

ANALYSIS OF WARM FORGING PROCESS

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ABSTRACT

ANALYSIS OF WARM FORGING PROCESS

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Forging is a metal forming process commonly used in industry. Forging process is strongly affected by the process temperature. In hot forging process, a wide range of materials can be used and even complex geometries can be formed. However in cold forging, only low carbon steels as ferrous material with simple geometries can be forged and high capacity forging machinery is required.

Warm forging compromise the advantages and disadvantages of hot and cold forging processes. In warm forging process, a product having better tolerances can be produced compared to hot forging process and a large range of materials can be forged compared to cold forging process.

In this study, forging of a particular part which is being produced by hot forging at 1200°C for automotive industry and have been made of 1020 carbon steel,

is analyzed by the finite volume analysis software for a temperature range of 850-1200°C. Experimental study has been conducted for the same temperature range in a forging company. A good agreement for the results has been observed.

Keywords: Warm Forging, Hot Forging, Metal Forming, Press Forging, Low Carbon Steel, Finite Volume Analysis

ÖZ

ILIK DÖVME İŞLEM ANALİZİ

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Dövme endüstride sıklıkla tercih edilen bir metal şekillendirme işlemidir. Dövme işlemi, işlem sıcaklığından şiddetle etkilenir. Sıcak dövme işleminde çok çeşitli malzemeler kullanılabilir ve karmaşık geometriler dahi işlenebilir. Ancak soğuk dövme işleminde demir esaslı malzemelerden sadece düşük karbonlu ve basit geometriye sahip çelik malzemeler dövülebilirler ve yüksek kapasiteli dövme makineleri gereklidir.

Ilık dövme, sıcak ve soğuk dövmenin avantaj ve dezavantajlarını birleştirir. Ilık dövme işleminde, sıcak dövme işlemine göre daha iyi toleranslara sahip bir ürün üretilebilir ve soğuk dövme işlemine göre daha çeşitli malzemeler dövülebilir.

Bu çalışmada otomotiv sektöründe kullanılan, 1200°C’de sıcak dövme ile üretilen ve 1020 karbon çeliğinden yapılan bir parçanın dövülmesi 850-1200°C

sıcaklık aralığı için sonlu hacim analizi yazılımıyla incelenmiştir. Deneysel çalışma bir dövme fabrikasında aynı sıcaklık aralığı için yapılmıştır. Sonuçlar birbirleri ile uyumludur.

Anahtar Kelimeler: Ilık Dövme, Sıcak Dövme, Metal Şekillendirme, Pres Dövme, Düşük Karbon Çeliği, Sonlu Hacim Analizi

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CHAPTER 1

INTRODUCTION

The term “forging” is applied to processes in which a piece of metal is worked in a machine to the desired shape by plastic deformation of the starting stock. The energy that promotes deformation is applied by a hammer, press, upsetter or ring roller, either alone or in combination. The shape is imparted by the tools that contact the workpiece and by careful control of the deformation process. A forging is produced in three distinct phases: stock preparation in the form of blooms, billets, bar or ingots; plastic deformation of the metal component to rough, close tolerance or net shape in one of the forging processes; and appropriate secondary operations [1].

The art of forging dates to at least 4000 BC and probably earlier. Metals such as bronze and wrought iron were forged by early man to produce hand tools and weapons of war. Forging of wrought iron and crucible steel continued until near the end of the 19th century for similar purposes and weapons of war are still produced by the forging process using more contemporary metals.

The forge-smiths of the 19th century were particularly skilled at hand or by open die forging of wrought iron. Many large shaft forgings weighing 10 tones and more were gradually built up by a process of forging. The invention of the Bessemer steel making process in 1856 was a major breakthrough for the ferrous forging industry. The forgers now had a plentiful supply of low cost steel for production of volume quantities of forgings. It has been accepted that the first cavity steel forgings using a closed die process commenced in the United States in 1862 for production of components for the Colt revolver.

The further development of the Bessemer process with the invention of the basic steel making technique meant that cheaper supplies of iron ore containing high phosphorus and sulphur levels could be smelted to produce good quality steel. The simultaneous development of the open hearth steel making process toward the end of the 19th century meant that the forging industry now had a reliable, low cost, high volume raw material.

With the introduction of motor vehicles, a considerable demand for forgings developed in the early years of the 20th century. Up until 1930, when the first forging press was introduced (Maxi press), all forgings were produced on hammers. The advantage of the forging press was exemplified by higher production rates and a lesser degree of skill in producing forgings as compared to hammer forging. The introduction of the forging press did not obsolete the forging hammer but rather challenged the manufacturers to improve their product and of course, there are many forgings which are best made on hammers [2].

Today we have computer controlled hammers and presses capable of making a wide range of components in a variety of materials for many applications including aerospace, automobile, mining and agriculture, to mention a few. So it is clearly seen that, since the dawn of mankind, metal working has assured strength, toughness, reliability, and the highest quality in a variety of products. Today, these advantages of forged components assume greater importance as operating temperatures loads and stresses increase [3].

The products of forging may be tiny or massive and can be made of steel (e.g. automobile axles), brass (e.g. water valves), tungsten (e.g. rocket nozzles), aluminium (e.g. aircraft structural members), or any other metal.

Forging is preferred in industry that because of having some basic advantages as reduced machining operations, ability of producing complex parts, refined grain structure and optimum grain flow, desirable directional properties. And also structural integrity of final product is an important advantage for the firms. There is

no voids and porosity, they have relatively uniform mechanical properties and also the response to heat treatment is predictable.

1.1 Forging Process

Forging process can be classified according to; (i) die type as closed die and open die, (ii) machine type as hammer, mechanical press, hydraulic press, screw press and upsetter and (iii) working temperature as hot forging, cold forging and warm forging.

1.1.1 Forging with respect to Die Type

Open die forging is carried out between flat dies or dies of very simple shape (Figure 1.1). The process is used mostly for large objects or when the number of parts produced is small. Often open die forging is used to prepare the workpiece for closed die forging [3]. The finished product in open die forging is a rough approximation of the die because there is no fully controlling of the geometry of the forging.

The simplest open die forging operation is the upsetting of a cylindrical billet between two flat dies. As the metal flows laterally between the advancing die surfaces, there is a less deformation at the die interfaces because of the friction forces than at the mid-height plane. Thus, the sides of the upset cylinder becomes barrelled as a general rule, metal will flow most easily toward the nearest free surface because this represents the lowest frictional path [4].

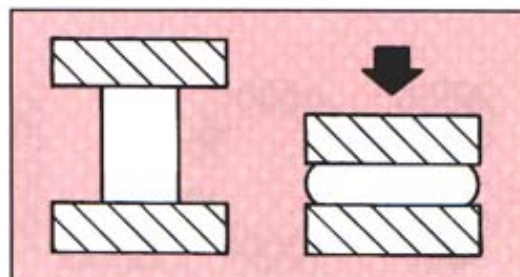


Figure 1.1 Open Die Forging

In closed die forging the workpiece is deformed between die halves which carry the impressions of the desired final shape (Figure 1.2) [3]. Since the workpiece is deformed under high pressure in a closed cavity, parts with more complex shapes and closer tolerances can be produced than with open-die forgings.

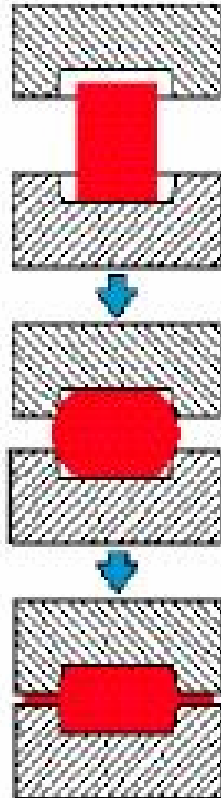


Figure 1.2 Closed Die Forging Operation



Figure 1.3 Schematic Drawing of Closed Die Forging

It is important to use sufficient metal in the forging blank so that the die cavity is completely filled. Because it is difficult to put just the right amount of metal in the correct places during fullering and edging, it is customary to use a slight excess of metal. When the dies come together for the finishing step, the excess metal squirts out of the cavity as a thin ribbon of metal called flash. In order to prevent the formation of a very wide flash, a ridge, known as a flash gutter, is usually provided (Figure 1.3). The final step in making a closed die forging is the removal of the flash with a trimming die. The ideal is to design for the minimum flash needed to do the job [3].

1.1.2 Forging with respect to Machine Type

Hammers are energy-restricted machines since the deformation results from dissipating the kinetic energy of the ram. Hammer forging is a preferred method for individual forgings. It is the shaping of a metal or other material, by an instantaneous application of pressure to a relatively small area. A hammer or ram, delivering intermittent blows to the section to be forged, applies this pressure [5].

The two basic types of hammers are the board hammer and the power hammer. In the board hammer the upper die and ram are raised by friction rolls gripping the board. When the board is released, the ram falls under the influence of gravity to produce the blow energy. The board is immediately raised again for another blow. Greater forging capacity is achieved with the power hammer in which the ram is accelerated on the down stroke by steam or air pressure in addition to gravity. Steam or air also is used to raise the ram on the upstroke.

Hammers can strike between 60 and 150 blows per minute depending on size and capacity [3]. Hammer forging can produce a wide variety of shapes and sizes and, if sufficiently reduced, can create a high degree of grain refinement at the same time. The disadvantage to this process is that finish machining is often required, as close dimensional tolerances can not be obtained [5].

The forging hammer is the cheapest source of a high forging load. It also has the shortest contact time under pressure, ranging from 1 to 10 ms however; hammers generally do not provide the forging accuracy obtainable in presses. Also, because of their inherent impact character, problems must be overcome with ground shock, noise, and vibration. Some of these problems are minimized with the counterblow hammer which uses two opposed rams which strike the workpiece at the same time so that practically all of the energy is absorbed by the work and very little energy is lost as vibration in the foundation and the environment.

Press forging is similar to kneading, where a slow continuous pressure is applied to the area to be forged. The pressure will extend deep into the material and can be completed either cold or hot. Press forging is more economical than hammer forging (except when dealing with low production numbers), and closer tolerances can be obtained. A greater proportion of the work done is transmitted to the workpiece, differing from that of the hammer forging operation, where much of the work is absorbed by the machine and foundation. This method can also be used to produce larger forgings, as there is no limitation in the size of the machine [5].

Forging presses are of either mechanical or hydraulic design. Mechanical presses are stroke-restricted machines. Most of them utilize an eccentric crank to translate rotary motion into reciprocating linear motion of the press slide (Figure 1.4). The ram stroke is shorter than in a hammer or hydraulic press, so that mechanical presses are best suited for low-profile forgings. The maximum load is attained when the ram is about 1/8 in of the bottom dead centre position. The blow of a press is more like a squeeze than like the impact of a hammer. However, the initial cost of a press is much higher than with hammer, so that large production runs are needed. The production rate is comparable to that of a hammer, but since each blow is of equal force, a press may be less suitable for carrying out preliminary shaping and finishing operations in the same piece of equipment [3].

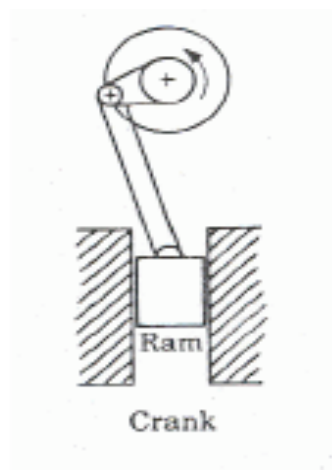


Figure 1.4 Schematic Drawing of Mechanical Press

Hydraulic presses are load-restricted machines in which hydraulic pressure moves a piston in a cylinder (Figure 1.5). A chief feature is that the full press load is available at any point during the full stroke of the ram. This feature makes the hydraulic press ideally suited for extrusion-type forging operation. The ram velocity can be controlled and even varied during the stroke. The hydraulic press is a relatively slow speed machine. This results in longer contact time, which may lead to problems with heat loss from the workpiece and die deterioration. On the other hand, the slow squeezing action of a hydraulic press results in close-tolerance forgings. The

initial cost of a hydraulic press is higher than that of a mechanical press of equal capacity [3].

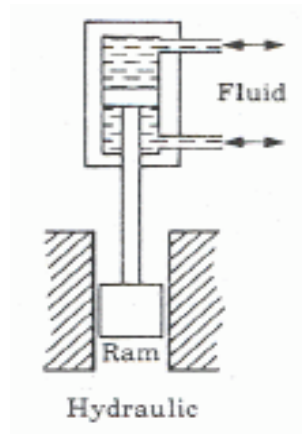


Figure 1.5 Schematic Drawing of Hydraulic Press

Screw presses (Figure 1.6) are widely used in Europe for both hot and cold closed die forging. In a screw press, the ram is connected by a rotary joint to a spindle, which is in effect a large screw. The rotary motion of a flywheel is transformed into linear motion by the multiple threads on the spindle and its nut [3].

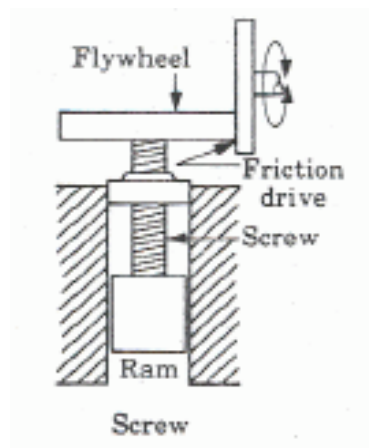


Figure 1.6 Schematic Drawing of Screw Press

Table 1.1 Typical Values of Velocity for Different Forging Equipment [6]

Forging Machine	Velocity (m/s)
Gravity drop hammer	3. 6-4.8
Power drop hammer	3.0-9.0
HERF machines	6.0-24.0
Mechanical press	0.06-1.5
Hydraulic press	0.06-0.30

More information about these machines can be found in several publications [7-9].

1.1.3 Forging with respect to Working Temperature

Cold forging involves either impression die forging or true closed die forging with lubricant and circular dies at or near room temperature. Small range of parts and materials can be utilized at cold forging. Carbon and standard alloy steels are most commonly cold-forged. Parts are generally symmetrical. Parts with higher precision with a high surface quality and close tolerances can be produced. No shrinkage occurs. Production rates are very high with exceptional die life. High forces are required and intermediate treatments are needed. While cold forging usually improves mechanical properties, the improvement is not useful in many common applications and economic advantages remain the primary interest. Tool design and manufacture are critical.

Hot forging is the plastic deformation of metal at a temperature and strain rate such that recrystallization occurs simultaneously with deformation, thus avoiding strain hardening. For this to occur, high workpiece temperature (matching the metal's recrystallization temperature) must be attained throughout the process, so energy needed for this preheating. By hot forging, it can be produced a great variety of

shapes with virtually any steel. The extensive scale formation occurs on the surface of the workpiece. Larger tolerances and allowances are needed for further machining. A form of hot forging is isothermal forging, where materials and dies are heated to the same temperature. In nearly all cases, isothermal forging is conducted on super alloys in a vacuum or highly controlled atmosphere to prevent oxidation.

Warm forging combines the advantages of both cold and hot forging; surface quality, precision and material utilization from cold forging and, processable range of materials and shapes from hot forging side. However, the implementation of warm forging is limited by high investment costs for the rearrangement of machines and expenses for tools and development. Temperature range is usually between 600°C and 900°C. Ferrite brittleness and scaling factor is limiting for this working temperature range.

Warm forging is a relatively new process that became known in early 70s. While it is more established in the industry of East-Asian countries and Japan, warm forging is not used widespread in Europe. It is mainly applied to rotationally symmetric parts and often combined with cold forging in the production of bevel gears, journals, etc. Warm forging will be discussed in Chapter 2 in detail.

1.2 Forging Defects in Forging

A defect is a flaw in a component that is typical of a process, but not inevitable. Good forging practice can eliminate most of them. They can be summarized in a table as below.

Table 1.2 Possible Forging Defects [10]

Possible Forging Defects		
Defect	Description	Problem
Segregation	Non-uniform distribution of elements in metal	Non-uniform hardness
High-hydrogen content	Forms of hydrogen fissures (flakes)	Embrittlement
Inclusions	Nonmetallic particles in metal	Act as stress-raisers; make machining difficult (tool breakage)
Bursts	Internal tears (effect of forging operations on inclusions, etc.)	Cracking
Poor grain structure	Overheating, improper billet size, poor die design, etc.	Poor properties in crucial directions; fatigue failure
Laps (folds)	Hot metal folded over and forged into surface, creating discontinuity	Stress-raisers; may cause machining or heat treat cracking problems
Seams	Hot surface tears in original ingot; embedded scale, etc.	Stress-raisers
Cold shuts	Defective metal flow	Low strength
Cracks, tears	Internal discontinuity (poor design; poor practice – metal too cold, etc.)	Cracking

1.3 Usage of CAD/CAM/CAE for Analysis of Forging Process

With the development of Computer-Aided-Design (CAD), Computer-Aided-Manufacturing (CAM) and Computer-Aided-Engineering (CAE) techniques, it become possible to reduce time and effort on design and manufacturing stages.

By using CAD/CAM softwares, the designer can create the 3-D model of the forgings, preform geometries, and the necessary dies. Modelling in detail gives the opportunity to change the parameters such as dimensions, taper angles, fillet radii, shrinking factor, etc. easily and to optimize the process by that trialling study form.

FEM - Finite Element Method or FEA - Finite Element Analysis is a numerical method for calculating stresses and deformations in complex geometrical structures. The structure is divided into so called "finite elements" connected through nodes. The physical facts are described on the basis of initial or boundary conditions for each of the elements concerned. The definitions of all elements are summarised in the global system of equations, which can be solved. Some programs used as simulation packages which use this algorithm are ANSYS, MARK, DEFORM, FORM etc. [11-14]. By using these programs, metal flow, stress, strain and temperature distributions can be predicted.

Development of FE simulation technology in forging area started in the late 1960s. During 1970s and early 1980s two-dimensional (2D here after) steady state simulation such as drawing/extrusion of round bar and plane strain sheet rolling, which do not require remesh, were available [15-17]. 2D non-steady state metal flow with manual remeshing, which required much time to complete a simulation, were applied in limited forging areas especially in hot forging of aero-space part development [18,19]. Since automatic meshing and remeshing technology was developed in the late 1980s and early 1990s [20] capability of practical use of FE simulation has been drastically increased and accompanied by the wide spread high cost-performance workstations. The automatic remeshing technology as well as the high cost-performance computer made the FE simulation softwares as a practical development tool in large size forging companies. From the middle of 1990s, 2D FE simulations were used widely as a practical tool even in small and medium size forging industries.

3D FE simulations have been used since softwares equipped with automatic remeshing capability were commercialized from the middle of 1990s. Recently, 2D

FE simulation softwares which run on PCs, with user friendly interface and short simulation lead times are being commercialized. On top of these backgrounds, various success stories on practical use of FE simulations encourage even small size forging companies to use FE simulation as a daily work tool [21].

Finite Volume Method (FVM) [22] is a method utilized in forging simulations. Unlike a traditional FE mesh, which distorts while attempting to follow the deformation material, the mesh is a fixed frame of reference and material simply flows through the finite volume mesh. Forging typically involves large material flow as well.

The finite volume method is a numerical method for solving partial differential equations that calculates the values of the conserved variables averaged across the volume. One advantage of the finite volume method over finite difference methods is that it does not require a structured mesh (although a structured mesh can also be used). Furthermore, the finite volume method is preferable to other methods as a result of the fact that boundary conditions can be applied noninvasively. This is true because the values of the conserved variables are located within the volume element, and not at nodes or surfaces. Finite volume methods are especially powerful on coarse nonuniform grids and in calculations where the mesh moves to track interfaces or shocks [23].

Hyman [24] have derived local, accurate, reliable, and efficient finite volume methods that mimic symmetry, conservation, stability, and the duality relationships between the gradient, curl, and divergence operators on nonuniform rectangular and cuboid grids.

MSC.SuperForge is a software package for the computer simulation of industrial forging processes. It combines a robust finite volume solver with an easy-to-use graphical interface specifically designed for the simulation of 3D bulk forming operations. MSC.SuperForge is being effectively utilized by forging companies and suppliers worldwide to successfully simulate the forging of a variety of practical industrial parts [25]. In the software, the advantages of the finite element and the

finite volume approach are combined; it employs a finite volume mesh for tracking material deformation and an automatically refined facet surface to accurately track the free surface of the deforming material. This approach is both fast and accurate since flow calculations are performed on a fixed finite volume mesh and material simply flows through it. It is also robust since re-meshing techniques are completely eliminated [26]. This provides a unique advantage in the simulation of three-dimensional parts; where finite element based solutions typically break down.

Some previous studies have been conducted on different types of forgings. As a Ph.D. study at University of Birmingham, Gökler [27] developed a computer program for the design of the operational sequences and the dies for horizontal forging machines. Upset forging has also been studied by Kazancı [28]. He developed a program named as Pro/UPSETTER for the sequence and die design of solid hot upset forgings having circular shanks and upset regions with non-circular cross-sections. In another study, Moğulkoç [29] rationalized the design rules for upsetting and piercing on horizontal forging machines and suggested a new methodology for the geometry of the profiles by using the finite element analysis technique.

Ceran [30] studied on hot upset forging process by using a commercial finite element code coupled with thermal analysis in order to determine effects of the process on the header die for the taper preform stages. A study on upset forging process and the design limits for tapered preforms had been conducted by Elmaskaya [31] by using the elastic-plastic finite element method. İsbir [32] studied on the finite element simulation of shearing using the element elimination method to examine trimming operation on forged parts. In the study of Doğan [33], the effects of the tapered preform shapes on the final product in cold upset forging had been investigated by using the elastic-plastic finite element method.

Alper [34] developed a computer program for axisymmetric press forgings, which designs the forging geometry and the die cavity for preforms and finishing operation.

Kutlu [35] studied on the design and analysis of preforms in hot forging for non-axisymmetric press forgings. Karagözler [36] studied on the analysis and preform design for long press forgings with non-planar parting surfaces. Gülbahar [37] studied on the preform design and analysis of hot forging process for a heavy vehicle steering joint. Civelekoğlu [38] studied on analysis of hot forging for three different alloy steels.

Also in warm forging studies, computer aided programs have been used to analyses. Shivpuri [39] has studied on advances of process modelling techniques in cold and warm forging by using DEFORM, ANSYS and ABAQUS. Just [40] were interested in the verifications of the damage model of effective stresses in cold and warm forging operations and used FE Software MSC.Superform 2002. He used model of effective stresses (MES) in the FE evaluation of the experiments.

Kim [41] made studies on effects of surface treatments and lubricants for warm forging die life and used DEFORM. Another study on die life and lubrication in warm forging belongs to Iwama [42]. Sheljaskow [43] has also studies on tool lubricating systems in warm forging.

Xinbo [44] studied on the flow stress characteristics of some specific materials in the temperature range of warm forging. Just [45] made a FE based fracture analysis in order to extend the forming limits in cold and warm forging by using MSC.Superform 2002. Kim [21] researched practical and effective use of FE simulation in cold and warm forging process and tool design. Xinbo [46] discussed the flow stresses of carbon steel 08F in temperature range of warm forging in his study. Lee [47] studied on application of numerical simulation for wear analysis of warm forging by using DEFORM as a FEM code.

1.4 Scope of the Thesis

The advantages and disadvantages of hot, cold and warm forging have been discussed in the previous section and it has been decided that it would be worth to study on analysis of forging at different temperatures.

In this study hot and warm forging processes of a part which is used in automotive industry, have been examined. The processes in different temperatures of the part, in which 1020 carbon steel has been used, have been analyzed by the finite volume analysis software, MSC. Superforge. The sample part and dies are modeled by using CatiaV5. The results of these analyses will be compared with the results of the experimental tests that have been performed in a forging company.

In Chapter 2, warm forging process is examined in detail. In Chapter 3, case study for an industrial forging is presented. Finally, conclusions and suggestions for future works are given in Chapter 4.

CHAPTER 2

WARM FORGING

2.1 Industrial History of Warm Forging

Warm forging is a relatively new process that became known in early 70s. The growth in the automotive industry brought the cold forging application in serial mass production of a wide range of component types. This caused that some cold forging techniques have been developed to be able to get near-net and net-shape components in large batch quantities. However; the limitations in economic production of parts with complex geometry, large size and in certain alloys caused the developments and commercial usage of warm forging process.

2.2 Warm Forging Technology

Warm forging can be applied to the steel parts within the temperature range of 600°C and 900°C except the austenitic stainless steels, since they are forged at 200-300°C [48]. It has some advantages compared to both hot forging and cold forging. Warm forging offers better utilization of material, improve a surface finish, and dimensional accuracy when compared with hot forging and reduced press loads when compared with cold forgings.

Independent of the fact that the temperature interval of warm forging is close to hot die forging temperatures, this forming process, with regard to the used design concepts for the tool and the achievable quality of the manufactures components, is often considered an expansion of cold forging to such workpiece materials that cannot be forged at room temperature or only with difficulty [49].

2.2.1 Basic Characteristics of Warm Forging

A comparison of the typical characteristics of hot, warm and cold forging processes is given in Table 2.1.

Table 2.1 A Comparison of Process Characteristics [49]

	Hot	Warm	Cold
Weight of the Workpiece	<60 kg	<10 kg	<2 kg
Steel Grade	Any	C desirable Other alloying elements < 10 %	Low alloyed steels (C<0.45%, other <3%)
Shape	Any without undercut	Rotationally- symmetrical without undercut	Rotationally- symmetrical without undercut
Surface Quality	Low	Medium	High
Intermediate Treatments	Not necessary	Normally no surface treatment	Annealing and bonderizing
Deformation Pressure	Low	Medium	High
Energy Costs	High	Medium	Low
Tolerances	Generous	Close	Closest
Tooling Costs	Lowest	High	High

2.2.2 Workpiece Material for Warm Forging

Warm forging can be applied to a larger variety of metal alloys, in particular to various grades of steels and to numerous non-ferrous metal alloys. Most engineering steels may be warm forged but there are limitations to deformation,

depending on chemical composition and forging temperature. For forging at temperatures of 600°C and above, metal should be used in the as-received hot rolled or drawn condition. For lower temperatures a spheroidize annealing treatment is often helpful. Different classes of steels have different characteristics which basically determine the working temperature [48].

- Carbon Steels: Since they may be brittle at 200-500°C, forging above 600°C is good to have reduction in flow stress and high ductility.
- Alloy Steels: The flow stress decreases while temperature increases. Generally they can be forged at any temperatures depending on circumstances.
- Austenitic Stainless Steels: Flow stress decreases greatly while temperature increases in small amounts, although they may strain harden. These kind of steels are usually forged at 200-300°C.

S. Sheljaskov [49] classifies the workpiece materials that used in warm forging as unalloyed or low alloy cementation steels, heat-treatable steels, steels for superficial hardening, ball-bearing steels and stainless steels. Some examples for these materials are given below;

- Cementation steels: Ck10 (AISI 1010), Ck15 (AISI 1015), 15CrNi 6 (AISI4320), 16MnCr5 (AISI 5117), 20 MnCr5 (AISI 5120).
- Heat-treatable steels: Ck35 (AISI 1035), Ck45 (AISI 1045), Ck60 (AISI 1060), 34Cr4 (AISI 5132), 34CrMo4 (AISI 4137), 42CrMo4 (AISI 4140), 50CrV4 (AISI 6150).
- Steels for superficial hardening: Cf53 (AISI 1053).
- Ball-bearing steels: 100Cr6 (AISI E52100).
- Stainless steels: X5CrNi 18 9 (AISI 304L), X10CrNiMo 17 12 (AISI 316).

2.2.3 Tools and Tool Steels in Warm Forging

The tools for warm forging and predominantly the active elements of these tools such as dies and punches are exposed to a high, mostly penetrating, cyclical mechanic stress that in the area close to the surface is superimposed by thermal, tribological and even chemical stresses. The combination between rather high forming temperatures and the still relatively high forming forces make the selection of suitable tool material as well as the design of the entire tool construction for warm forging more difficult than for cold or hot forging [49].

Conditional on the considerably higher forming forces in comparison to hot forming, the tool design and the tool structure must be orientated towards the ones of cold forging tools. On account of the still high flow stress, the tools must be prestressed. For this reason, forming of mainly rotationally symmetrical or axially symmetrical components is a prerequisite for the use of this process.

In warm forging, as with any forming operation, the choice of tool material can be critical both technically and economically. Technical failures of tooling due to excessive wear, deformation, cracking or heat checking occur because either the wrong steel has been selected or because the heat treatment, coating or machining procedures have not been optimized. All technical failures lead to financial loss due to lower tool life and therefore increased tool material costs, repair costs, maintenance costs and increased stand still time leading to lower productivity.

The stresses the tool experiences during warm forging lead to requirements that can be summarized in three basic properties and the tool material must comply with them, namely dimensional stability, security against fracture and resistance to wear.

A general classification for tool steels may be done as followings [48]:

- High Speed Steel: Longest tool life is achieved with high speed steel such as M2 or its equivalents in powder metallurgy form. High speed steels have low

temperature shock resistance. They must be preheated and can be cooled during production only by air. The use of water cooling or water based lubricants will cause rapid fracture. This characteristic of high speed steels may limit productivity if a high rate of forging would result in a significant heat build up in the tools.

- Hot Work Steels: Steels of the chromium, molybdenum, vanadium family such as, X40CrMoV51 and H13 do not possess the strength or hardness of high speed steels but are tougher with greater resistance to thermal shock. Therefore they can be rapidly cooled in service. A variety of these steels is available enabling hardness's between 50 and 60 HRC to be achieved appropriate to various process conditions.
- High Nickel Alloys: Nickel alloys can be used to achieve excellent service lives under extreme conditions. These alloys have: high fatigue strength, high thermal shock resistance and high toughness over a range of temperatures. The use of Inconel 718 has been reported in [50]. The successful use of an 18% nickel maraging steel extrusion punch was reported in [51]. This was solution treated at 820°C and aged for 3 hours at 500°C to give a proof stress of 1850 MPa. The use of these alloys is usually prohibited by their high cost which can be an order of magnitude greater than that of conventional steels.
- Tungsten Carbide: This material can be used as inserts for warm forging tools [49]. However it has been reported that failure of carbide tools may occur when forging ceases and cooling takes place [50].
- Cobalt Alloys: Cobalt based alloys, available under the trade name Stellite, may be used in regions of tools which deform and erode due to overheating. These alloys are usually welded to the surface of the tools. A known example of the use of Stellite is as a welded ring around the periphery of a hot work steel counterpunch which could not be adequately cooled.

2.2.4 Heat Treatment for Warm Forging

Materials can be improved before or after manufacturing by different heat treatment processes. Forging is usually performed to hot metals, allowing for smoother flow and easier deformation. Steel is heated to varying temperatures, usually between 930°C to 1100°C but can reach as high as 1315°C for hot forming, depending on the carbon content. Depending on the amount of work required to the piece, it may be necessary to reheat the piece one or more times. The temperature of the metal when completely forged is called the finishing temperature. After forging, the material must be cooled uniformly and protected from moisture or cold air. This is done by placing the material into dry ashes, lime or mica dust in order to retard the rate of cooling [5].

Preheating: Preheating of materials is done to help prevent cracking or distortion of the material. This is done by placing the metal in a series of furnaces of increasing temperatures instead of throwing it directly into the furnace used to heat the metal for forging, annealing, normalizing or hardening. Another way to achieve this is to start in a cold furnace and slowly bring it to temperature.

Annealing: Annealing should follow forging as soon as possible whenever machining is required. Annealing is the heating and then cooling of metal to make the metal less brittle, or more malleable and ductile. This will soften the steel that was previously hardened and reduce internal stresses. Annealing is done by heating the metal to a temperature beyond the critical temperature and holding it there for a period of time. The metal is then cooled in the furnace and not removed until the furnace is cold. It can also be cooled to a temperature within the furnace that is known to be below the lower critical temperature, at which the annealing is complete. Slower cooling rates are required as carbon content increases in the metal.

Normalizing: Normalizing is done to improve the crystalline structure of the steel, thus obtaining superior properties. Heating the forged part just beyond the critical temperature and then allowing it to air-cool completes normalizing. This

allows the grain-size to be refined and, if not held at that temperature too long, will result in a newly formed crystalline structure. The internal stresses, if any, will be relieved, hardened steels will be softened, overheated steels will have a more favourable, normal fine-grained structure, and structural distortion will be removed.

Hardening: Hardening of steels can also be done after forging. The workpiece is heated slowly, to obtain the finest grain-sizes, to its hardening temperature – much higher than annealing temperatures. The metal is kept at this temperature only until uniform heat distribution and completion of the thermal transformation. Prolonged exposure at these elevated temperatures will result in increased grain growth and surface decarbonization, if no protection from oxidation is provided. Oxidation can be avoided by surrounding the metal with some material that will use up the oxygen that is present in the furnace. Once the metal has been uniformly heated to temperature, it is removed from the furnace and placed directly into a quenching tank. This rapidly cools the metal and the metal retains its new qualities.

Surface treatment operations may be performed on forgings to remove scale formed during forging and heat treatment, improve corrosion resistance, enhance appearance and improve surface properties. Surface treatment requirements are based on the alloy and forging process employed [1]. For example:

- Cold and warm forging operations are performed on steel alloys below the temperature range at which scale forms and do not require the removal of scale.
- Scale formation of stainless steel alloys is not generally a problem.
- Aluminum alloys can be given a hard anodized surface to improve abrasion and corrosion resistance.
- Forgings made from copper based alloys generally exhibit good surface quality and high corrosion resistance that eliminates the need for most surface treatment operations.

2.2.5 Lubrication for Warm Forging

The service life of the die is restricted by wear, thermal cracking and fatigue, and plastic deformation, etc. there have been many research projects to investigate the influence of these factors on tool life [52-55]. In general, however, the surface hardness of die increases during repeated operations, which induces thermal softening in warm forging processes. The thermal softening accelerates the wear, thermal cracking and fatigue, and the plastic deformation of the die [56,57].

In order to increase the die life, heat treatments have been performed for the die to increase the surface hardness, and surface treatments are also applied to the die to reduce the friction and to increase the thermal insulation. The thermal properties of the die are changed due to the surface treatments.

The roles of lubricants are to reduce friction between the die and the workpiece and to reduce heat-transfer from the billet to the die during the forming processes. Graphite, a solid lubricant, is sprayed onto the die or workpiece before the warm forming process. The heat-transfer coefficient, from the billet to the die, has different values according to the kind of graphite [58]. In addition, the selection of suitable lubricant for the extending die life leads to reduce heat transfer from the workpiece to the die life.

Spraying is almost always used to apply tool lubrication and automatic lubricating systems synchronized to the stroking of the forging machine are essential in high productivity mass production lines. In some cases tools are flooded with lubricant.

Some lubrication systems sequentially blast air into the cavities to clear debris, blow air/water mist mixture for cooling and then spray a lubricant. Depending on the tool materials and the lubricant one or all three of these operations can be used in a sequence of forging operations.

An important rule to observe is that the quantity of lubricant to be applied should be sufficient only to maintain an interfacial barrier between workpiece and tools during forging. If this is inadequate to cool the tools sufficiently two possibilities exist to remedy the situation:

1. If the lubricant is water-based, dilute it and increase the spray time. By this means a greater quantity of water will be applied to the tools for a given quantity of lubricant.
2. Apply an air, water or air/water spray before applying the lubricant. Such a measure depends on sufficient time being available in a forging stroke, for two different spraying operations.

The study on die life and lubrication in warm forging, by Iwama and Morimoto [42], is resulted as die life of the punch is affected by heat cracks and softening of the surface layer. To improve die life, it is essential that there is dry lubrication adhesion layer which binds strongly to the die. The die temperature range which provides the appropriate lubrication adhesion layer thickness is between 200 and 300°C. The most favorable die surface temperature at the start of the lubricant spraying is 300°C. The lubricant adhesion layer can be created in the shortest time by making the lubricant spray granules small.

Also there is a study made by S. Sheljaskow [43] on tool lubricating in warm forging which focuses on the environmental effects of these systems. In order to secure healthier working conditions for the operators and the other workers in the forging shop as well as a minimal environmental impact in combination with an optimal tool life, the European Community has funded a Brite-Euram industrial research project on the development of environmentally friendly tool lubricating systems. The result of the experiments made by this community is showed that slug coating and die lubricant selection should be treated as a package. The best results concerning environmental impact and tool life are achieved by the application of tool

lubricating systems consisting of a graphite-based slug coating and an oil-graphite-free die lubricant.

2.2.5.1 Lubricant Types

Lubricants may be grouped into the following types [48]:

- Colloidal Graphite-Oil:

These lubricant types have a lower latent heat of evaporation than the water based ones and are suitable for use with high-speed steel tools for which rapid cooling is detrimental. In many cases flooding of the tools is employed (the tools are designed with drains and vents to allow its escape) and if extra cooling is required an air blast is used also. A disadvantage of this type of lubricant is the smoke and fumes which are formed on contact with a heated workpiece as well as the high cost of disposal in conformation with environmental control.

- Colloidal Graphite-Water:

These lubricants are essentially pollution free and non toxic, with the qualification that graphite forms carbon monoxide and carbon dioxide. Also small amounts of organic compounds added to improve adhesive properties and increase temperature stability, decompose on contact with the workpiece to form traces of noxious gas but with no known significant health hazard. The lubricants are corrosive however largely due to the presence of ammonia as a bactericide and fungicide, so that pipes and fittings should be of stainless steel.

Water based graphite lubricants used under the correct conditions form a solid coating on the tools. This is an advantage in situations when an oil based lubricant would run off the tool surface or be squeezed out of the workpiece/tool interface. To perform properly a water based lubricant must adhere to the tools as the carrier evaporates. The durability of graphite coatings is enhanced by the

presence of binding agents which also raise the wetting temperature of the lubricants. Current products are commonly used to coat tool surfaces at temperatures of 400°C and above and using special spraying techniques have been used to coat tools at temperatures up to 800°C. Because of their good coating and friction reducing properties water based graphite lubricants are probably the most popular at present. However; although they are environmentally, virtually harmless the fact that they cause plant and equipment to be covered in a black film has brought them into disfavour and attempts are underway to develop white or colourless lubricants. Another disadvantage of colloidal graphite is that unless continuously agitated it tends to flocculate, forming a sediment in the holding tanks and clogging up pipes and spray nozzles.

- White Mineral in Water:

The compositions of these lubricants are largely known only to the manufacturers. The substances used have a molecular structure which allows the relative sliding of lamellae. Boron nitride and aluminium silicate are minerals known to have been used and although they form robust interfacial boundaries to obviate pick-up they are not very effective at reducing friction.

- Colourless Solutions in Water:

(a) Synthetic or vegetable based emulsions with additives usually comprise about 40% of the lubricant. They may be sprayed or flooded and are recyclable but have a wetting temperature of only 300°C.

(b) Solutions of up to 18% salts or soaps in water have wetting temperatures of about 400°C. They can be used as the sole lubricant in a process but with pregraphited billets the lubricity of the system is improved significantly [59].

The development of white/colourless lubricants has been underway for several years and noticeable performance improvements have been achieved. The question of tool life vis a vis graphited lubricants has yet to be answered.

One distinct advantage of these lubricants is that being water soluble the plant and workshop environment is readily washed clean. Also as the lubricating substances remain in solution pipework does not become clogged.

CHAPTER 3

CASE STUDY

As case study, forging of a particular part which is used in automotive industry and have been made of 1020 carbon steel, is analyzed for a temperature range of 850-1200°C. Firstly, the forging process is simulated by a finite volume program. The effective stress values obtained on the part, considering the ultimate strength of the die material, showed that the currently used die set is applicable for the same temperature range. Then, experimental studies are conducted for the same temperature range in a forging company. When it is observed that, the results of the first series of simulation and experimental studies do not correspond, finite volume analyses are repeated by using the values determined from experiment. In the following sections, results of the case study are presented.

3.1 Sample Part

The “Ring”, which has been analyzed as the case study, is being produced in AKSAN Forging Company, Ankara for automotive industry. The technical drawing and the model of the part are shown in Figure 3.1 and Figure 3.2, respectively. The material of the part is designated as AISI 1020 (DIN 1.1151) and its properties are given in Appendix A. The operation instructions of this part followed by AKSAN [60] are provided in Table 3.1. Forging steps are given in Figure 3.3. The billet is heated initially. Then, in the first stage, it is upset by open die forging. Subsequently the preform is forged in closed dies to obtain the forged part. Finally, the forged part is trimmed to obtain the finished part. Trimming is not analyzed in this study. Intermediate shapes of the part are shown in finish forging stage, in Figure 3.3.

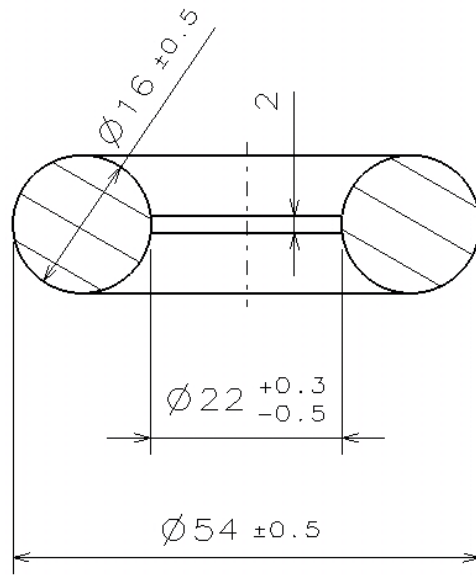


Figure 3.1 Technical Drawing of “Ring” [60] (Dimensions are in millimetres.)

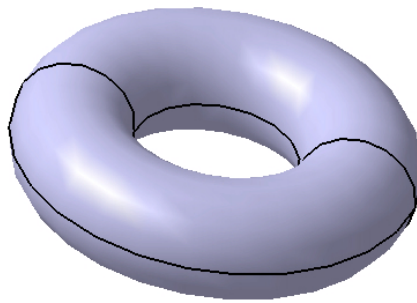


Figure 3.2 Model of Part “Ring”

Table 3.1 Operation Instructions [60]

Op #	Operation	Equipment
1	Saw the bar to length of 34 mm with billet diameter 32 mm	Sawing Machine
2	Heat the billet up to 1200°C	970 KW Induction Heater
3	Check the temperature with optical pyrometer	Optical Pyrometer
4	Upset the billet to clean scale	1000 tonf Mech. Press
5	Place the billet on the blocker and preform the billet	1000 tonf Mech. Press
6	Place the preform on the finisher die and forge the final shape	1000 tonf Mech. Press
7	Place the finished part on the punch die and punch out the hole	320 tonf Mech. Press
8	Place the finished part on the trimmer and trim the flash	320 tonf Mech. Press

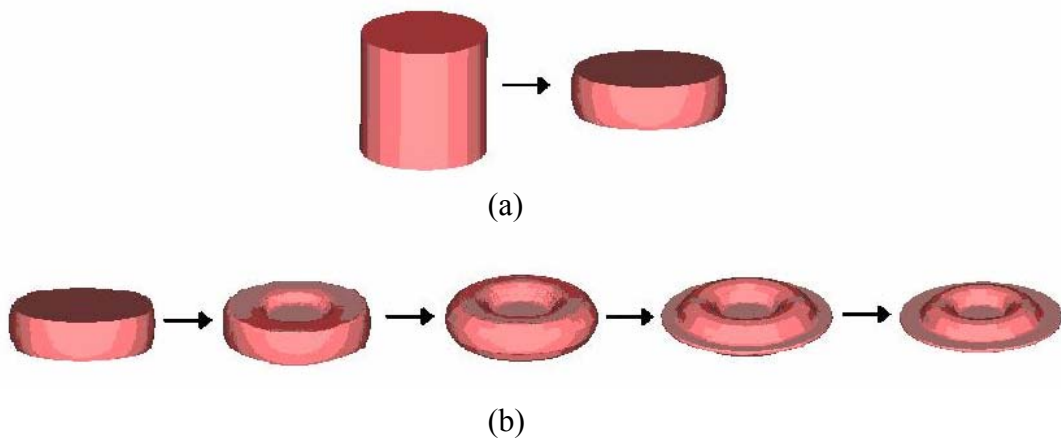


Figure 3.3 Simulation of Forging Steps of Sample Part

(a) First stage (b) Second stage of forging

3.2 First Series of Simulation of Forging

The forging process is modelled by Superforge Program [25,26], which is a commercially available finite volume code. Parameters of 1000 tonf (10 MN) mechanical press used in the particular forging company are entered in the numerical analysis software. In the program, the press is represented as given in Figure 3.4 with crank radius (R) of 125 mm, rod length (L) of 665 mm and rotational speed (ω) of 90 rpm.

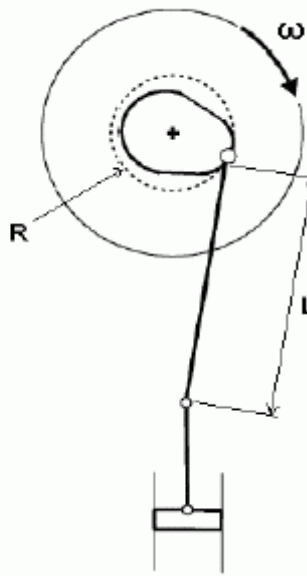


Figure 3.4 The input parameters of 10 MN mechanical press

Plastic shear friction model is used with 0.3 as the interface friction factor [61]. The element size used in the modelling of the workpiece is taken as 1 mm. The preform dies are composed of flat cylindrical blocks. The finish dies are modelled in Catia V5. The models of the finish dies can be seen in Figures 3.5 and 3.6. The dies are assumed as rigid surfaces in the analysis. The die temperature is taken as 250°C during the analysis. The die material is DIN 1.2714 or L6 and its properties are given in Appendix B. In the simulation, a facial clearance of 1.5 mm is maintained. The numerical results are taken at the temperatures between 870-1200°C with the increments of 50°C.

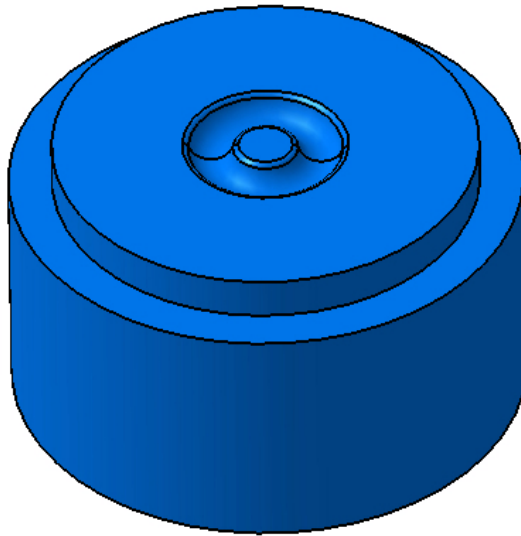


Figure 3.5 Model of Lower Finish Die

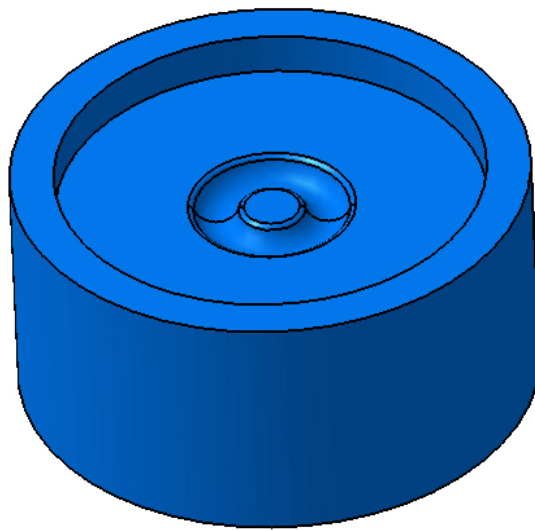


Figure 3.6 Model of Upper Finish Die

When stress distribution values given in Figures 3.7 - 3.14 are examined, it can be seen that warm forging process results in higher stress values than hot forging.

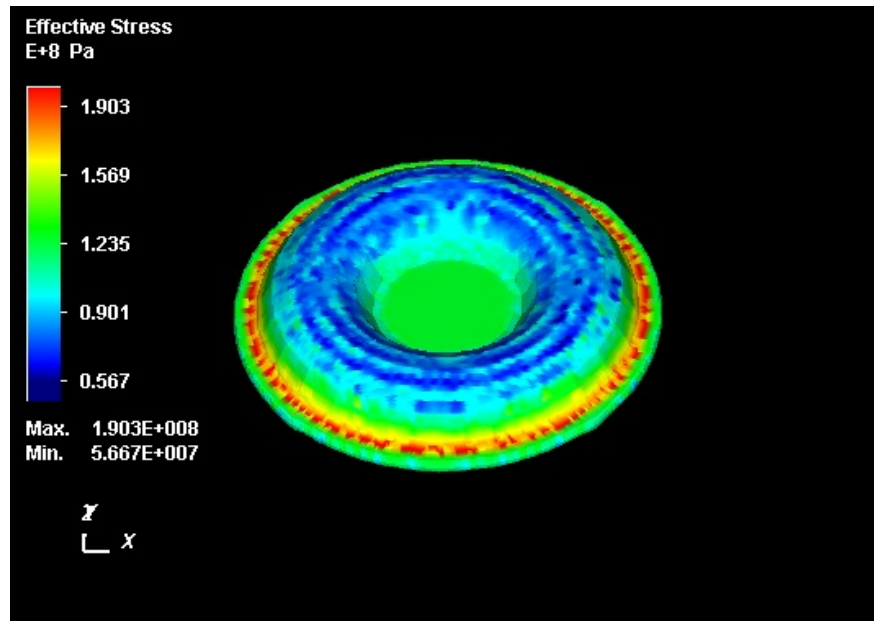


Figure 3.7 Effective Stress Distributions for Forging Process at 1200°C

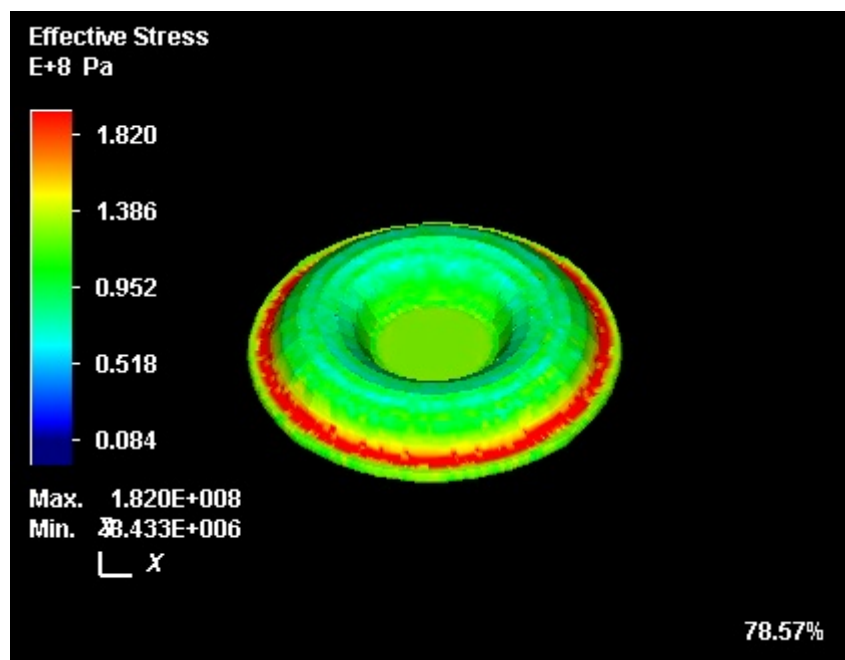


Figure 3.8 Effective Stress Distributions for Forging Process at 1150°C

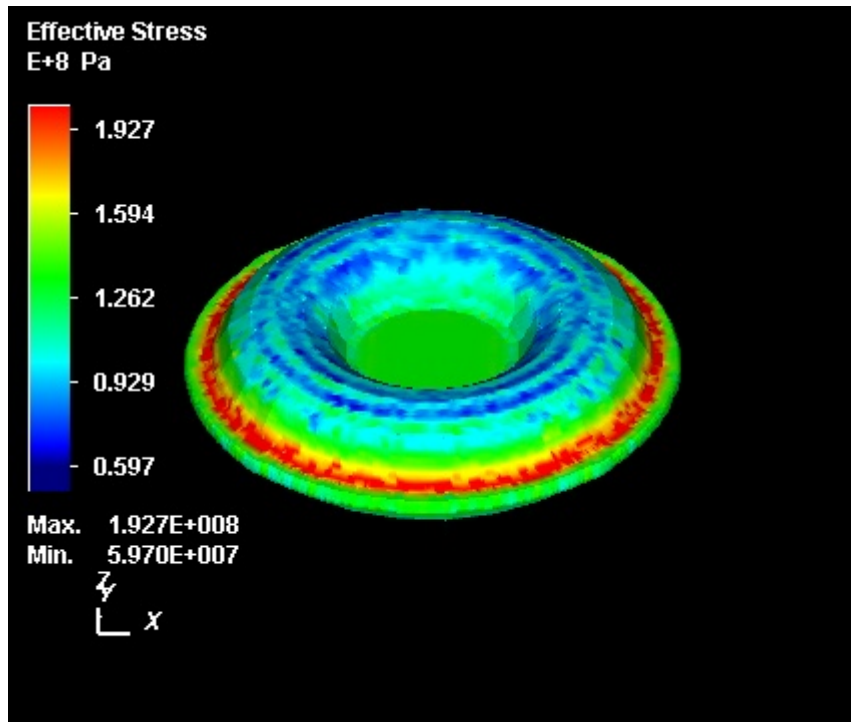


Figure 3.9 Effective Stress Distributions for Forging Process at 1100°C

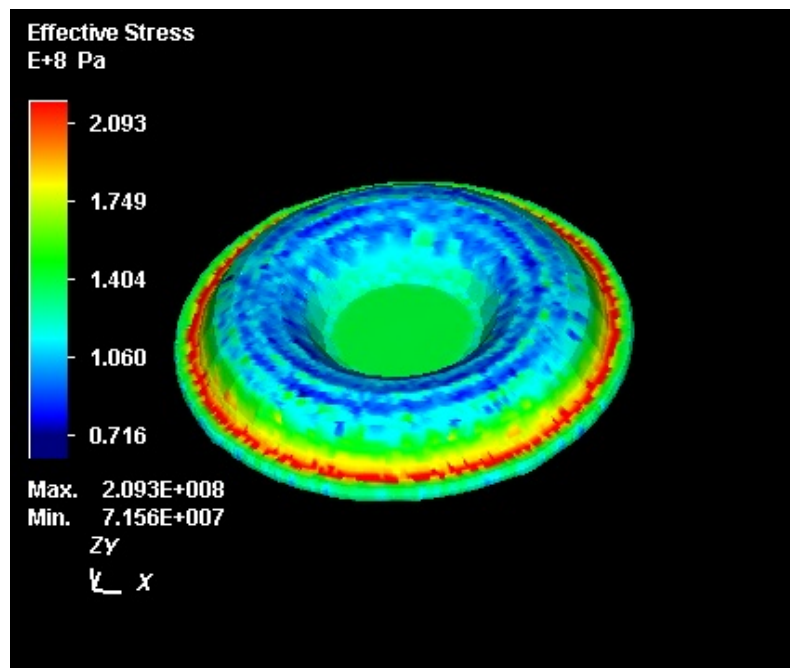


Figure 3.10 Effective Stress Distributions for Forging Process at 1050°C

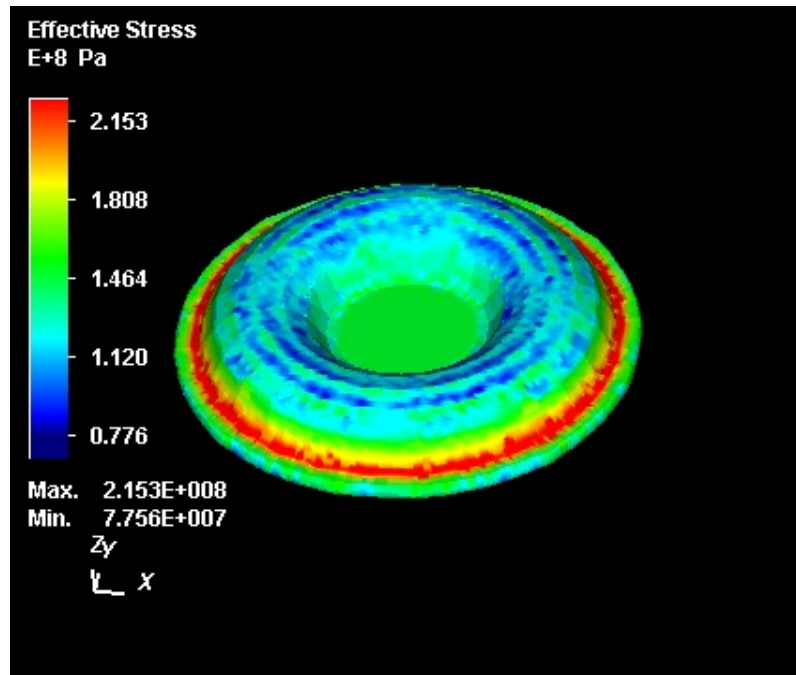


Figure 3.11 Effective Stress Distributions for Forging Process at 1000°C

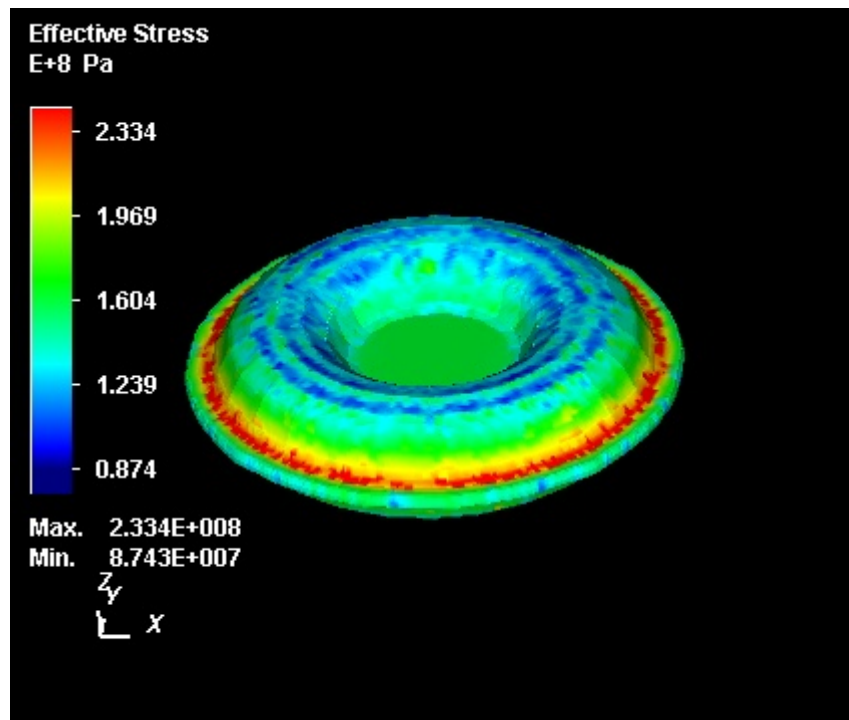


Figure 3.12 Effective Stress Distributions for Forging Process at 950°C

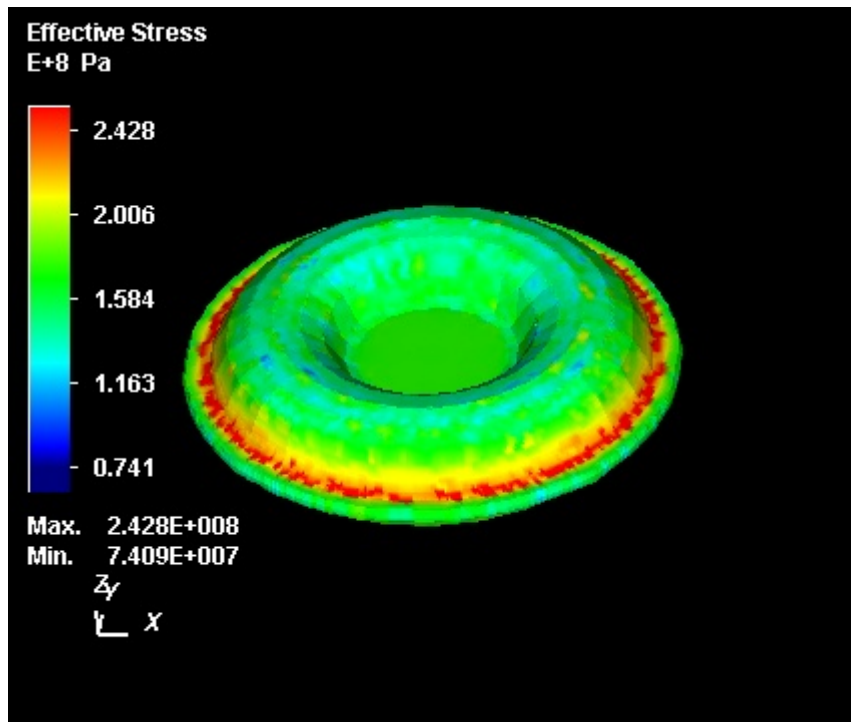


Figure 3.13 Effective Stress Distributions for Forging Process at 900°C

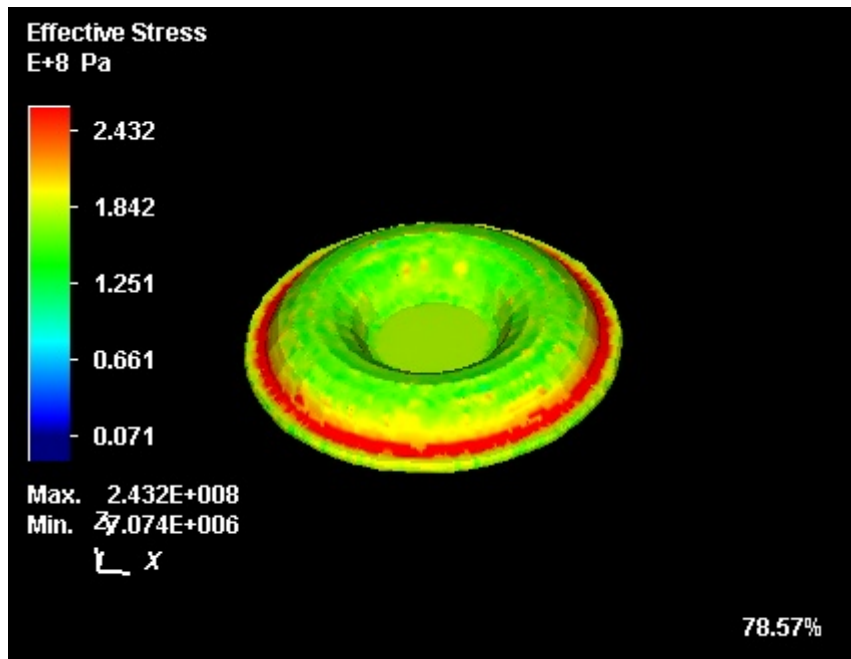


Figure 3.14 Effective Stress Distributions for Forging Process at 870°C

The punch force diagrams are given in Figures 3.15 - 3.22. The die forces obtained in warm forging process are higher than hot forging process. Therefore, at lower temperatures higher capacity presses are needed to deform the material.

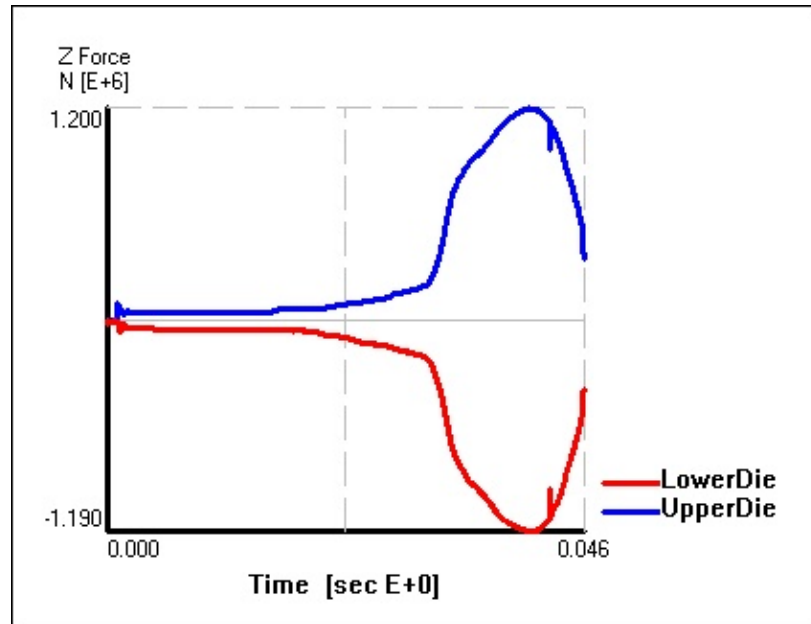


Figure 3.15 Punch Force Diagram for Forging Process at 1200°C

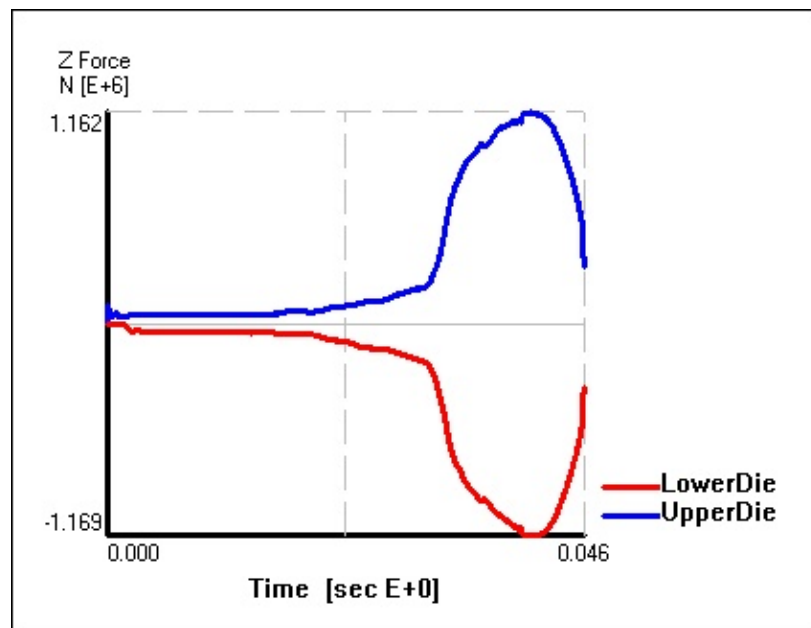


Figure 3.16 Punch Force Diagram for Forging Process at 1150°C

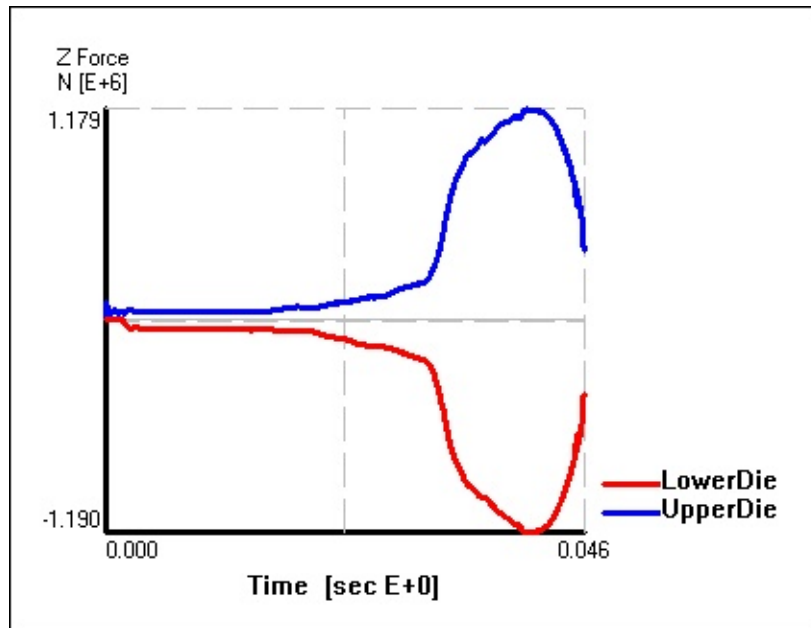


Figure 3.17 Punch Force Diagram for Forging Process at 1100°C

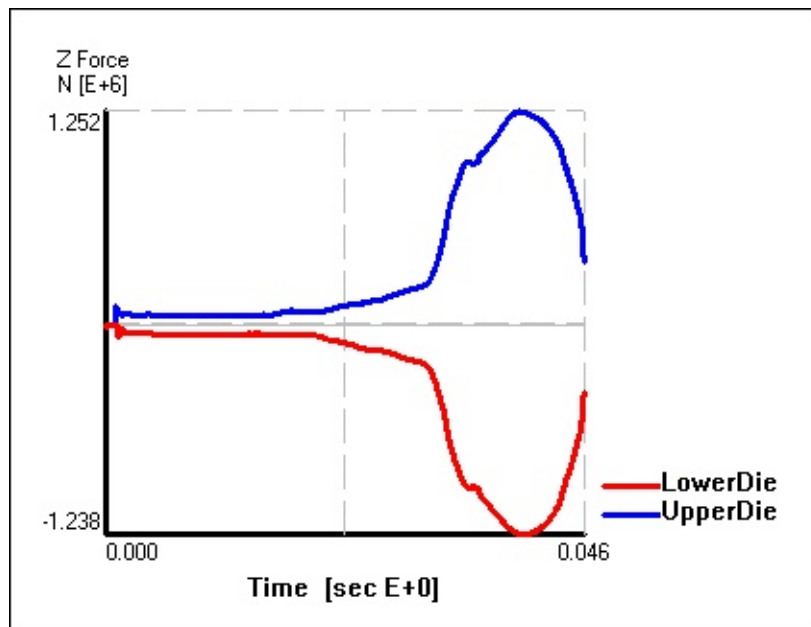


Figure 3.18 Punch Force Diagram for Forging Process at 1050°C

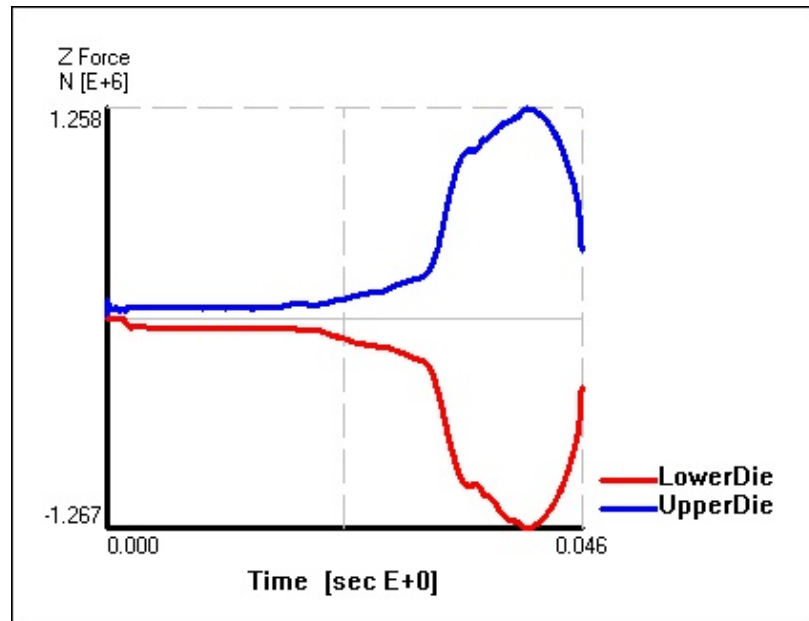


Figure 3.19 Punch Force Diagram for Forging Process at 1000°C

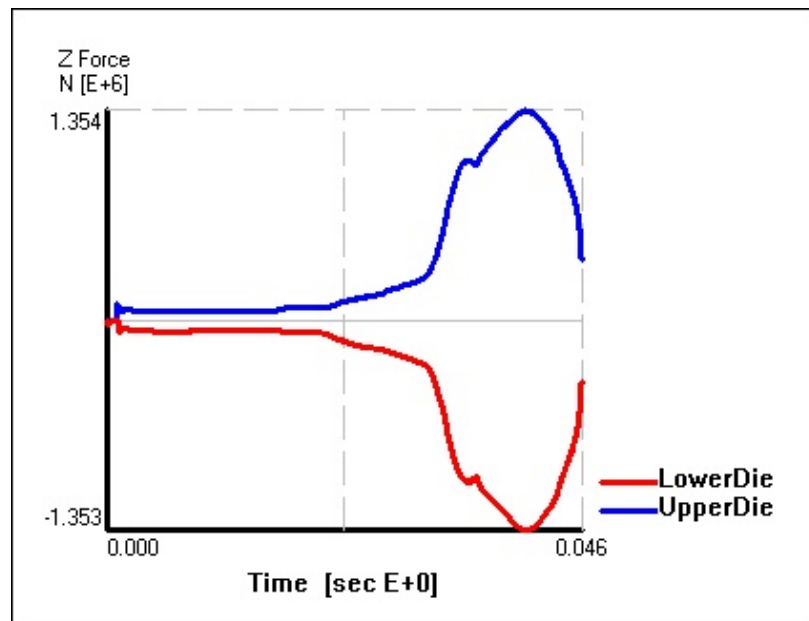


Figure 3.20 Punch Force Diagram for Forging Process at 950°C

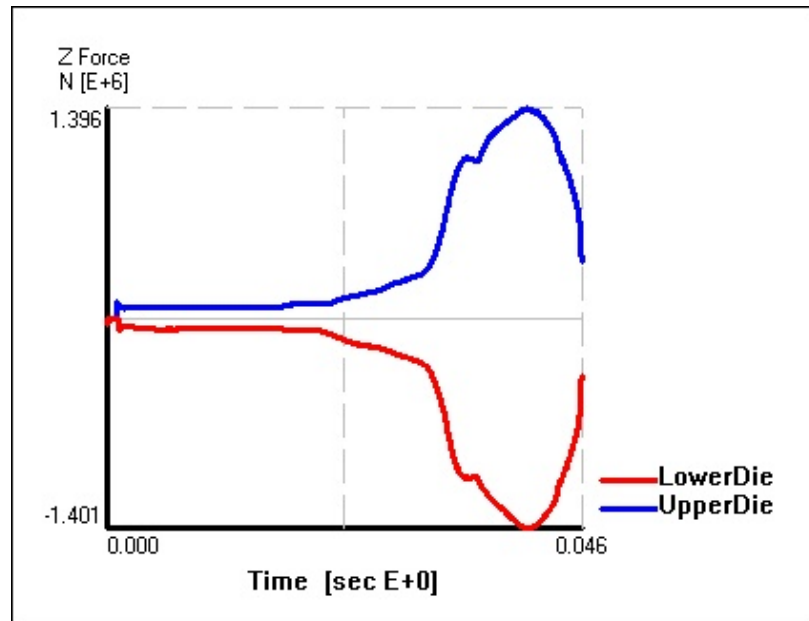


Figure 3.21 Punch Force Diagram for Forging Process at 900°C

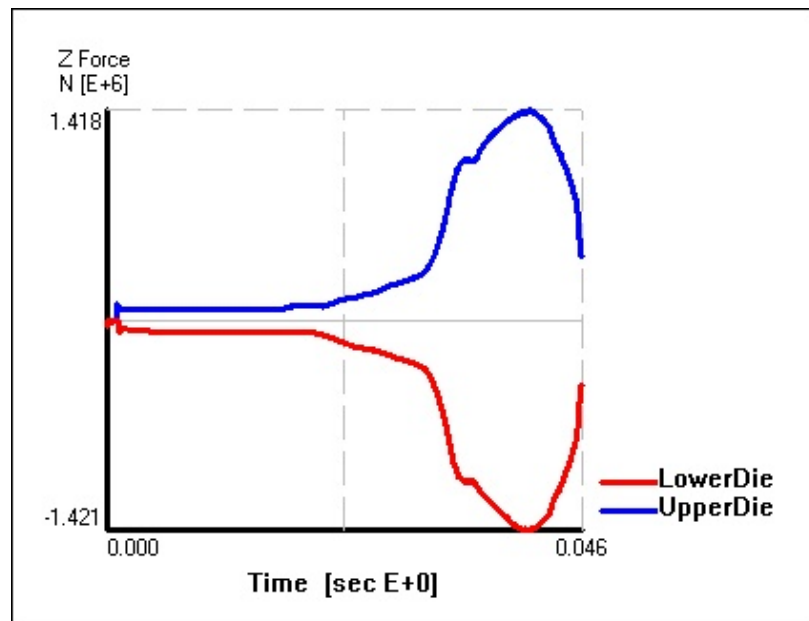


Figure 3.22 Punch Force Diagram for Forging Process at 870°C

The maximum values of effective stresses and punch forces are given at different temperatures for the first series of simulation in Table 3.2. As shown in Table 3.2, successful die fillings have been observed for the temperature range of 870-1200°C.

Table 3.2 Max Values at Different Temperatures for First Series of Simulation

Workpiece Temperature	Max. Effective Stress	Max. Punch Force	Die Filling Success
1200 °C	190.3 MPa	1.200 MN	Filled
1150 °C	182.0 MPa	1.162 MN	Filled
1100 °C	192.7 MPa	1.179 MN	Filled
1050 °C	209.3 MPa	1.252 MN	Filled
1000 °C	215.3 MPa	1.258 MN	Filled
950 °C	233.4 MPa	1.354 MN	Filled
900 °C	242.8 MPa	1.369 MN	Filled
870 °C	243.2 MPa	1.418 MN	Filled

3.3 Experiment Results

The finite volume analyses results showed that, since the stress values obtained on the parts are smaller than the ultimate tensile strength value of die material, and maximum punch force needed to forge the raw material in these temperatures are smaller than forging press capacity (1000tonf), it has been decided that the available die set can also be used for lower temperatures. Therefore, experiments have been conducted for different temperatures in Aksan Forging Company. For this purpose 10000 kN (1000 tonf) mechanical press is used. The 1000 tonf mechanical press, and the preform and finish dies fastened on the press can be seen in Figures 3.23 and 3.24, respectively.



Figure 3.23 1000 tonf Mechanical Press



Figure 3.24 Preform and Finish Dies Fastened to the Press

According to TS 2756 Standard, at least five samples of products should be taken to obtain reliable results for the experiments. Therefore, for each temperature, 1 heated billet, 5 preformed and 5 finished parts have been taken. During the

experiment, the temperatures of the billet and dies are measured by two different pyrometers.



Figure 3.25 Lower and Upper Finish Dies Used in Experiment

The finish dies are shown in Figure 3.25. The two different pyrometers were used to measure workpiece and dies temperatures. The pyrometer used to measure the workpiece temperature has the range of 600 – 1400°C whereas the pyrometer used to measure the die temperature has the range of -32 – 600 °C. In the Figure 3.26 the forged parts in experiment can be seen.

After completing the experiments measurements are taken on the finished part. The diameters and flash thicknesses are measured by compass, plug thicknesses (central region) are measured by comparometer, the heights are measured by CMM and the roughness values are measured by roughness measurement device. The experimental data is presented in Appendix C in detail. Finally, for each temperature group, averages of these values have been calculated and given in Table 3.3.



Figure 3.26 The parts in box waiting for cooling

Since the material did not fill the die cavity completely for the temperatures 1015°C, 957°C, 908°C and 853°C, the lower finish die is raised by 1 mm in the last two experiment groups.

The finish dies are also measured in CMM and it has been seen that they have larger sizes compared to the dies, which are applied in the first series of simulations by using the values given by AKSAN Forging Company. The difference may be attributed wear due to the usage.

Table 3.3 Average Values For Each Temperature Group

Billet Temp.	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Min Required Mass (g)	Finish Die Temp. (Lower)	Finish Die Temp. (Upper)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) mm*10-3	Plug Thickness (mm)
1191	32.48	34.04	222.01	217.22	221	222	54.45	16.096	213.6	2.648	4.496	3.486
1150	32.23	34.17	219.49	217.73	152	164	54.26	16.270	216.0	2.730	3.898	3.542
1096	32.26	34.10	219.34	217.71	166	164	54.29	16.288	214.8	2.738	3.324	3.558
1049	34.02	34.02	217.99	217.65	162	165	54.16	16.326	215.6	2.756	2.892	3.498
1015	32.16	34.11	218.08	217.88	239	248	54.16	16.273	215.6	2.858	2.682	3.658
957	32.23	34.22	219.73	217.85	161	161	54.46	16.345	216.8	2.904	2.272	3.700
908	32.19	34.17	218.86	217.96	238	208	54.32	16.314	216.4	2.926	1.966	3.728
853	32.29	34.26	220.83	218.18	275	269	54.24	16.352	216.0	3.016	1.796	3.882
Experiments by using the die set with raised lower die at amount of 1mm												
903	32.22	34.05	218.47	217.70	151	151	54.52	16.192	215.2	2.734	1.568	3.528
868	32.21	34.08	218.55	217.71	143	140	54.39	16.271	216.0	2.732	1.588	3.532

3.4 Second Series of Simulation of Forging

When the results of the experiments have been compared with the results of the first series of the simulation of forging, it is observed that there are significant differences. The analyses are repeated by using the actual die geometries and actual clearances for the determined material mass and temperatures.

The finish dies that used in the experiment, have been measured in CMM and then remodelled in Pro Engineer. The models can be seen in Figure 3.27 and Figure 3.28.

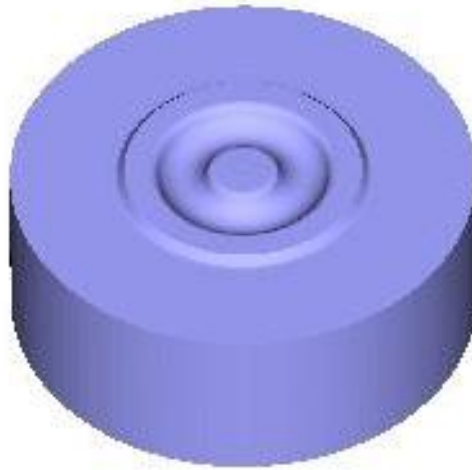


Figure 3.27 Model of Lower Finish Die

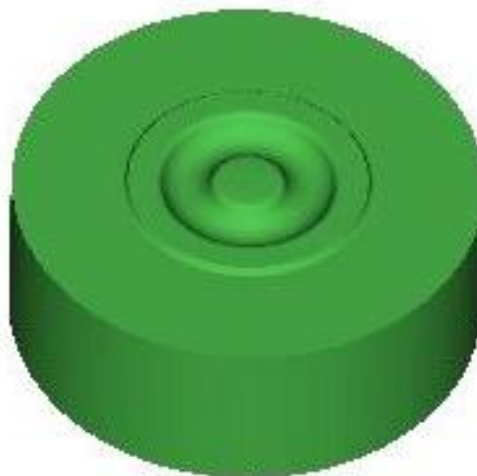


Figure 3.28 Model of Upper Finish Die

The effective stress distributions obtained in the second series of forging simulations are given in Figures 3.29-3.38. The maximum effective stress values obtained on part at different temperatures can be seen in Table 3.4.

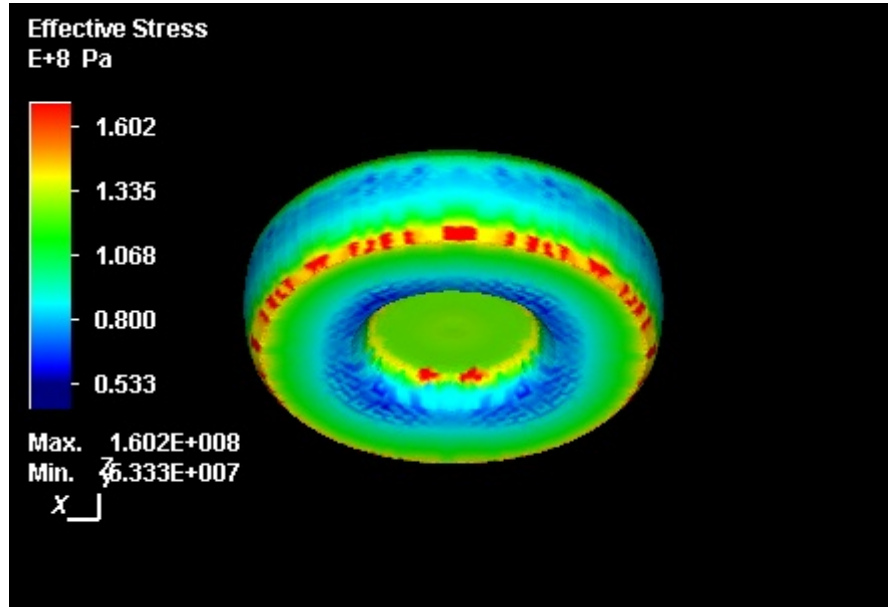


Figure 3.29 Effective Stress Diagram for Forging Process at 1191°C

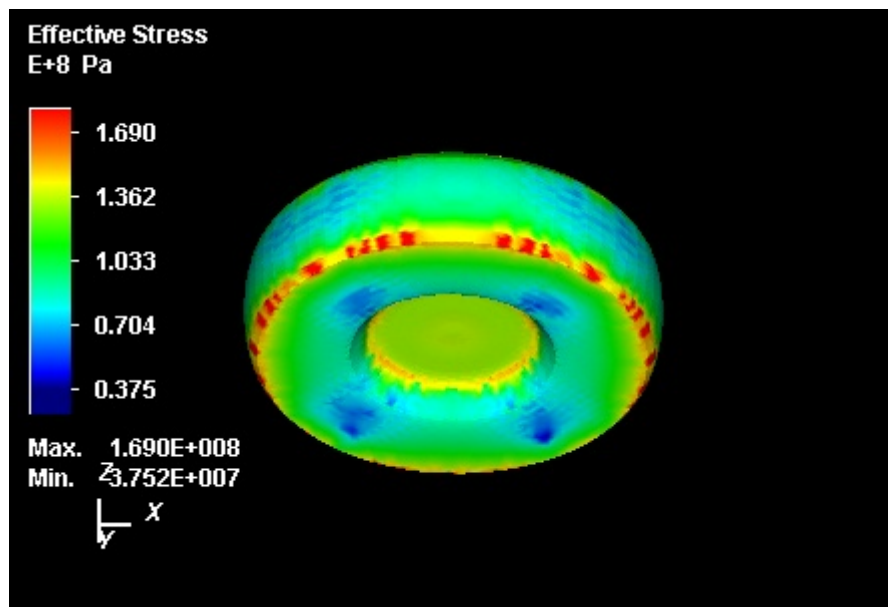


Figure 3.30 Effective Stress Diagram for Forging Process at 1150°C

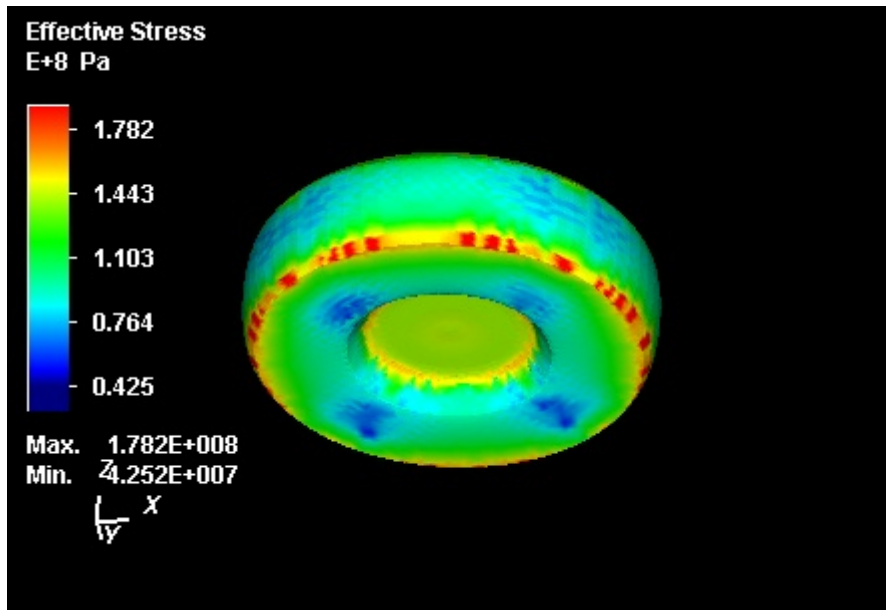


Figure 3.31 Effective Stress Diagram for Forging Process at 1096°C

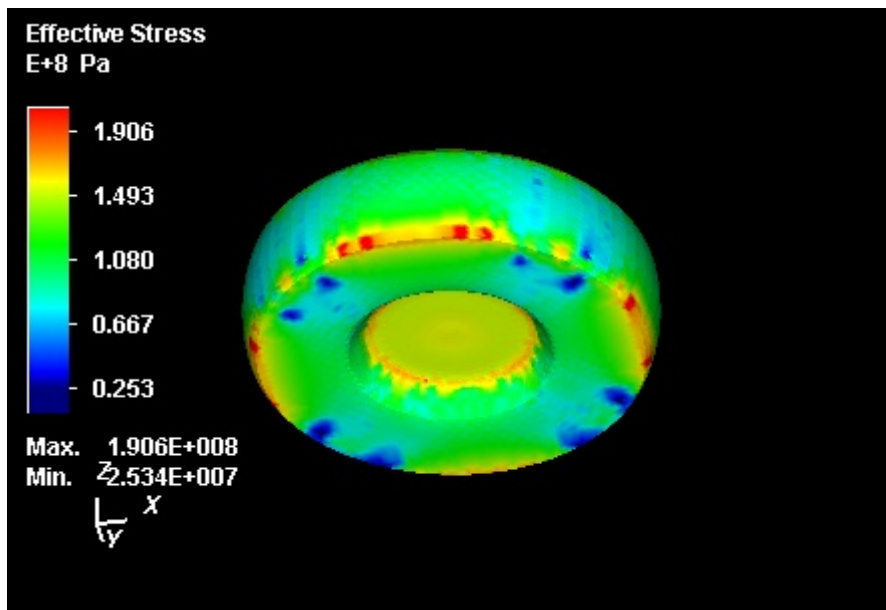


Figure 3.32 Effective Stress Diagram for Forging Process at 1049°C

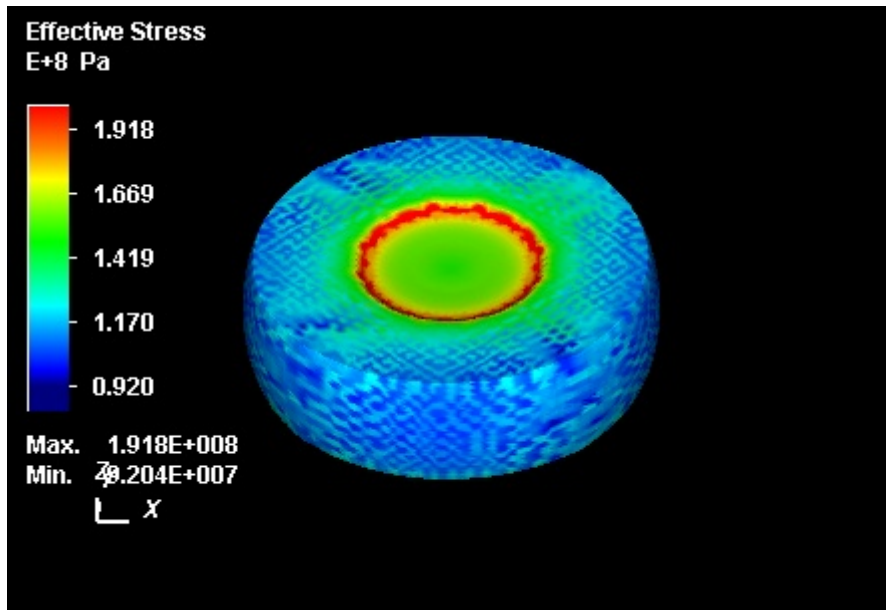


Figure 3.33 Effective Stress Diagram for Forging Process at 1015°C

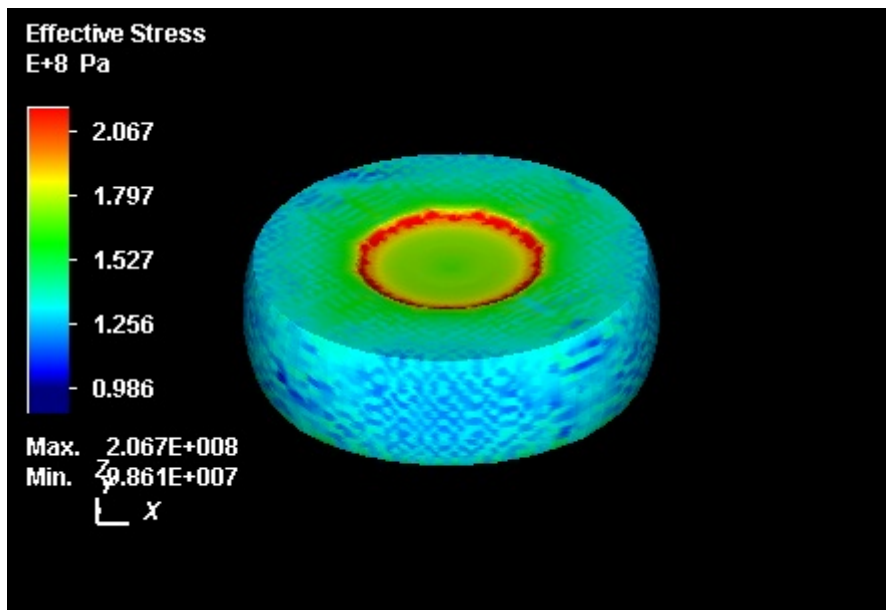


Figure 3.34 Effective Stress Diagram for Forging Process at 957°C

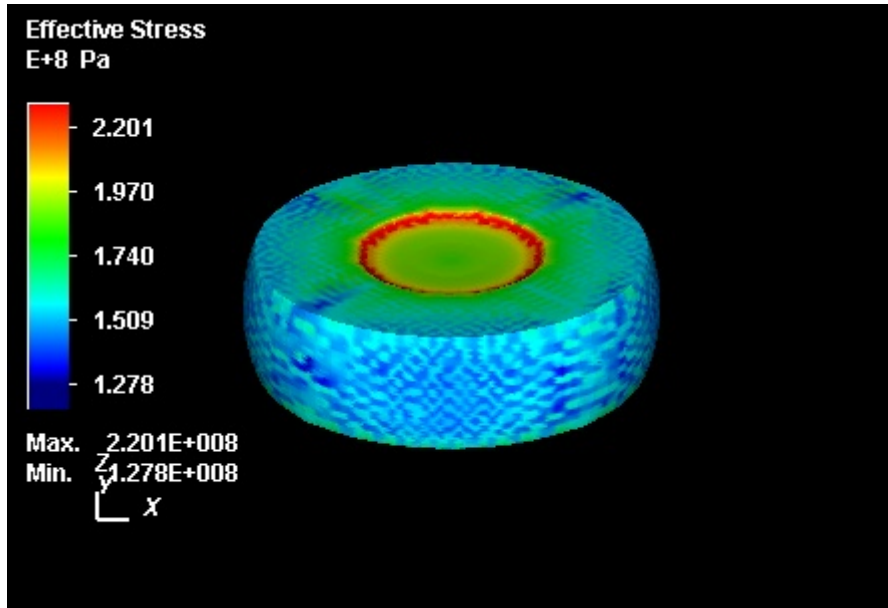


Figure 3.35 Effective Stress Diagram for Forging Process at 908°C

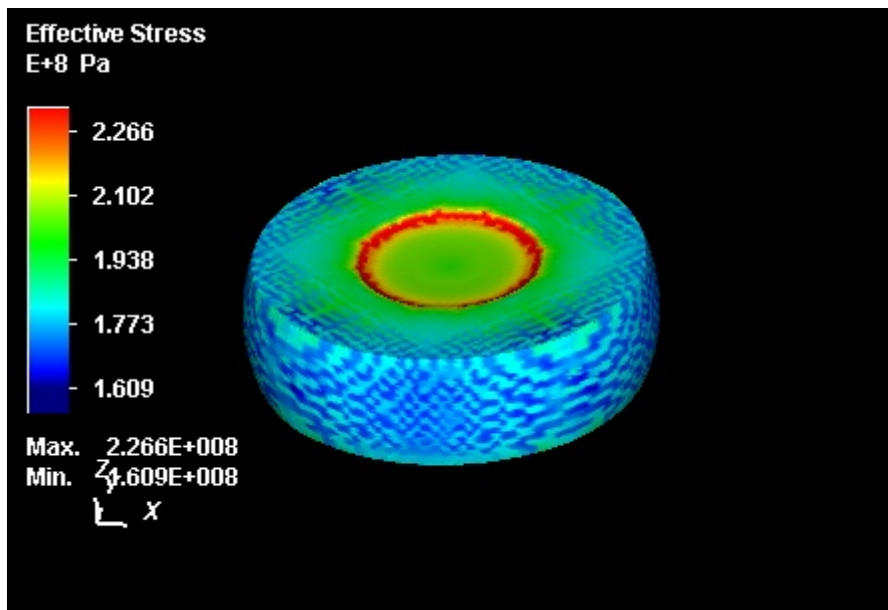


Figure 3.36 Effective Stress Diagram for Forging Process at 853°C

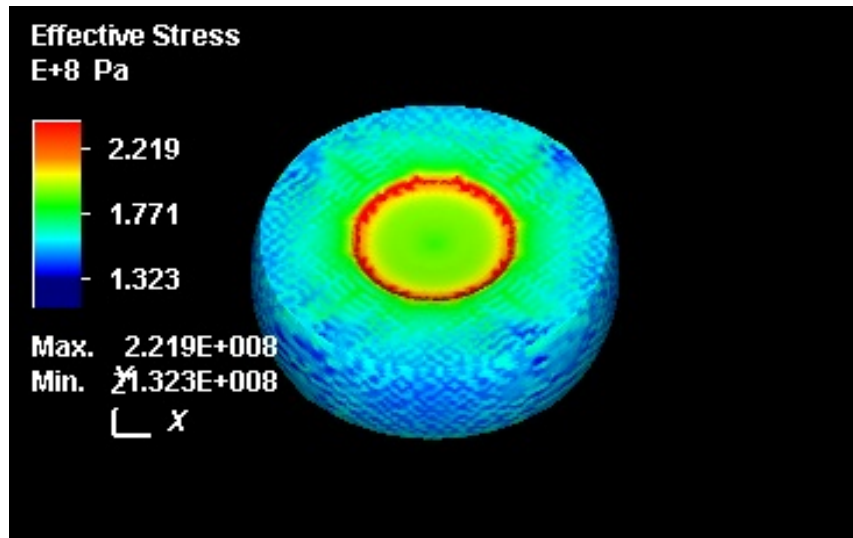


Figure 3.37 Effective Stress Diagram for Forging Process at 903°C with 1mm raised lower finish die

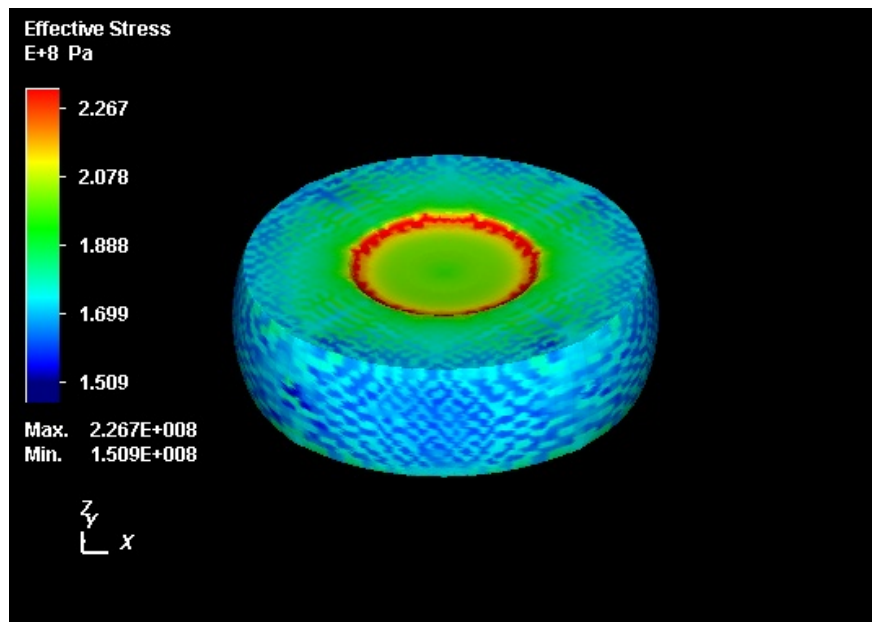


Figure 3.38 Effective Stress Diagram for Forging Process at 868°C with 1mm raised lower finish die

The punch force diagrams for the second series of simulation of forging are given in Figures 3.39-3.48. In the diagrams the net punch force is given as a function of time. The maximum values of effective stress and punch forces are given for the second series of simulation of forging in Table 3.4.

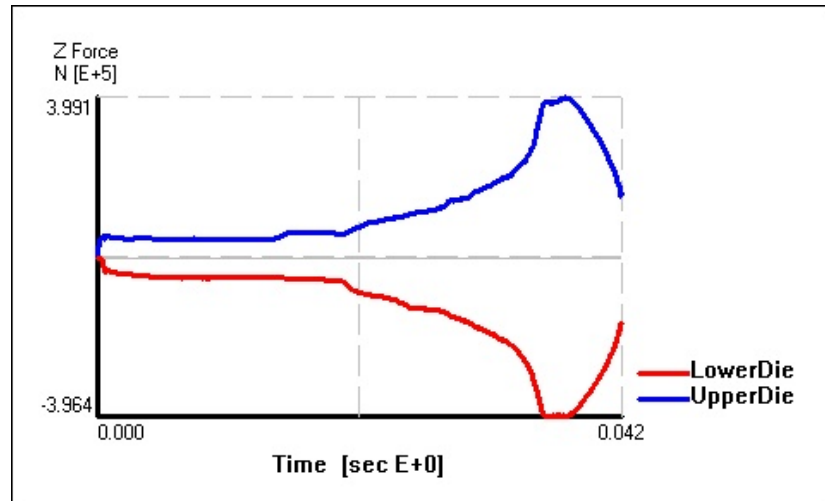


Figure 3.39 Z-Force Diagram for Forging Process at 1191°C

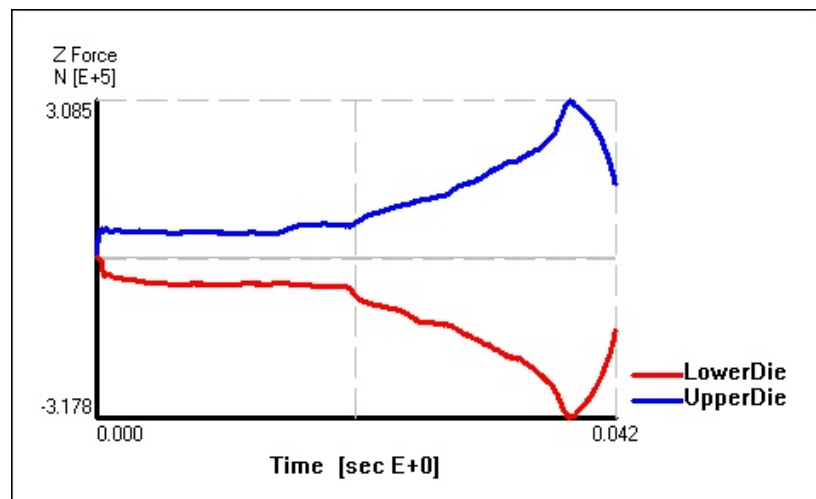


Figure 3.40 Punch Force Diagram for Forging Process at 1150°C

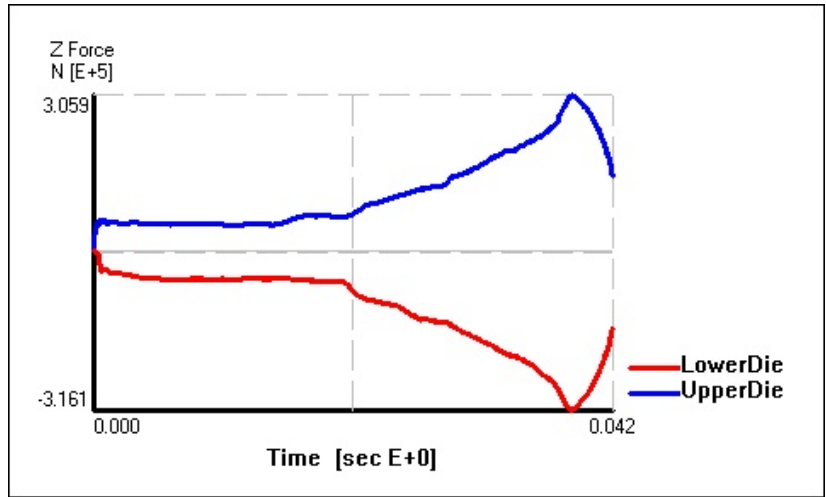


Figure 3.41 Punch Force Diagram for Forging Process at 1096°C

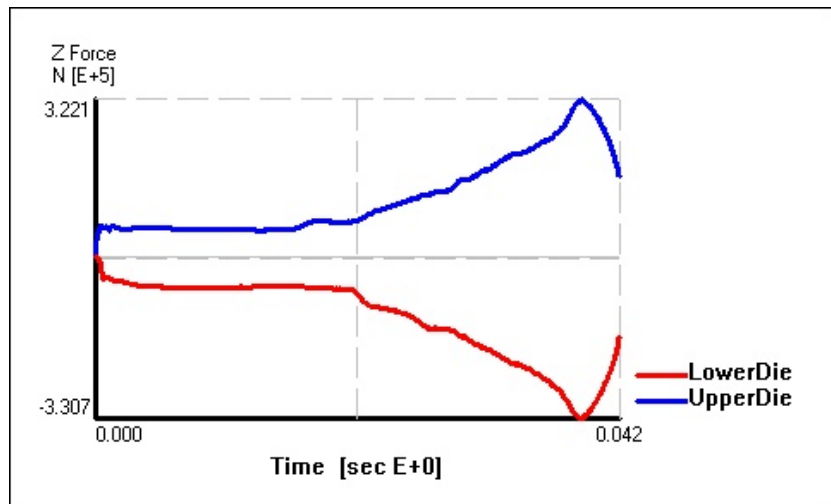


Figure 3.42 Punch Force Diagram for Forging Process at 1049°C

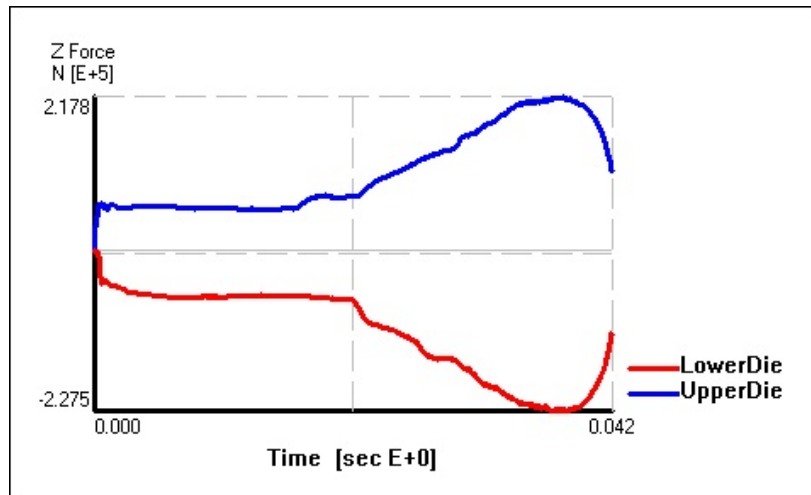


Figure 3.43 Punch Force Diagram for Forging Process at 1015°C

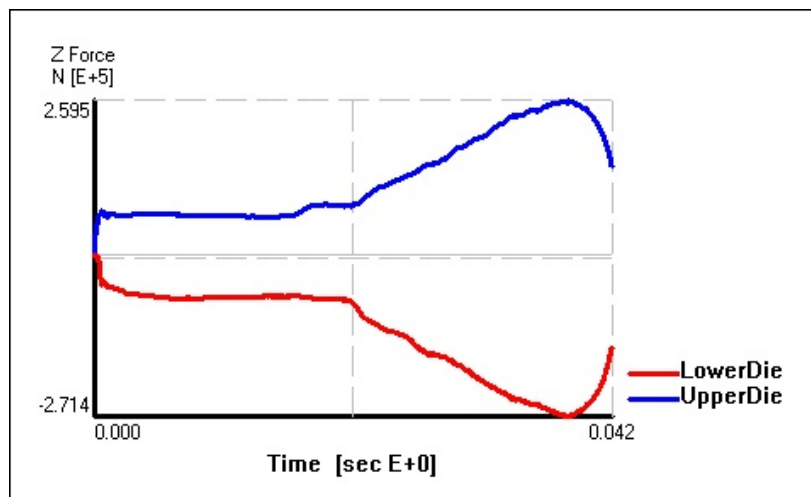


Figure 3.44 Punch Force Diagram for Forging Process at 957°C

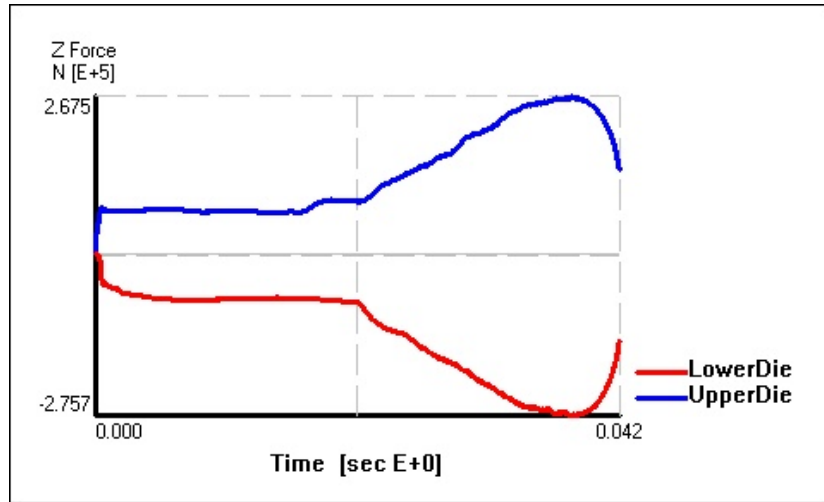


Figure 3.45 Punch Force Diagram for Forging Process at 908°C

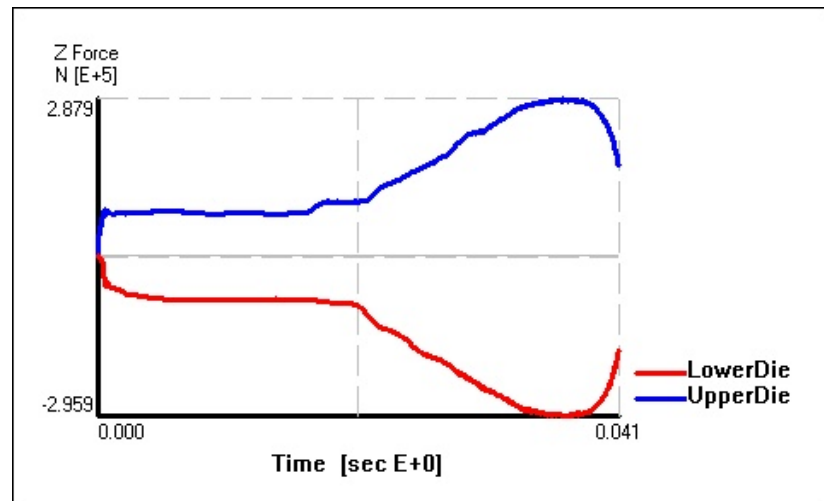


Figure 3.46 Punch Force Diagram for Forging Process at 853°C

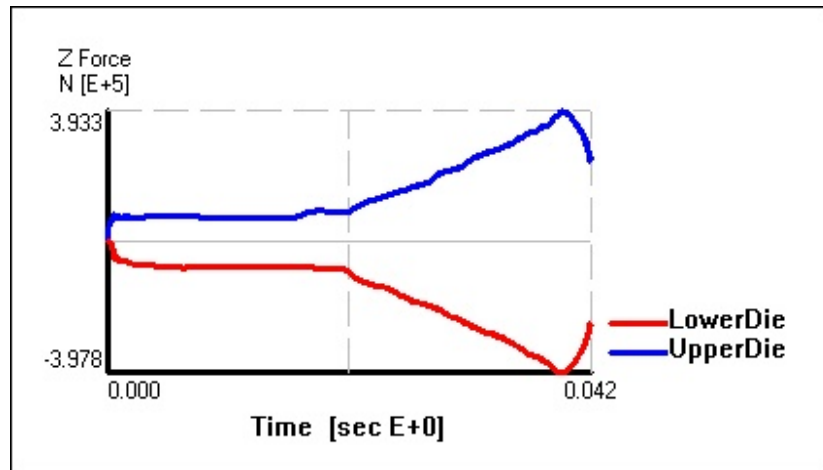


Figure 3.47 Punch Force Diagram for Forging Process at 903°C with 1mm raised lower finish die

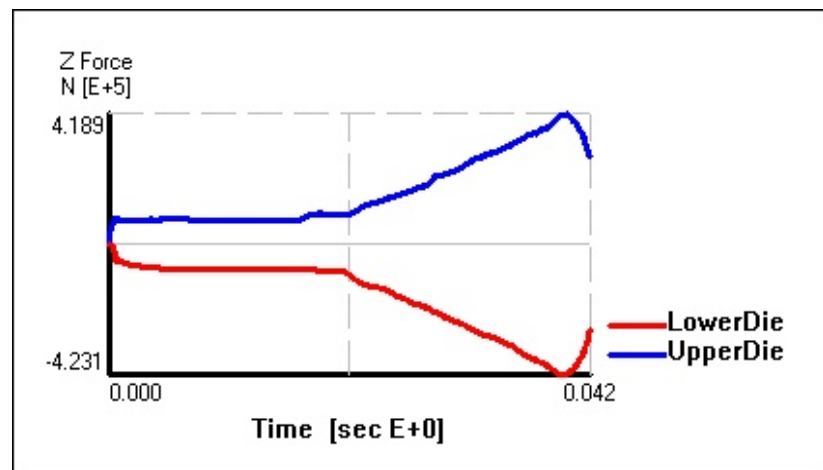


Figure 3.48 Punch Force Diagram for Forging Process at 868°C with 1mm raised lower finish die

Table 3.4 Max Values at Different Temperatures for Second Series of Simulation

Workpiece Temperature	Max. Effective Stress	Max. Punch Force	Die Filling Success
1191 °C	160.2 MPa	0.399 MN	Filled
1150 °C	169.0 MPa	0.308 MN	Filled
1096 °C	178.2 MPa	0.306 MN	Filled
1049 °C	190.6 MPa	0.322 MN	Filled
1015 °C	191.8 MPa	0.217 MN	Not Filled
957 °C	206.7 MPa	0.259 MN	Not Filled
908 °C	220.1 MPa	0.267 MN	Not Filled
853 °C	226.6 MPa	0.287 MN	Not Filled
Experiments by using the die set with raised lower die at amount of 1mm			
903 °C	221.9 MPa	0.393 MN	Filled
868°C	226.7 MPa	0.418 MN	Filled

Comparison of experimental results and the second series of simulation of forging are given in Figures 3.49-3.58. On the left side, figures of the parts that are obtained from experiment and on the right side figures from the simulation are given for different temperatures. A good agreement in the results of simulation and experiment has been observed. The white circles in Figures 3.53-3.56 indicate that the material could not fill the die completely.

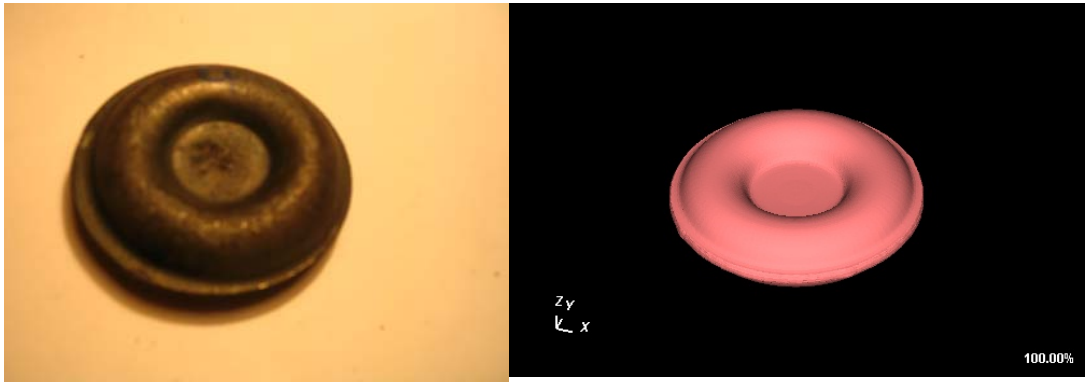


Figure 3.49 Experiment Result and Analysis Result at 1191°C

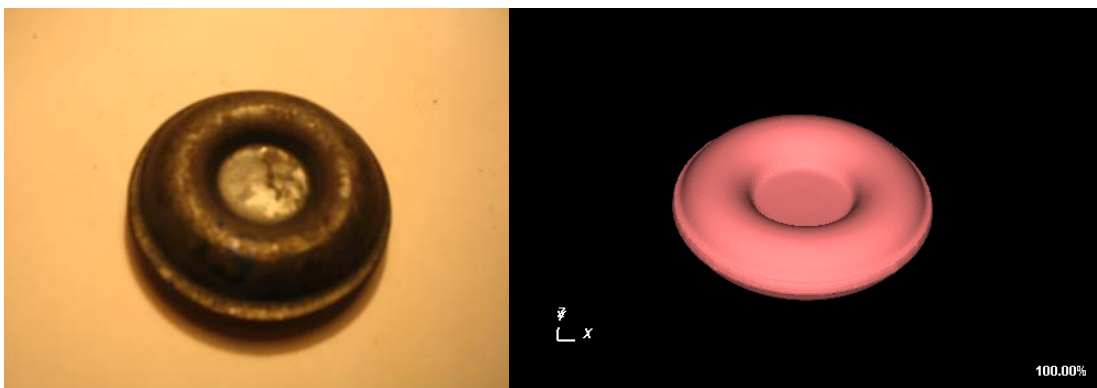


Figure 3.50 Experiment Result and Analysis Result at 1150°C

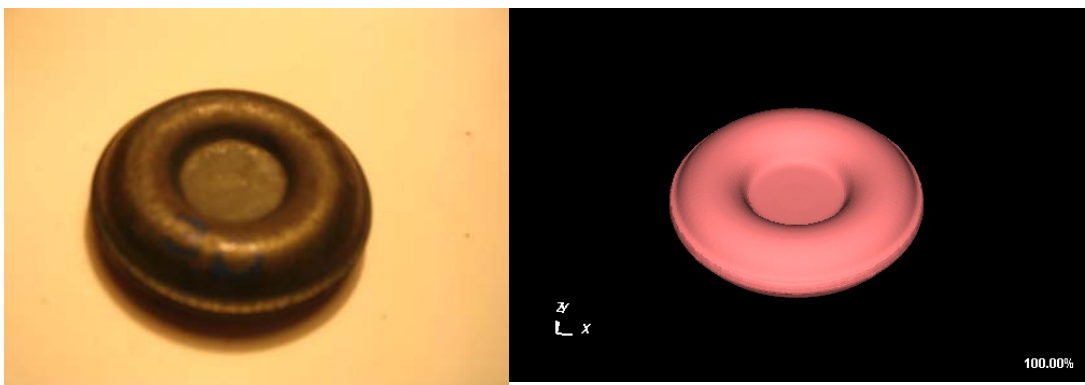


Figure 3.51 Experiment Result and Analysis Result at 1096°C

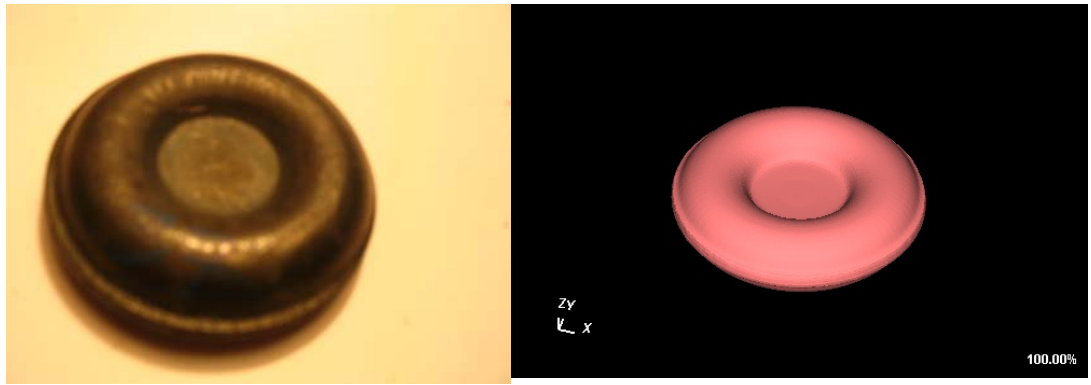


Figure 3.52 Experiment Result and Analysis Result at 1049°C

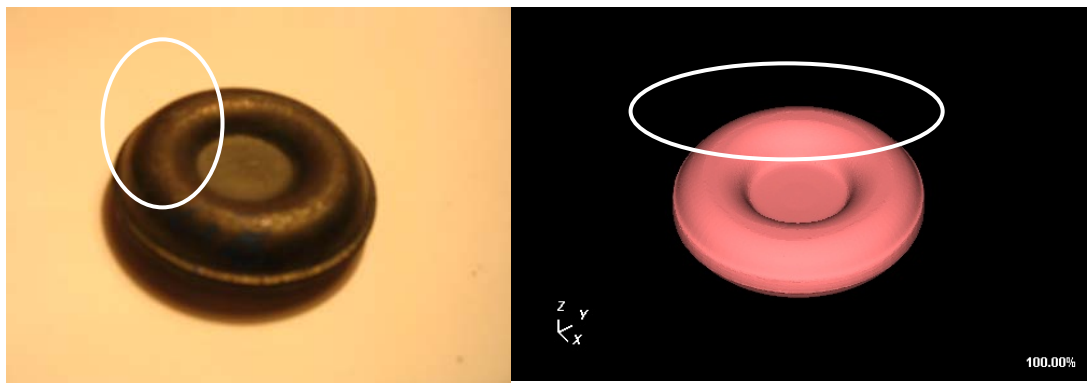


Figure 3.53 Experiment Result and Analysis Result at 1015°C

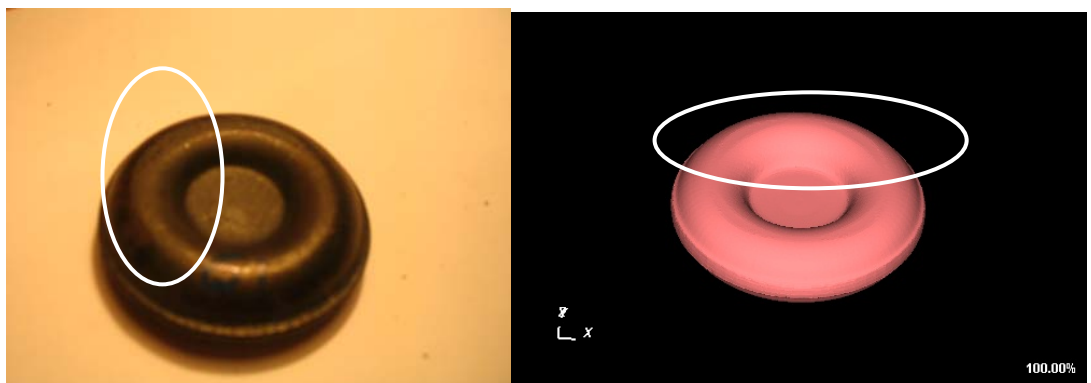


Figure 3.54 Experiment Result and Analysis Result at 957°C

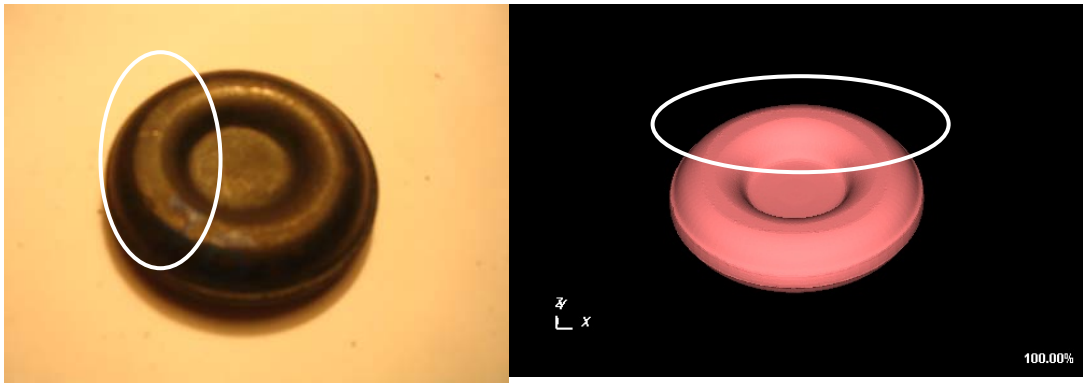


Figure 3.55 Experiment Result and Analysis Result at 908°C

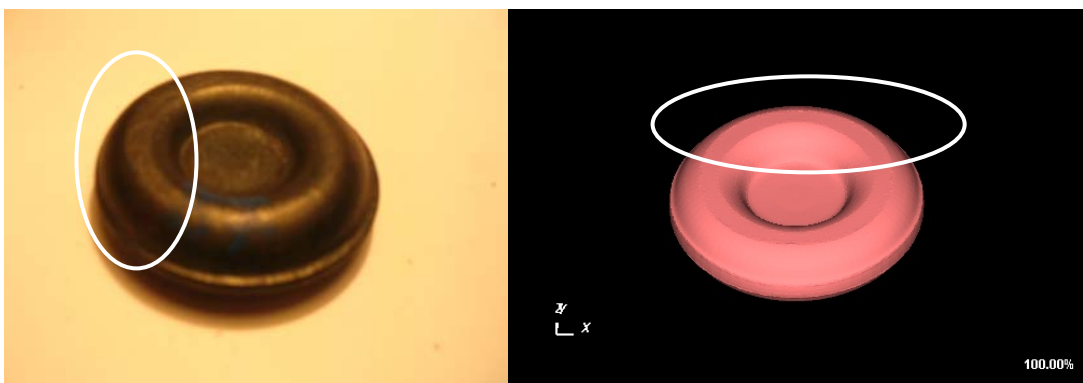


Figure 3.56 Experiment Result and Analysis Result at 853°C

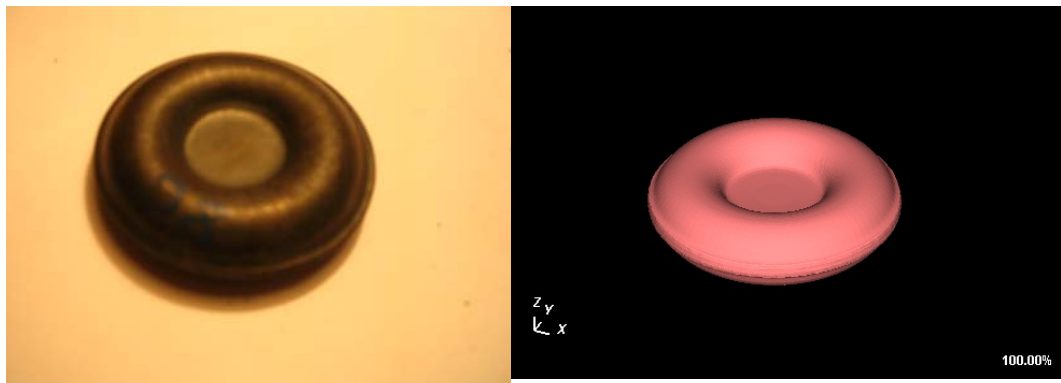


Figure 3.57 Experiment Result and Analysis Result at 903°C with 1mm raised lower finish die

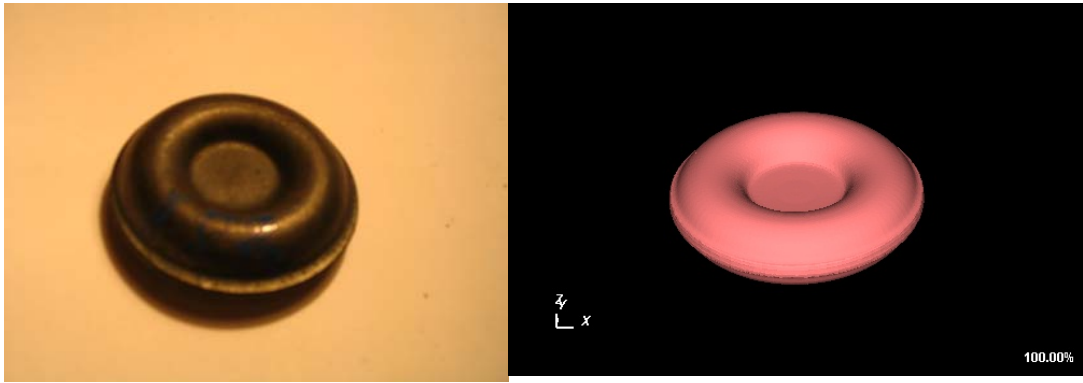


Figure 3.58 Experiment Result and Analysis Result at 868°C with 1mm raised lower finish die

For the simulations done at workpiece temperatures 1191°C, 1150°C, 1096°C and 1049°C, the preforms filled the die cavities properly. The variation at the punch forces may be explained by the differences in the facial clearance values which were determined from the experiments. As seen from Table 3.3, for the workpiece temperature of 1191°C, the plug thickness is the minimum and the workpiece mass is the maximum. However, at workpiece temperatures 1015°C, 957°C, 908°C and 803°C, at the end of the finite volume analyses it was found that preforms could not fill the die cavity completely as in the experiments. Hence, a sudden drop occurred at the punch force values at these temperatures compared to the forces determined at higher temperatures. The finite volume analyze results showed that the performs filled the die cavities completely in the last two experiments which were conducted at workpiece temperatures 903°C and 868°C and where the lower finish die was raised by 1mm. Hence, the maximum punch force values were obtained higher in these processes, and it was observed that punch force increased as the process temperature decreased.

The punch forces in the second series of simulation have lower values compared to the punch forces in the first series of simulation. This is attributed to the facial clearance differences. In the second series of simulation of forging, the plug thicknesses which have been measured from the forged parts obtained by experiments are input to finite volume analysis software as facial clearance values.

The facial clearance values are approximately 3.5 mm, while in the first series of simulation it is taken as 2 mm. It is expected that if the facial clearance were kept at 2 mm in the second series of simulations, the punch forces would increase as in the first series of simulations. For this purpose, with the data of the second series of simulation of 1200°C workpiece temperature, a new analyse has been done for a facial clearance of 2 mm. While the punch force is about 1.200 MN at the first series of simulation, it is obtained as 1.692 MN as seen in the Figure 3.59. This increase is attributed to lower ambient and dies temperatures used in the experiments.

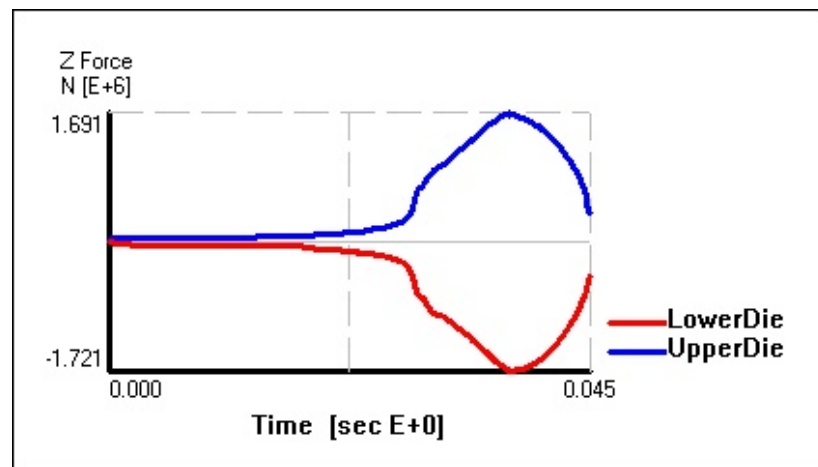


Figure 3.59 Punch Force at 1200 °C with 2mm mid thickness

It is known that, as the temperature decreases the surface finish quality increases. To verify this result, the surface roughness values of the experimental parts are measured and given in Table 3.3.

CHAPTER 4

CONCLUSION AND FUTURE WORK

4.1. Conclusion

In this study, hot and warm forging processes of a sample part, which is being produced by hot forging process in a company, made of low carbon steel, AISI 1020, have been investigated. The analyses of this product is initially performed in a temperature scale from 850°C to 1200°C with increments of 50°C by a finite volume analysis program, MSC Superforge, to verify the use of same die set for lower temperatures of warm forging. After it is determined that the die set can be used for warm forging numerically the experiments have been performed in AKSAN Forging Company. However, the finite volume and experimental results have not shown a good agreement. Hence, the simulations have been renewed with the inputs obtained from the experiments. The following results are conducted:

1. The results in the first series of simulation show that, as temperature decreases the maximum effective stress and the required punch force values increase and it becomes difficult to deform the material.
2. For the workpiece temperatures of 1191°C, 1150°C, 1096°C and 1049°C, proper forged parts are obtained in the second series of simulations. The variation in the punch force is due to different material amounts and facial clearance values used in the experiments.

3. For the workpiece temperatures 1015°C, 957°C, 908°C and 803°C the preforms did not fill the die cavities completely in the second series of simulations. Also the punch force values decreased as a result of non-complete filling of dies.
4. Proper forged parts are obtained for the workpiece temperatures of 903°C and 868°C in the last two analyses of the second series of simulations. For this purpose, the facial clearance is decreased by raising the lower die 1 mm to ensure die filing. Also, higher punch forces are obtained compared to the other simulations with higher workpiece temperatures.
5. It is observed, that the numerical results obtained in the second series of simulations are in good agreement with the experiment results.
6. It is shown that, the part can be forged at lower temperatures as 850°C by using the same die sets. So it will be possible for the company to save from the energy as a result of lower initial heating of billets and to obtain better quality products.

4.2. Future Work

As a future work, different die and workpiece materials can be utilized; preform geometries and forging of the part at lower temperatures can be analyzed. By using the results of this study, finish dies can be redesigned. Numerical analyses may be performed by different finite element programs.

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APPENDIX A

MATERIAL PROPERTIES OF STEEL AISI 1020

Subcategory: Carbon Steel; AISI 1000 Series Steel; Low Carbon Steel

Close Analog: DIN 1.1151, Ck22

Composition (%):

C	Fe	P	Mn	S
0.17 - 0.23	99.08 – 99.53	Max 0.04	0.3 – 0.6	Max 0.05

Physical Properties:

Density : 7.87 g/cm³

Hardness : 137 HBr, 75 HRc-B, 10 HRc-C

Mechanical Properties (at room temperature):

Tensile Strength (Ultimate) : 472 MPa

Tensile Strength (Yield) : 384 MPa

Modulus of Elasticity : 200 GPa

Bulk Modulus : 140 GPa

Shear Modulus : 80 GPa

Thermal Properties :

Thermal Conductivity : 51.9 W/m²-K

Coefficient of Thermal Expansion : 11.7 μm/m-°C

APPENDIX B

MATERIAL PROPERTIES OF TOOL STEEL L6

Subcategory: Alloy Steel; Hot Work Steel; Metal; Tool Steel

Close Analog: DIN 1.2714

Composition (%):

C	Fe	Cr	Mn	Mo	Ni	Si	V
0.5	94.85	1.3	0.85	0.5	1.65	0.25	0.1

Physical Properties:

Critical Temperature : 732°C

Mechanical Properties (at room temperature):

Tensile Strength (Ultimate) : 700 MPa

Hardness : HRC 55

Machinability : 75-80%

Thermal Properties :

Thermal Conductivity : 35 W/m²-K

Coefficient of Thermal Expansion : 14.2 μm/m-°C

APPENDIX C

EXPERIMENTAL DATA

Table C.1 – Experimental Data: Billet Dimensions and Measured Temperatures

Billet No	Sample No	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Total Stroke Number	Workpiece Temp. 0 (°C)	Workpiece Temp. 1 (°C)	Workpiece Temp. 2 (°C)	Preform Die Temp.0 (Lower) (°C)	Preform Die Temp.0 (Upper) (°C)	Finished Die Temp.0 (Lower) (°C)	Finished Die Temp.0 (Upper) (°C)
15	13	32.10	34.05		0	1225						
8	7	32.18	34.40		1	1210	1250	-	140	145	260	170
9	8	32.30	34.10		1	1202	1235	-	145	145	200	150
11	9	32.15	34.15		1	1210	1200	-	130	100	260	170
12	10	32.25	34.10		1	1210	1220	-	145	120	280	160
13	11	32.10	34.15		1	1215	1220	-	130	110	260	140
3	2	32.30	33.90	218.63	2	1200	1210	1150	150	160	220	225
4	3	33.31	34.10	233.89	2	1200	1210	1110	150	160	220	225
5	4	32.28	33.90	218.31	2	1205	1215	1080	140	150	215	220
6	5	32.28	34.25	220.59	2	1180	1185	1085	145	170	225	220
7	6	32.25	34.05	218.86	2	1172	1206	1185	145	170	225	220
14	12	32.15	34.10		0	1156						
22	20	32.30	34.50		1	1170	1153	-	105	105	160	140
23	21	32.05	34.35		1	1140	1102	-	105	100	125	130
24	22	32.20	34.35		1	1140	1175	-	100	95	110	105
25	23	32.15	34.00		1	1135	1060	-	95	100	175	130
26	24	32.25	34.15		1	1135	1145	-	95	105	105	110
16	14	32.30	34.20	218.08	2	1150	1020	1956	135	130	170	180
17	15	32.20	34.00	217.92	2	1150	1180	1085	100	120	150	160
18	16	32.20	34.30	219.81	2	1170	1210	1050	120	125	160	170

Billet No	Sample No	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Total Stroke Number	Workpiece Temp. 0 (°C)	Workpiece Temp. 1 (°C)	Workpiece Temp. 2 (°C)	Preform Die Temp.0 (Lower) (°C)	Preform Die Temp.0 (Upper) (°C)	Finished Die Temp.0 (Lower) (°C)	Finished Die Temp.0 (Upper) (°C)
20	18	32.30	34.25	220.83	2	1140	1156	1098	105	120	140	155
21	19	32.18	34.10	218.24	2	1140	1156	1096	100	105	140	155
27	25	32.15	34.20		0	1080						
33	31	32.10	34.20		1	1005	1140	-	100	100	160	130
34	32	32.20	34.25		1	1092	1132	-	100	110	120	115
35	33	32.30	34.20		1	1082	1096	-	100	120	125	125
36	34	32.10	34.15		1	1080	1100	-	90	100	130	125
37	35	32.05	34.00		1	1077	1170	-	90	95	140	130
28	26	32.35	34.00	218.16	2	1093	1120	980	90	110	130	135
29	27	32.25	34.10	219.26	2	1085	1100	1086	90	90	120	130
30	28	32.15	34.00	217.21	2	1093	1140	1076	95	100	170	160
31(P)	29	32.30	34.30	221.23	2	1120	1138	1000	95	100	200	205
32	30	32.25	34.10	219.26	2	1092	1135	980	95	100	210	190
43	41	32.15	33.95		0	1053						
44	42	32.15	34.05		1	1026	986	-	90	95	135	100
45	43	32.30	34.50		1	1040	1060	-	90	95	135	115
46	44	32.25	33.60		1	1050	1035	-	90	95	140	105
47	45	32.25	33.85		1	1043	1060	-	90	95	150	115
48	46	32.10	34.30		1	1045	1085	-	90	100	170	120
38	36	32.20	33.90	217.29	2	1053	1060	1008	90	95	170	175

Table C.1 (Continued)

Billet No	Sample No	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Total Stroke Number	Workpiece Temp. 0 (°C)	Workpiece Temp. 1 (°C)	Workpiece Temp. 2 (°C)	Preform Die Temp.0 (Lower) (°C)	Preform Die Temp.0 (Upper) (°C)	Finished Die Temp.0 (Lower) (°C)	Finished Die Temp.0 (Upper) (°C)
39	37	32.05	34.00	215.87	2	1043	1110	932	90	100	165	160
40	38	32.20	33.95	217.61	2	1041	1072	982	90	100	165	160
41	39	32.30	34.30	221.23	2	1054	1015	986	90	105	155	165
42	40	32.25	33.95	218.24	2	1055	1063	1000	90	95	155	165
60	57	32.35	34.20		0	1010						
49	47	32.15	34.40		1	1000	1015	-	102	103	175	130
56	53	32.30	34.30		1	1012	1025	-	110	113	160	130
57	54	32.15	34.02		1	1006	1015	-	102	103	175	130
58	55	32.15	34.05		1	1000	1035	-	105	115	125	115
59	56	32.25	34.20		1	1000	1018	-	110	110	145	110
50	48	32.20	34.05	218.24	2	1005	1000	900	110	114	263	270
51	49	32.20	34.15	218.86	2	1008	1005	1009	110	105	240	255
53	50	32.30	34.30	221.23	2	998	1007	945	105	120	250	260
54	51	32.05	33.80	214.61	2	996	1015	945	110	115	220	240
55	52	32.05	34.25	217.45	2	1072	1036	986	105	110	225	215
73	70	32.15	33.85		0	954						
66	63	32.25	33.60		1	948	972	-	105	100	160	110
67	64	32.20	33.60		1	925	896	-	95	105	155	110
68	65	32.20	33.60		1	953	903	-	100	110	150	110
70	67	32.20	34.00		1	956	942	-	100	103	150	110

Table C.1 (Continued)

Billet No	Sample No	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Total Stroke Number	Workpiece Temp. 0 (°C)	Workpiece Temp. 1 (°C)	Workpiece Temp. 2 (°C)	Preform Die Temp.0 (Lower) (°C)	Preform Die Temp.0 (Upper) (°C)	Finished Die Temp.0 (Lower) (°C)	Finished Die Temp.0 (Upper) (°C)
71	68	32.10	34.20		1	952	970	-	100	104	150	105
61	58	32.25	34.25	220.20	2	965	965	870	100	110	170	175
62	59	32.20	34.35	220.12	2	957	958	923	100	105	165	155
63	60	32.20	34.10	218.55	2	951	975	918	95	110	160	170
64	61	32.20	34.17	219.02	2	955	958	860	105	110	150	145
65	62	32.30	34.25	220.83	2	960	986	938	105	100	160	160
72	69	32.25	34.30		0	905						
69	66	32.15	33.65		1	903	876	-	105	115	155	115
79	78	32.20	34.35		1	906	912	-	100	110	150	120
80	79	32.15	34.10		1	905	913	-	110	105	150	120
81	80	32.20	34.40		1	901	945	-	105	105	130	125
82	81	32.30	34.10		1	900	910	-	100	110	135	115
84	83	32.35	34.40		1	905	912	-	96	94	125	120
74(P)	71	32.20	34.40	220.44	2	917	886	878	110	120	200	160
75	72	32.15	34.10	217.84	2	905	908	840	110	120	250	200
76	73	32.25	33.95	218.24	2	915	923	876	110	120	200	190
77	76	32.20	34.30	219.81	2	905	906	902	110	120	260	230
78	77	32.15	34.10	217.84	2	902	908	876	110	120	280	260
83	82	32.25	34.10		0	850						
90	89	32.30	34.30		1	848	833	-	105	110	150	120

Table C.1 (Continued)

Billet No	Sample No	Billet Diameter (mm)	Billet Height (mm)	Calculated Billet Mass (g)	Total Stroke Number	Workpiece Temp. 0 (°C)	Workpiece Temp. 1 (°C)	Workpiece Temp. 2 (°C)	Preform Die Temp.0 (Lower) (°C)	Preform Die Temp.0 (Upper) (°C)	Finished Die Temp.0 (Lower) (°C)	Finished Die Temp.0 (Upper) (°C)
91	90	32.15	33.90		1	858	876	-	105	110	140	125
92	91	32.25	33.40		1	852	880	-	108	106	150	131
93	92	32.20	34.20		1	853	875	-	112	114	154	142
94	93	32.15	34.00		1	848	872	-	108	103	154	125
95	94	32.20	34.30		1	849	874	-	110	105	155	130
85	84	32.25	34.30	220.52	2	856	860	848	110	115	300	300
86	85	32.30	34.35	221.54	2	854	896	876	110	115	265	245
87	86	32.30	34.40	221.86	2	855	876	858	122	140	280	280
88	87	32.30	34.25	220.83	2	856	836	879	130	140	270	260
89	88	32.30	34.00	219.26	2	846	855	865	150	110	260	260
Experiments by using the die set with raised lower die at amount of 1mm												
96	95	32.25	34.00	218.55	2	905	925	892	105	100	170	165
97	96	32.20	33.80	216.58	2	903	920	880	105	100	150	147
98	97	32.15	34.40	219.81	2	907	930	895	100	115	150	155
99	98	32.25	34.10	219.26	2	901	918	875	100	115	142	146
100	99	32.25	33.95	218.24	2	903	930	889	100	95	147	142
101	100	32.25	34.35	220.83	2	855	878	828	95	100	147	135
102	101	32.20	34.20	219.18	2	851	853	836	95	100	145	149
103	102	32.25	33.95	218.24	2	855	880	856	95	100	144	147
104	103	32.20	33.75	216.27	2	853	880	836	95	100	142	140
105	104	32.15	34.15	218.16	2	848	851	807	95	100	137	130

Table C.1 (Continued)

Table C.2

Table C.2 – Experimental Data: Measurements on the Finished Parts

Billet No	Sample No	Total Stroke Number	Workpiece Temp. 0 (°C)	Preform Die Temp.1 (Lower) (°C)	Preform Die Temp.1 (Upper) (°C)	Finished Die Temp.2 (Lower) (°C)	Finished Die Temp.2 (Upper) (°C)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) (mm*10 ⁻³)	Plug Thickness (mm)
15	13	0	1225							216			
8	7	1	1210										
9	8	1	1202										
11	9	1	1210										
12	10	1	1210										
13	11	1	1215										
3	2	2	1200	150	160	220	225	54.56	15.99	214	2.67	3.37	3.54
4	3	2	1200	250	160	240	240	54.52	16.056	212	2.57	4.63	3.42
5	4	2	1205	152	160	235	240	54.52	16.13	214	2.63	4.09	3.41
6	5	2	1180	250	160	230	200	54.23	16.056	212	2.64	6.79	3.47
7	6	2	1172	225	160	220	215	54.42	16.25	216	2.73	3.60	3.59
14	12	0	1156							214			
22	20	1	1170										
23	21	1	1140										
24	22	1	1140										
25	23	1	1135										
26	24	1	1135										
16	14	2	1150	170	130	180	190	54.28	16.238	216	2.67	2.92	3.48
17	15	2	1150	180	140	180	190	54.14	16.258	216	2.80	5.45	3.60
18	16	2	1170	150	120	170	160	54.20	16.257	216	2.67	3.25	3.55

Billet No	Sample No	Total Stroke Number	Workpiece Temp. 0 (°C)	Preform Die Temp.1 (Lower) (°C)	Preform Die Temp.1 (Upper) (°C)	Finished Die Temp.2 (Lower) (°C)	Finished Die Temp.2 (Upper) (°C)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) (mm*10 ⁻³)	Plug Thickness (mm)
20	18	2	1140	180	120	160	155	54.42	16.294	216	2.63	4.43	3.50
21	19	2	1140	160	120	170	165	54.24	16.306	216	2.88	3.44	3.58
27	25	0	1080							216			
33	31	1	1005										
34	32	1	1092										
35	33	1	1082										
36	34	1	1080										
37	35	1	1077										
28	26	2	1093	100	98	135	145	54.29	16.331	214	2.62	2.90	3.59
29	27	2	1085	103	100	130	135	54.37	16.354	216	2.88	3.24	3.53
30	28	2	1093	110	110	170	160	54.27	16.202	214	2.58	3.34	3.52
31(P)	29	2	1120	110	110	200	210	54.26	16.275	216	2.71	3.68	3.65
32	30	2	1092	110	110	220	200	54.30	16.276	214	2.90	3.46	3.50
43	41	0	1053							216			
44	42	1	1026										
45	43	1	1040										
46	44	1	1050										
47	45	1	1043										
48	46	1	1045										
38	36	2	1053	140	130	177	180	54.11	16.181	214	2.82	2.63	3.37

Table C.2 (Continued)

Billet No	Sample No	Total Stroke Number	Workpiece Temp. 0 (°C)	Preform Die Temp.1 (Lower) (°C)	Preform Die Temp.1 (Upper) (°C)	Finished Die Temp.2 (Lower) (°C)	Finished Die Temp.2 (Upper) (°C)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) (mm*10 ⁻³)	Plug Thickness (mm)
39	37	2	1043	140	130	170	175	54.18	16.464	216	2.95	3.27	3.47
40	38	2	1041	130	125	168	155	54.15	16.293	214	2.89	2.60	3.40
41	39	2	1054	150	110	160	165	54.19	16.395	218	2.48	3.36	3.65
42	40	2	1055	120	100	155	165	54.18	16.296	216	2.64	2.60	3.60
60	57	0	1010							218			
49	47	1	1000										
56	53	1	1012										
57	54	1	1006										
58	55	1	1000										
59	56	1	1000										
50	48	2	1005	107	118	280	266	54.17	16.368	216	2.82	3.36	3.83
51	49	2	1008	125	110	255	260	54.20	16.26	216	2.97	1.90	3.70
53	50	2	998	125	135	255	265	54.11	16.297	216	2.87	3.20	3.65
54	51	2	996	115	110	235	243	54.20	16.118	214	2.61	2.64	3.55
55	52	2	1072	140	115	225	220	54.12	16.323	216	3.02	2.31	3.56
73	70	0	954							214			
66	63	1	948										
67	64	1	925										
68	65	1	953										
70	67	1	956										

Table C.2 (Continued)

Billet No	Sample No	Total Stroke Number	Workpiece Temp. 0 (°C)	Preform Die Temp.1 (Lower) (°C)	Preform Die Temp.1 (Upper) (°C)	Finished Die Temp.2 (Lower) (°C)	Finished Die Temp.2 (Upper) (°C)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) (mm*10 ⁻³)	Plug Thickness (mm)
71	68	1	952										
61	58	2	965	110	125	170	175	54.39	16.327	216	2.77	2.08	3.69
62	59	2	957	130	110	165	162	54.49	16.451	218	2.93	2.23	3.72
63	60	2	951	130	100	165	170	54.43	16.229	216	2.81	2.14	3.65
64	61	2	955	115	110	160	170	54.49	16.299	216	2.95	2.44	3.72
65	62	2	960	170	110	160	165	54.51	16.42	218	3.06	2.47	3.72
72	69	0	905							216			
69	66	1	903										
79	78	1	906										
80	79	1	905										
81	80	1	901										
82	81	1	900										
84	83	1	905							218			
74(P)	71	2	917	160	120	210	175	54.22	16.398	218	2.92	1.93	3.77
75	72	2	905	140	120	260	200	54.40	16.272	216	2.55	2.01	3.83
76	73	2	915	150	120	200	160	54.37	16.247	214	2.98	2.28	3.69
77	76	2	905	160	125	260	240	54.33	16.392	218	3.10	1.89	3.72
78	77	2	902	165	125	310	320	54.30	16.261	216	3.08	1.72	3.63
83	82	0	850										
90	89	1	848										

Table C.2 (Continued)

Billet No	Sample No	Total Stroke Number	Workpiece Temp. 0 (°C)	Preform Die Temp.1 (Lower) (°C)	Preform Die Temp.1 (Upper) (°C)	Finished Die Temp.2 (Lower) (°C)	Finished Die Temp.2 (Upper) (°C)	Part Diameter (mm)	Part Height (mm)	Measured Part Mass (g)	Flash Thickness (mm)	Roughness (Ra) (mm*10 ⁻³)	Plug Thickness (mm)
91	90	1	858										
92	91	1	852										
93	92	1	853										
94	93	1	848										
95	94	1	849										
85	84	2	856	145	120	300	320	54.26	16.408	218	3.09	3.09	3.76
86	85	2	854	145	130	265	250	54.19	16.383	216	2.91	2.91	3.91
87	86	2	855	150	140	278	280	54.27	16.297	216	2.94	2.94	3.99
88	87	2	856	130	140	270	265	54.15	16.422	216	3.11	3.11	3.90
89	88	2	846	160	130	265	260	54.33	16.252	214	3.03	3.03	3.85
Experiments by using the die set with raised lower die at amount of 1mm													
96	95	2	905	150	125	168	170	54.43	16.100	214	1.95	2.71	3.48
97	96	2	903	158	120	156	165	54.74	16.078	214	2.05	2.58	3.53
98	97	2	907	135	120	160	157	54.22	16.236	218	1.98	2.79	3.60
99	98	2	901	135	120	140	150	54.46	16.240	216	2.27	2.66	3.55
100	99	2	903	140	125	147	155	54.76	16.308	214	2.33	2.93	3.48
101	100	2	855	145	120	145	144	54.42	16.258	218	2.30	2.79	3.55
102	101	2	851	147	115	148	148	54.39	16.485	216	2.43	2.57	3.55
103	102	2	855	115	110	146	148	54.36	16.209	216	2.61	2.63	3.58
104	103	2	853	150	110	141	142	54.32	16.132	214	2.36	2.88	3.53
105	104	2	848	150	110	138	143	54.47	16.243	216	2.39	2.79	3.45

Table C.2 (Continued)

