the effects of the aluminum forging on the dies.

- Experimental study can be performed by obtaining force-stroke diagrams for the forging press.

- Warm forging of the aluminum alloys can be studied in detail.

- Cold forging of the aluminum alloys can be studied.

- Precision forging of the aluminum alloys can be analyzed.

- Heating experiments can be performed with different heating equipment.

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APPENDIX A

TECHNICAL DRAWING OF THE FORGING PART

Technical drawing of the forging part has been prepared by using PRO/ENGINEER Wildfire 3.0 as given in Figure A.1. The first angle projection system is used for the technical drawing since the first angle projection is the standard in Turkey and; throughout the Asia and Europe.

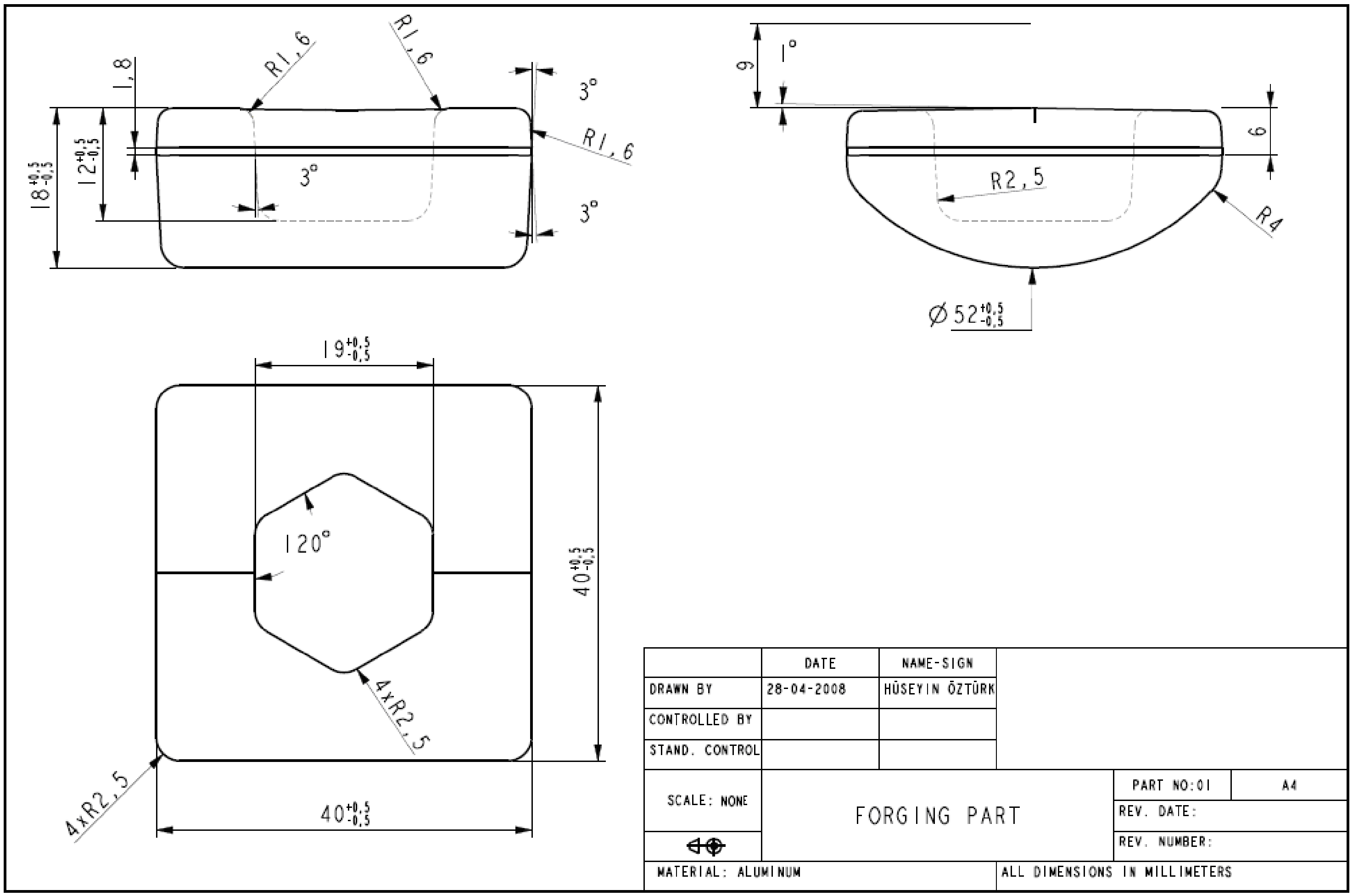

Figure A.1 Technical Drawing of the Forging Part

APPENDIX B

TECHNICAL INFORMATION OF 10 MN (1000 TON) SMERAL MECHANICAL PRESS

The press used in the experimental study is shown in Figure B.1.

Figure B.1 Smeral 10 MN Mechanical Press in METU-BILTIR Center Forging Research and Application Laboratory

The technical information of the press is given as follows:

Nominal Forming Force	: 10 MN
Ram Stroke	: 220 mm
Shut Height	: 620 mm
Ram Resetting	: 10 mm
Rod Length	: 750 mm
Crank Radius	: 110 mm
Number of Strokes at Continuous Run	: 100 min^{-1}
Press Height	: 4840 mm
Press Height above Floor	: 4600 mm
Press Width	: 2540 mm
Press Depth	: 3240 mm
Press Weight	: 48000 kg
Die Holder Weight	: 3000 kg
Main Motor Input	: 55 kW
Max. Stroke of the Upper Ejector	: 40mm
Max. Stroke of the Lower Ejector	: 50 mm
Max. Force of the Upper Ejector	: 60 kN
Max. Force of the Lower Ejector	: 150 kN

APPENDIX C

TECHNICAL DRAWING OF THE FORGING DIES

Technical drawing of the forging part is obtained by using PRO/ENGINEER Wildfire 3.0 as given in Figure C.1 to Figure C.3.

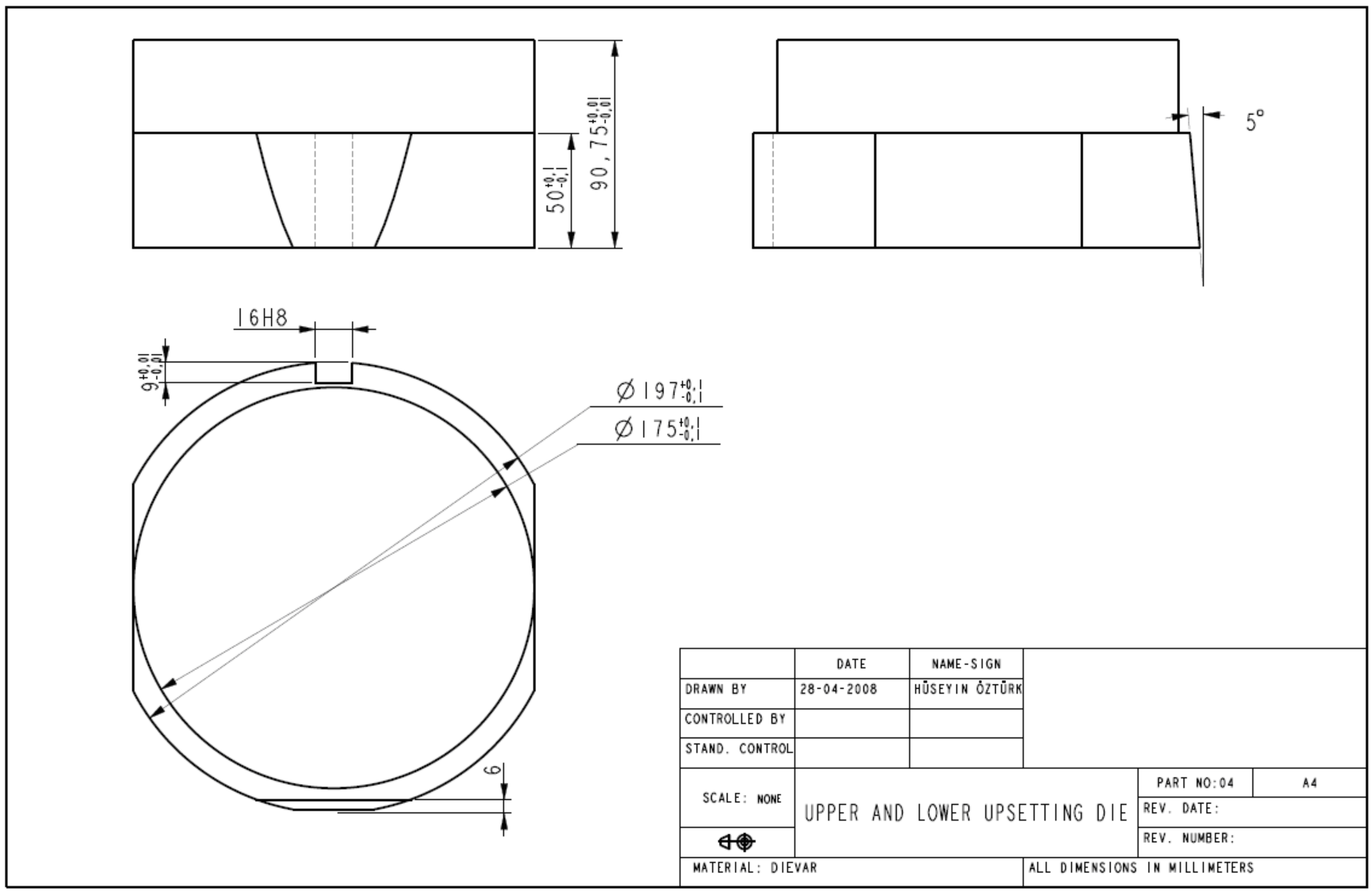

Figure C.1 Technical Drawing of the Upper and Lower Upsetting Dies

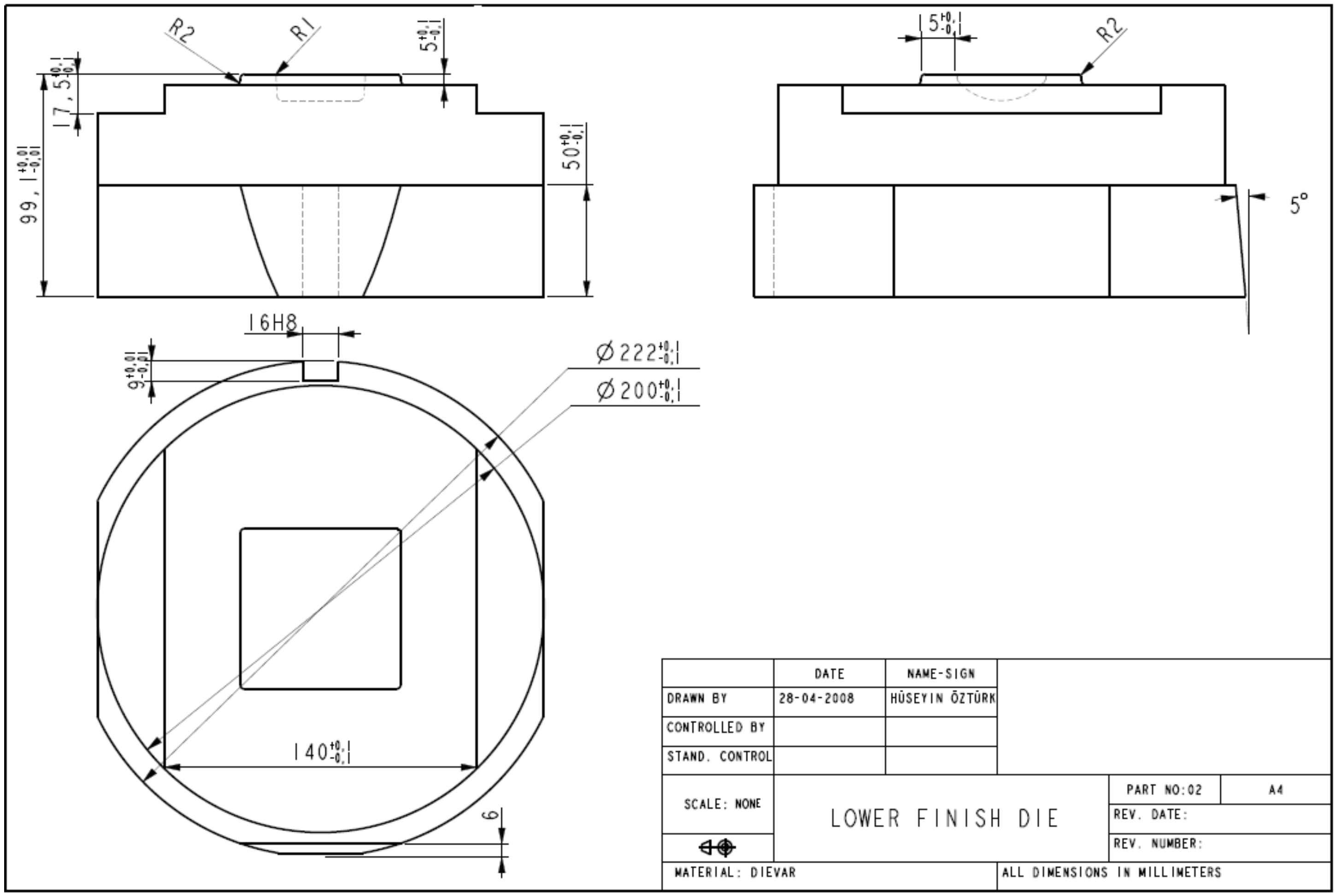

Figure C.2 Technical Drawing of the Lower Finish Die

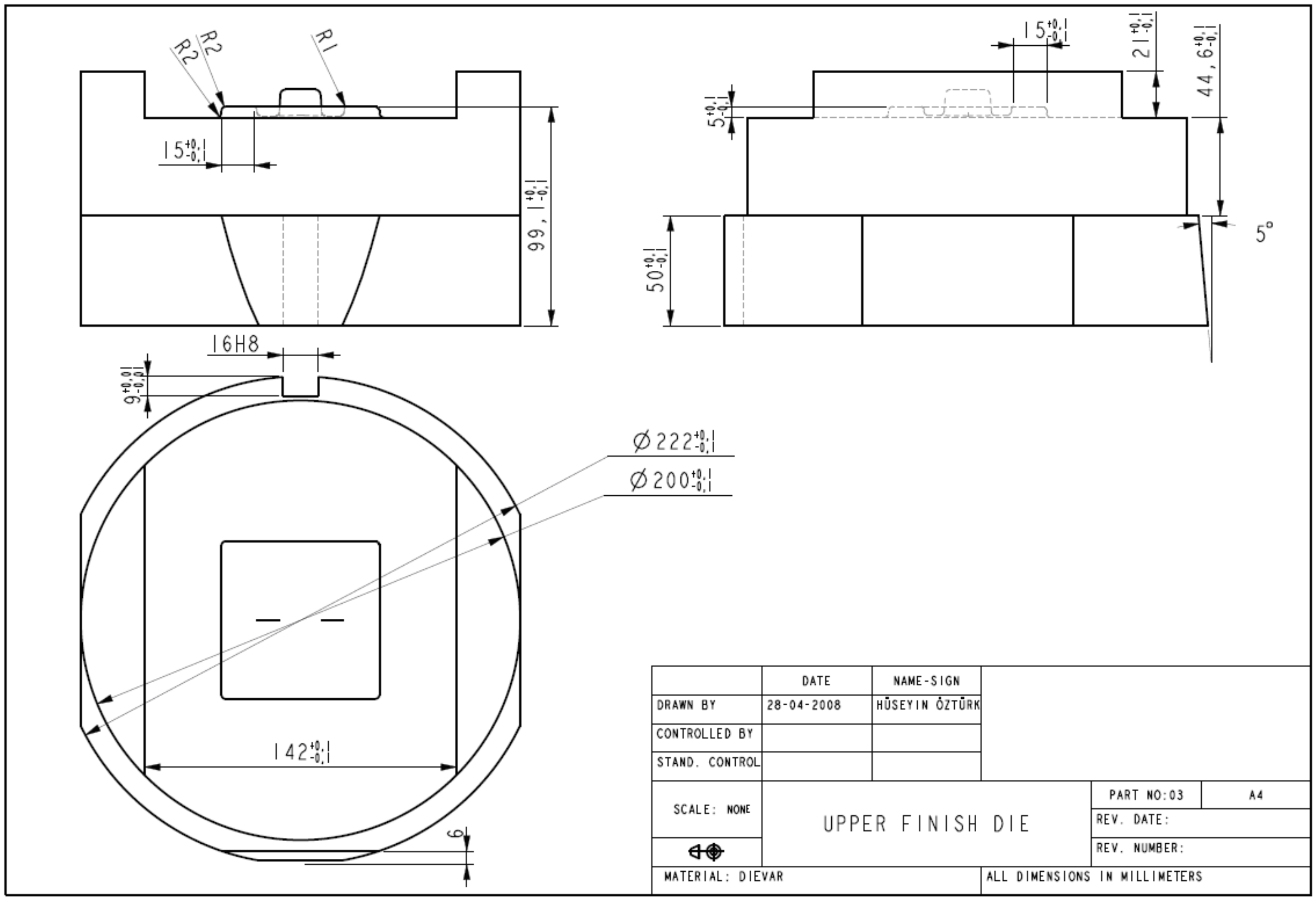

Figure C.3 Technical Drawing of the Upper Finish Die

APPENDIX D

MATERIAL PROPERTIES OF DIEVAR AND HEAT TREATMENT PROCESS

D.1 Material Properties of Dievar

Dievar is high performance chromium-molybdenum- vanadium alloyed hot work tool steel which offers a very good resistance to heat checking, gross cracking, hot wear and plastic deformation. Dievar is characterized by [53]:

- Excellent toughness and ductility in all directions
- Good temper resistance
- Good high-temperature strength
- Excellent hardenability
- Good dimensional stability throughout heat treatment and coating operations.

Information about chemical composition, physical and mechanical properties of Dievar is given in Table D.1, Table D.2 and Table D.3 respectively.

Table D.1 Chemical Composition of Dievar (%) [53]

C	Si	Mn	Cr	Mo	V
0.35	0.20	0.50	5.00	2.30	0.60

Table D.2 Physical Properties of Dievar [53]

Temperature	20 ^oC	400 ^oC	600 ^oC
Density (kg/m^3)	7800	7700	7600
Modulus of Elasticity (MPa)	210000	180000	145000
Coefficient of Thermal Expansion per ^oC from 20 ^oC	-	12.7×10^{-6}	13.3×10^{-6}
Thermal Conductivity (W/m^oC)	-	31	32

Table D.3 Mechanical Properties of Dievar at Room Temperature for Different Hardness Values [53]

Hardness (HRC)	44	48	52
Ultimate Tensile Strength (MPa)	1480	1640	1900
Yield Strength (MPa)	1210	1380	1560

Heat checking is one of the most common failure mechanisms in forging applications. Dievar's superior ductility yields the highest possible level of heat checking resistance. With Dievar's outstanding toughness and hardenability the resistance to heat checking can further be improved. Dievar offers the potential for significant improvements in die life and then resulting in better tooling economy regardless of the dominant failure mechanism; e.g. heat checking, gross cracking, hot wear or plastic deformation in hot work applications [53].

D.2 Heat Treatment Process

Heat treatment process is required for the hot work applications to prevent to die failure such as plastic deformation of dies, cracking of dies or wearing of dies. Recommended hardness values of the tool steel for the hot forging of the aluminum alloys are provided in Table D.4. Hardness value of the Dievar for this study is chosen as 44 HRC according to Table D.4 and heat treatment is applied to obtain these hardness values. However, as given in Tables D.5-D.7 which are the tabulated results of the portable hardness machine available in METU-BILTIR Center Forging Research and Application Laboratory, the hardness values show variation for the different measuring points of the dies. But, they are in the desired hardness range.

Otherwise indicated Dievar is hardened at 1025°C, quenched in oil and tempered twice at 625°C for two hours; yielding a working hardness of 44-46 HRC [53].

Table D.4 Hardness Values of the Tool Steel for Hot Aluminum Forging [53]

Parts	**Hardness (HRC)**
Dies	44-52

Table D.5 Hardness Values of the Upsetting Dies

Data Report DataView for TH140

Material: Steel   Hardness system: HRC
Impact Dir.: Down   Probe Type: D
Average: 20

[1]	45.4	[2]	42.8	[3]	45.0	[4]	45.2
[5]	45.1	[6]	44.0	[7]	43.7	[8]	44.4
[9]	45.4	[10]	43.7	[11]	44.4	[12]	45.5
[13]	44.1	[14]	44.3	[15]	43.9	[16]	42.3
[17]	44.9	[18]	42.7	[19]	44.2	[20]	43.9

Average: 44.2   StdDev: 0.9   Maximum: 45.5   Minimum: 42.3

Table D.6 Hardness Values of the Upper Finish Die

Data Report DataView for TH140

Material: Steel   Hardness system: HRC
Impact Dir.: Down   Probe Type: D
Average: 20

[1]	44.8	[2]	44.7	[3]	42.7	[4]	43.4
[5]	45.5	[6]	44.3	[7]	44.0	[8]	44.5
[9]	43.5	[10]	43.8	[11]	44.9	[12]	45.1
[13]	44.8	[14]	44.1	[15]	44.2	[16]	44.3
[17]	44.1	[18]	43.9	[19]	44.7	[20]	44.4

Average: 44.3   StdDev: 0.6   Maximum: 45.5   Minimum: 42.7

Table D.7 Hardness Values of the Lower Finish Die

Data Report DataView for TH140

Material: Steel Hardness system: HRC

Impact Dir.: Down Probe Type: D

Average: 20

[1]	44.7	[2]	44.4	[3]	43.8	[4]	44.6
[5]	43.8	[6]	43.9	[7]	44.1	[8]	44.2
[9]	42.4	[10]	45.2	[11]	44.0	[12]	43.5
[13]	44.9	[14]	44.0	[15]	43.8	[16]	44.5
[17]	44.9	[18]	44.0	[19]	44.5	[20]	45.6

Average: 44.2 StdDev: 0.7 Maximum: 45.6 Minimum: 42.4

The creep tests for the Dievar material of 44 HRC after the heat treatment process for the different die temperature values are realized in METU Central Laboratory and true stress-true strain curves obtained for the different temperatures are given in Figures D.1-D.4.

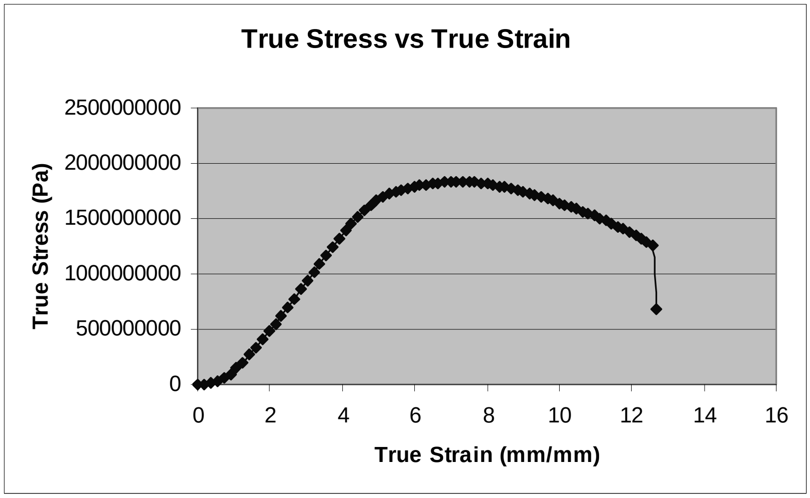

Figure D.1 True Stress vs. True Strain Curve for 125 ^{o}C

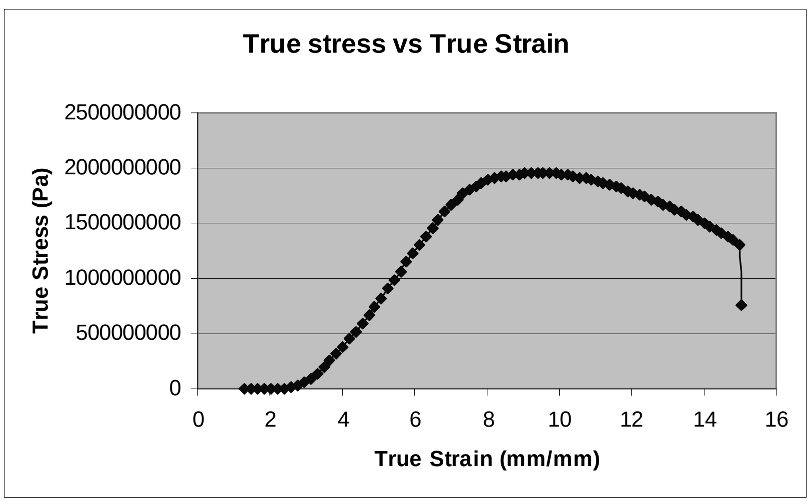

Figure D.2 True Stress vs. True Strain Curve for 200 ^{o}C

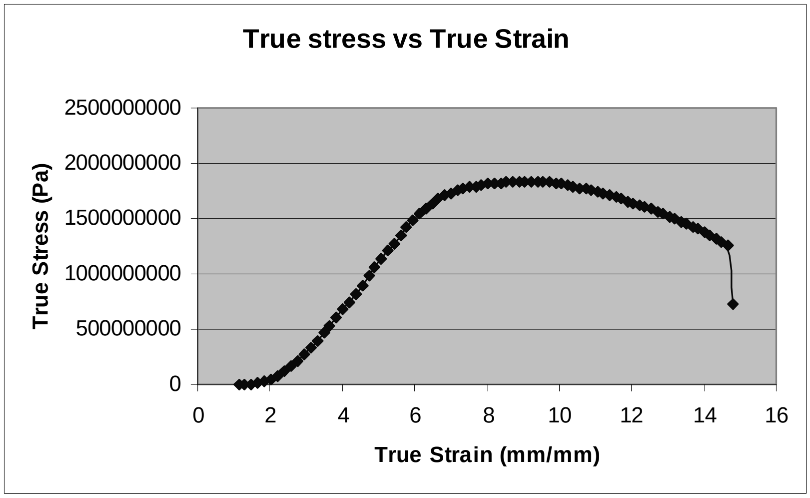

Figure D.3 True Stress vs. True Strain Curve for 275 ^{o}C

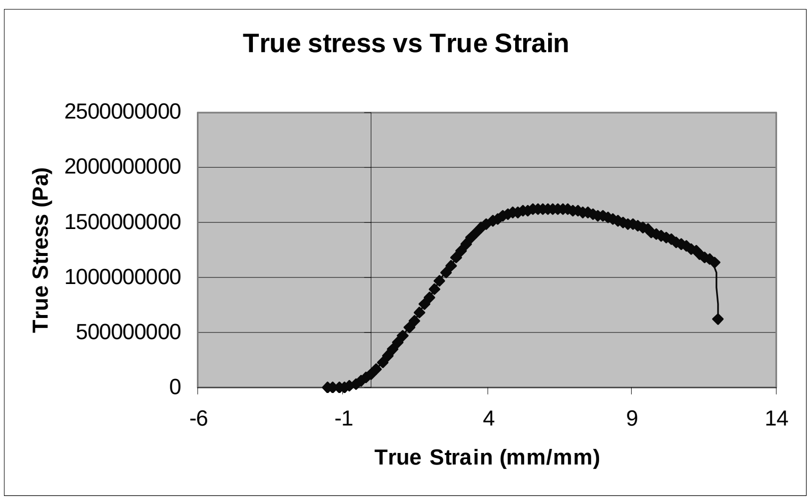

Figure D.4 True Stress vs. True Strain Curve for 350 ^{o}C

APPENDIX E

TECHNICAL INFORMATION OF THE COLORLESS WATER SOLUBLE LUBRICANT

Technical properties of the colorless water soluble lubricant are given as follows:

- Appearance: buff emulsion
- Density: 0.970 g/cc
- Solution Percentage: 5 %
- PH Value: 7-8
- Solvent: water (clean and not hard water)
- Application: spraying with air

The other properties can be given as:

- It is not flammable and used for hot working applications.
- It does not generate toxic gas during application.
- It is easy to clean from produced part.

APPENDIX F

EXPERIMENTAL DATA OF ALUMINUM ALLOY 7075-0 FOR THE BILLET TEMPERATURES OF 350 ^{o}C, 300 ^{o}C, 250 ^{o}C AND 200 ^{o}C

The experimental data recorded before the forging operation and after the forging operation for the temperatures of 200 ^{o}C, 250 ^{o}C, 300 ^{o}C, 350 ^{o}C of 7075-0 type of aluminum alloy are given in Table F.1 and F.2 respectively. The billet masses are measured within the tolerance limits of the balance from the tables. The dimensions of the forged parts are also inside the tolerance limit given in Appendix A. In addition to this, the forgings which have the cracks in their flash zone are indicated in Table F.2 according to the billet temperatures and the billet numbers.

Table F.1 Billet Dimensions and Billet Weights of the Aluminum Alloy 7075 for Different Temperatures

Billet Temp. (^oC)	Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
200	1	30.20	32.27	64.30
	2	30.19	32.17	64.12
	3	30.20	32.07	64.05
	4	30.13	32.35	64.03
	5	30.27	32.37	64.84
	6	30.22	32.22	64.23
	7	30.21	32.28	64.27
	8	30.20	31.92	63.85
	9	30.17	32.23	63.91
	10	30.21	32.09	63.92
250	1	30.15	32.18	63.96
	2	30.14	32.11	63.83
	3	30.19	31.95	63.59
	4	30.25	32.14	64.42
	5	30.22	32.00	63.98
	6	30.16	32.29	64.24
	7	30.17	31.86	63.37
	8	30.14	32.28	64.09
	9	30.24	31.98	63.76
	10	30.20	31.94	63.57
300	1	30.15	31.98	63.74
	2	30.06	32.12	63.61
	3	30.21	31.90	63.96
	4	30.24	32.16	64.10
	5	30.14	32.04	63.96

Table F.1 Billet Dimensions and Billet Weights of the Aluminum Alloy 7075 for Different Temperatures (Continued)

Billet Temp. (^oC)	Billet No	Billet Diameter (mm)	Billet Length (mm)	Billet Mass (g)
300	6	30.18	31.96	63.94
	7	30.05	32.09	63.48
	8	30.19	32.42	64.83
	9	30.01	32.10	63.40
	10	30.15	32.54	64.92
350	1	30.15	32.12	63.93
	2	30.08	32.09	63.53
	3	30.14	32.10	63.87
	4	30.21	32.08	64.18
	5	30.12	32.05	63.63
	6	30.17	32.02	63.87
	7	30.20	32.10	64.19
	8	30.26	32.16	64.46
	9	30.20	32.12	64.31
	10	30.22	32.24	64.61

Table F.2 Experimental Data Recorded after the Forging Process for Forging of Aluminum Alloy 7075

Billet Temp. (ºC)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)	Crack Observed in Flash
200	1	64.31	18.12	40.21	40.22	12.11	19.06	1.83	No
	2	64.12	18.12	40.19	40.19	12.08	19.08	1.82	No
	3	64.05	18.14	40.17	40.18	12.09	19.02	1.85	No
	4	64.03	18.09	40.20	40.20	12.05	19.10	1.81	Yes
	5	64.83	18.14	40.15	40.17	12.10	19.02	1.86	Yes
	6	64.23	18.08	40.23	40.20	12.06	19.11	1.81	Yes
	7	64.28	18.11	40.19	40.21	12.06	19.09	1.82	No
	8	63.84	18.10	40.21	40.20	12.07	19.10	1.81	Yes
	9	63.91	18.16	40.18	40.15	12.13	19.01	1.87	No
	10	63.92	18.14	40.18	40.21	12.09	19.04	1.85	No
250	1	63.96	18.25	40.08	40.10	12.13	18.85	1.96	No

Table F.2 Experimental Data Recorded after the Forging Process for Forging of Aluminum Alloy 7075 (Continued)

Billet Temp. (^oC)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)	Crack Observed in Flash
250	2	63.83	18.19	40.12	40.13	12.15	18.90	1.91	No
	3	63.59	18.15	40.10	40.12	12.10	18.96	1.87	No
	4	64.42	18.08	40.16	40.16	12.05	19.08	1.81	No
	5	63.97	18.06	40.15	40.14	12.05	19.07	1.81	No
	6	64.24	18.08	40.15	40.16	12.04	19.07	1.82	Yes
	7	63.36	18.07	40.17	40.17	12.06	19.06	1.81	Yes
	8	64.10	18.06	40.16	40.15	12.05	19.08	1.81	No
	9	63.76	18.10	40.14	40.12	12.08	19.05	1.83	Yes
	10	63.56	18.06	40.15	40.15	12.02	19.07	1.79	No
300	1	63.74	18.04	40.09	40.10	12.04	19.04	1.65	No
	2	63.60	18.05	40.10	40.10	12.03	19.04	1.78	No

Table F.2 Experimental Data Recorded after the Forging Process for Forging of Aluminum Alloy 7075 (Continued)

Billet Temp. (^oC)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)	Crack Observed in Flash
300	3	63.96	18.08	40.06	40.08	12.04	19.03	1.82	No
	4	64.10	18.04	40.11	40.10	11.97	19.05	1.80	No
	5	63.97	18.09	40.07	40.06	12.07	19.00	1.84	No
	6	63.94	18.05	40.11	40.11	12.03	19.05	1.79	Yes
	7	63.47	18.06	40.07	40.08	12.04	19.04	1.82	No
	8	64.83	18.04	40.10	40.10	11.96	19.05	1.75	No
	9	63.40	18.05	40.10	40.10	12.02	19.06	1.76	Yes
	10	64.93	18.03	40.10	40.11	12.03	19.04	1.72	No
350	1	63.95	18.01	40.07	40.04	12.02	19.01	1.74	No
	2	63.55	18.02	40.05	40.05	12.00	19.02	1.79	No
	3	63.88	18.04	40.04	40.05	12.02	19.04	1.81	No

Table F.2 Experimental Data Recorded after the Forging Process for Forging of Aluminum Alloy 7075 (Continued)

Billet Temp. (ºC)	Billet No	Forging Part Mass (g)	Height (mm)	Length (mm)	Width (mm)	Hexag. Cavity Height (mm)	Hexag. Cavity Length (mm)	Flash Thickness (mm)	Crack Observed in Flash
350	4	64.18	18.02	40.06	40.04	12.00	19.02	1.80	No
	5	63.63	18.02	40.05	40.05	11.98	19.01	1.79	No
	6	63.87	18.01	40.04	40.05	11.98	19.02	1.74	No
	7	64.18	18.04	40.03	40.04	12.03	19.04	1.81	No
	8	64.44	18.06	40.03	40.04	12.05	19.06	1.82	No
	9	64.33	18.03	40.05	40.03	12.02	19.05	1.80	No
	10	64.61	18.01	40.06	40.06	12.05	19.02	1.80	No