FINITE ELEMENT ANALYSIS AND MANUFACTURING OF FIN CONNECTOR ROD BY HOT FORGING PROCESS

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ABSTRACT

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Forging operation is one of the most commonly used manufacturing techniques in defense industry. The products of forging operation have higher material strength when comparing to traditional manufacturing operations. Especially, for the mass production, it is a beneficial method considering metal and cost saving.

The commonly used part named Fin Connector Rod in defense industry requires high material strength due to working conditions. In this thesis, manufacturing of this part by hot forging operation is accomplished after analyzing by using the finite element method.

Two alternative forging processes are compared and the applicable alternative method is selected by using a finite element program. Dies are designed for applied processes. The stress distribution and the current temperature variation within the parts analyzed to evaluate the results. The fin connector rod is manufactured according to the results of the finite element analysis. It has been observed that, manufacturing of the fin connector rod by hot forging is succeeded and the waste material and cost is reduced when compared to the machining operation which is being used currently.

Keywords: Defense Industry, Manufacturing Techniques, Forging Operation, Fin Connector Rod, Finite Element Analysis

ÖZ

KANAT BAĞLANTI MİLİNİN SONLU ELEMANLAR ANALİZİ VE SICAK DÖVME İLE ÜRETİMİ

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Dövme işlemi savunma sanayiinde kullanılan en önemli üretim tekniklerinden birisidir. Dövmeden çıkan ürünler, alışılmış üretim yöntemlerine kıyasla daha yüksek mukavemete sahiptir. Dövme, maliyet açısından ele alındığında özellikle seri üretimde oldukça yararlı bir imalat yöntemidir.

Savunma sanayiinde yaygın olarak kullanılan bileşenlerden Kanat Bağlantı Mili isimli parçanın mukavemet gereksinimi, çalışma şartları dolayısıyla oldukça yüksektir. Bu çalışmada, bahsedilen parçanın sonlu elemanlar yöntemi kulanılarak analizi yapılmış ve parçanın sıcak dövme işlemi ile üretilmesi hususu değerlendirilmiştir.

İki adet alternatif dövme prosesi karşılaştırıldı ve kullanılan sonlu elemanlar analizi programıyla uygun alternatif yöntem seçildi. Bu proseslerde kullanılan kalıpların tasarımı yapıldı. Parçalardaki sonuçları değerlendirmek için anlık sıcaklıklardaki stress dağılımları analiz edildi. Kanat bağlantı mili de sonlu elemanlar analizindeki sonuçlar doğrultusunda üretildi. Üretim sonucunda kanat bağlantı milinin sıcak dövme yöntemiyle başarılı bir şekilde üretildiği gözlemlendi. Dövme yöntemiyle üretilen kanat bağlantı nilinin, şu andaki talaşlı üretim yöntemiyle üretilen kanat bağlantı miline göre daha az fire malzeme ve daha düşük maliyetle üretildiği görülmüştür.

Anahtar Sözcükler: Savunma Sanayii, Üretim Yöntemleri, Dövme Operasyonu, Kanat Bağlantı Mili, Sonlu Elemanlar Analizi

To My Family...

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CHAPTER 1

INTRODUCTION

1.1 Guided Munitions and Fin Connector Rod

In defense industries, guided munitions have gained popularity in recent years because of the need of hitting strategical targets in a more precise manner. Using well-defined guidance algorithms in accordance with accurate autopilots and inertial measurement units, prescribed targets can be destroyed no matter if they are moving or stationary with guided munitions. Figure 1.1 indicates a disassembly of guided munitions.

Guided munitions can be categorized into two main groups:

a) Guided bombs
b) Missiles

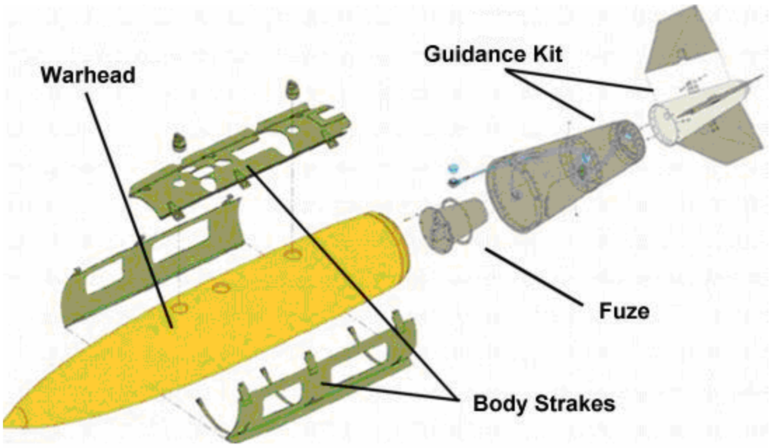


Figure 1.1 Guided Munitions [1]

In both kinds of munitions, fin actuation systems are utilized in order to steer the munitions toward intended targets. In this scene, the success of the fin actuation systems is directly dependent on the endurance of their connection elements subjected to aerodynamic excitation effects. One of these elements is *Fin Connector Rod (FCR).* Figure 1.2 represents some important elements of guided munitions and Figure 1.3 shows an isometric view of the fin connector rod.

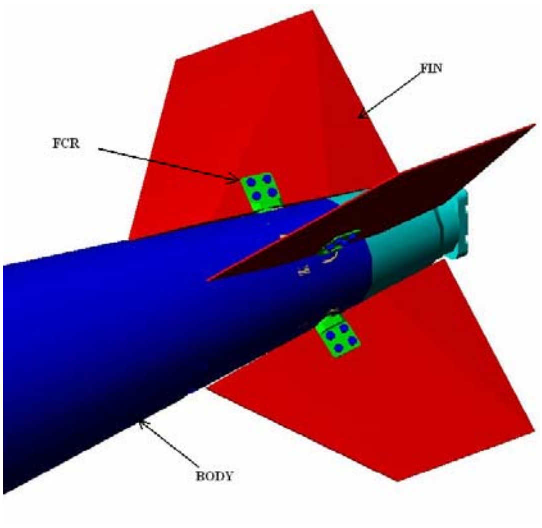


Figure 1.2 Some Elements of Guided Munitions

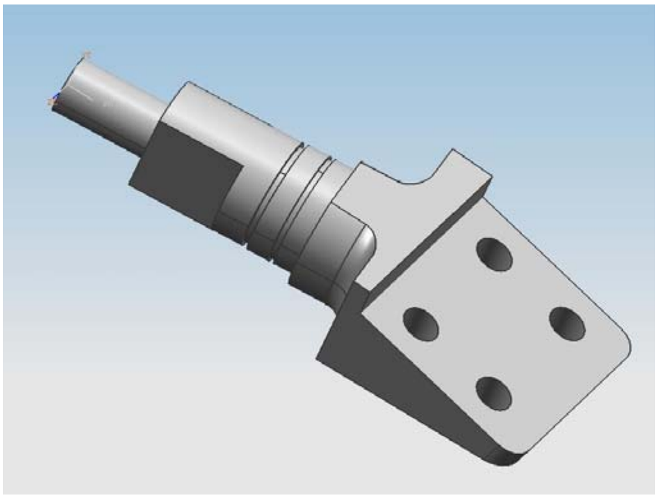


Figure 1.3 Isometric View of the Fin Connector Rod

FCR is a broadly-used element in defense industry. Guided munitions require FCRs in order to rotate the control fins to desired angles during a planned trajectory. One of its most significant characteristics is its strength. Unless it is designed and then produced in a way that it satisfies the necessary specifications, it is inevitable for the fin actuation system to fail during operation.

In order to attain the specified the high strength levels of FCRs, AISI 4140 is used in the project of TUBITAK-SAGE. If the mass production of those munitions is considered, manufacturing technique of the FCR becomes an important subject. The composition of AISI 4140 is given in Appendix B as well as its application features.

Today, the FCR of guided missiles is produced by conventional machining operations in TÜBİTAK-SAGE. However, the manufacturing efficiency of the FCR is quite low by considering producing technique, cost, time, and geometrical results. Therefore, alternative manufacturing techniques are considered in order to improve the quality of the part and decrease the time-cost as well. In this thesis, forging process is utilized to produce the FCR.

1.2 Forging Process

Forging may be defined as the plastic deformation of metals or alloys into some predetermined size and shape, generally at elevated temperatures, by a hammer, press or upsetting machine. Compared to all manufacturing processes, forging technology crucially takes place to produce parts of superior mechanical properties with minimum waste of material. Another opportunity of forging process is easy to produce complex parts with the desired directional strength. Moreover, forging helps for refining the grain structure and developing the optimum grain flow of the desired geometry of the part. However, in conventional machining process, end grains are exposed that makes the produced part more liable to fatigue with less mechanical properties. Casting or welding processes are mostly makes metallurgical defects with unwanted directional of grain flow [2].

Forging process is one step forward to other manufacturing techniques if large numbers of parts are required to manufacture. The application field of forging is shown on the Table 1.1[3].

Table 1.1 Common Field and Application of Forging

FIELD	**APPLICATION**
Ball and Roller Bearings	Rolling and equipment extruding
Industrial Machinery	Engines and turbines
Hand Tooling	Finishing mills and rolling
Internal Combustion Engine	Special industry machines
Aerospace	Transmission
Automotive	Pump, connecting rod, and compressor
Defense Industry	External cases of missiles and control elements

As it is shown in Table 1.1, defense industry is one of the most common fields of forging process. Basically, most of the defense industry products require high material strength, easy manufacturing, and low cost. In this scene, a significant numbers of these conditions can be satisfied by forging operation.

Some advantages of forging process are shown in Table 1.2 compared to the other manufacturing processes [4, 5].

Table 1.2 Advantages of Forging to Some Other Manufacturing Methods

Machining	Grain flow provides higher strength More economical material using Requires fewer operations
Welding	Repeatable Cost effective design Better metallurgical properties
Casting	Stronger Refined defects by reworking More reliable Better response to heat treatment
Composites	Less costly materials Greater productivity Broader working temperature range
Powder Metal	Higher integrity Greater design flexibility Less costly materials

1.3 Classification of Forging

In order to handle the forging operations in a more systematic manner, they can be classified according to forging temperature, type of die set, and type of machine used as explained in detail in the following manner.

1.3.1 Classification of Forging According to Forging Temperature

1.3.1.1 Hot Forging

In hot forging, metal is plastically deformed at a recrystallization temperature. The primary advantage is the material savings achieved through precision shapes that require little finishing. A greater degree of deformation can be achieved in a single operation compared to cold or warm forging. In hot forging, flow stress and the forging pressures are reduced compared to cold forging. Hot forged materials can be manufactured with excellent definition and can incorporate features that are not possible with conventional forgings [2, 6].

1.3.1.2 Cold Forging

In cold forging, plastic deformation takes place at or near room temperature. The tool stresses are high when comparing warm and hot forging. Limited geometry and volume can be forged. It is not easy to produce complex parts in cold forging. Moreover, less die life and high flash loss can be seen [6].

1.3.1.3 Warm Forging

In warm forging, the billet is heated to temperatures about the recrystallization temperature. For example, the range of 600-800°C, which is lower than the conventional hot forging range, is considered in the warm forging of steels. In warm forging, flow stress and the forging pressures are reduced compared to cold forging [2, 5]. However, required load is higher with respect to hot forging.

1.3.2 Classification of Forging According to Type of Die Set

Making the classification according to the type of die set, there exist two main forging processes one of which is closed die forging and the other is open die forging.

1.3.2.1 Closed Die Forging

Closed die forging is of two general types of construction: solid and inserted dies. Inserted dies are made up of different type of inserts to provide economy in the production of some forgings. In general, they prolong the life of the die block into which inserts fit. More forgings can be produced accurately using an inserted die instead of solid dies because steel of higher alloy content and greater hardness can be used in inserts more economically and safely than in solid dies [3].

1.3.2.2 Open Die Forging

Open die forging involves the shaping of heated metal parts between a top die, attached to a ram and a bottom die, attached to a hammer anvil or press bed. Metal parts are gradually shaped into the desired configuration though the skillful hammering or pressing of the workpiece. While closed die forging confines the metal in dies, in open die forging metal is never completely confined or restrained in the dies. Most of the open die forgings are produced on flat dies. Round swaging dies, V-dies, mandrels, and pins may also be used.

Open die forging is feasible of part production when compared to closed die forging. If the adjustments of dies are well, the product quality could be better than expected [3]. Selection of the most suitable combination of steel and hardness for die blocks are influenced by;

- Shape, size and weight of the forging,
- Composition of the metal to be forged,
- Temperature at which the work metal is to be forged,
- Number of forgings to be made,
- Type of forging equipment,
- Cost of the die steel,

- Sequence of machining the die impressions,
- Forging tolerances,
- Established plant practice and previous experience with similar applications,
- Availability of auxiliary equipment.

1.3.3 Classification of Forging According to Type of Machine Used

Forging processes can also be grouped depending on their sources of power for the forging presses. In this sense, mechanical and hydraulic type presses are usually quite massive. The squeezing pressure as developed by the forging press differs somewhat in character from the impact pressure of a drop hammer. The energy is exerted by the squeeze pressure of the forging press which increases in intensity as the plastic metal and the maximum pressure is exerted at the end of the press stroke.

Mechanical presses are driven by a motor and controlled by an air clutch. They have crank or different type of drives that imparts a constant length stroke to a vertically operating ram. The ram carries the top die whereas the bottom die is clamped to the die seat of the main frame. The ram stroke is shorter than that of a forging hammer or hydraulic press. Ram speed is greater at the center of the stroke but force is greatest at the bottom of stroke. Because of the short stroke they are best suited for low profile forgings. It is stated in that capacities of these forging presses are rated on the maximum force they can apply and range from the 300 to 8000 ton [3, 5]. Schematic view of a mechanical press is given in Figure 1.4.

The ram of a hydraulic press is driven by hydraulic cylinders and pistons, which are part of a high pressure hydraulic or hydro-pneumatic system. Following a rapid approach speed, the ram moves at the low speed while exerting squeezing action on the work metal contained in lower die.

Pressing speed can be accurately controlled thus permitting control of metal flow velocities [5, 6, 7]. This is particularly an important advantage in producing close tolerance forgings. A schematic view of a hydraulic press is shown in Figure 1.5.

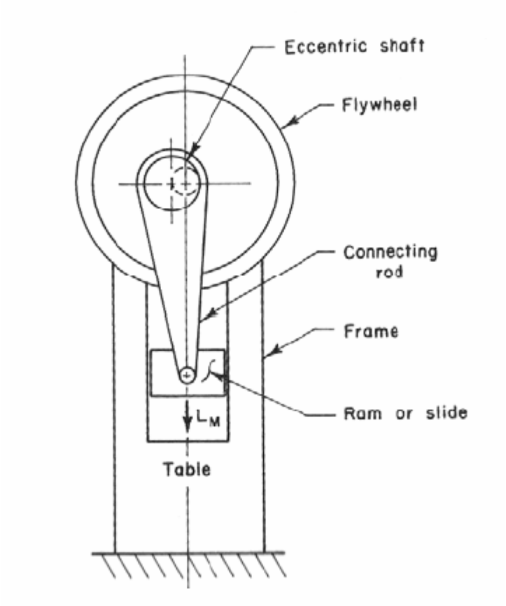


Figure 1.4 Mechanical Press [7]

Figure 1.5 Hydraulic Press [8]

1.4 Hot Upsetting

Hot upsetting, which is also called hot heading, hot upset forging or machine forging, is basically a process for enlarging and reshaping the cross-sectional area of a bar, tube or other uniform sections, usually round. In its simplest form, hot upset forging is accomplished by holding the heated forging stock between the grooved female dies and applying pressure to the end of the stock in the direction of its axis by use of a heading tool, which spreads (upsets) the end by metal displacement. A sequence of dies may be used to control the workpiece geometry gradually until it achieves its final shape [9].

Although hot upsetting originally is restricted to single-blow heading of parts such as bolts, present-day machines and tooling permit the use of multiple pass dies that can produce complex shapes accurately and economically. The process now is widely used for producing finished forgings ranging in complexity from single headed bolts or flanged shafts to wrench sockets that require simultaneous upsetting and piercing. Forgings requiring center or offset upsets may also be completed.

Because the transverse action of the moving die and longitudinal action of the heading tool are available for forging in both directions, either separately or simultaneously, hot upset forging is not limited to simple gripping and heading operations. The die motion can be used for swaging, bending, shearing, slitting and trimming. In addition to upsetting, the heading tools are used for punching, internal displacement, extrusion, trimming and bending.

In the upset forging process, the working stock is frequently confined in the die cavities during forging. The upsetting action causes the stock to fill the die impressions completely. Thus, a wide variety of shapes can be forged and removed from the dies by this process. Upsetting processes are generally performed on vertical and horizontal forging machines.

1.5 Computer Aided Design and Computer Aided Manufacturing (CAD-CAM) in Forging

The conventional methods of designing forging dies are based on empirical guidelines, experience, and intuition. On the other hand, developed computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE) methods may be used to design the preforming dies, predict forging loads, and stresses for manufacturing the dies by NC (Numerical Control) machining [5, 9, 10].

Using convenient CAD/CAM software, the designer can create the 3-D model of the forgings, preform geometries, and the necessary dies. These provide the comfort of easily changing the parameters such as dimensions, taper angles, fillet radii, shrinking factor, etc. The designer can also point out the problems that may occur during the preforming stages by the help of the computer analysis techniques; thus, reduces the cost and time. However, the experienced designer who should manage to design the process and dies properly is still essential in real-life applications.

Finite Element Method (FEM), which is one of the computer analysis techniques, is a widely used numerical technique for finding solutions in metal forming processes. Applications of finite element method include linear and nonlinear structural, thermal, dynamic, electromagnetic, and flow analyses. Some programs used as simulation packages which use this algorithm are ANSYS, MARK, Superforge, Autoforge, DEFORM, etc. By using these programs, metal flow, stress, and temperature distributions can be predicted [2, 5].

1.6 Previous Studies about Forging Process

Some previous studies related to forging have been summarized in this section. As a Ph.D. study at University of Birmingham, Gökler [11] developed a computer program for the design of the operational sequences and the dies for horizontal forging machines.

Maşat [5] studied on implementation of hot precision forging die for a spur gear. Kazancı [9] studied the analysis of hot upset forgings with non-circular cross-sections. Alper [10] developed a computer program for axisymmetric press forgings, in which the forging geometry and the die cavity for reforms and finishing operation has been designed.

Mogulkoç [15] studied on upsetting and piercing on horizontal forging machines by using the finite element analysis technique. Güler [26] estimated the cost for injection molds. He used computerized method for this purpose.

A study on upset forging process and the design limits for tapered preforms had been conducted by Elmaskaya [32] by using the elastic-plastic finite element method.

Özgen [33] studied about cutting strategies for forging die manufacturing on CNC milling machines.

Karagözler [34] studied on the analysis and preform design for long press forgings with nonplanar parting surfaces. Also, Gülbahar [35] studied on the preform design and analysis of hot forging process for a heavy vehicle steering joint. Civelekoğlu [36] worked on analysis of hot forging for three different alloy steels.

There are also some studies related to high precision forging in literature. Shan, Xu, and Lu [37] described the key problems in the precision forging of large and complex-shaped light alloy components. By means of a developed technique, several magnesium alloy and aluminum alloy forgings have been produced successfully.

Hua, Wang, and Liu [38] developed three design schemes with different die shapes. Finite element method is used to simulate the cold forging process and the strain distributions and velocity distributions are presented.

Dean [39] mentioned about net shape forging. He gave some examples on die design of precision forging and also mentioned the advantages and told about the restrictions of the method.

Lee, Kim B.H and Kim K.H [40] worked on estimation about service life against plastic deformation and wear during hot forging processes. Zuo, Wei and Chen [41] also researched about 3D (three-dimensional) finite element modeling simulation of multi-stage forging process using solid modeling of forging tools.

In the study of Lee and Jou [42], the experimental techniques, wear model, and numerical simulation method are combined to predict the wear of warm forging die. The non-isothermal ring compression test is adopted to estimate the friction coefficient in different temperatures and the on-line temperature recording system was setup to correct the heat transfer coefficient of the interface. The wear coefficients in different temperatures are acquired from high temperature wear experiment. Additionally, the Archard wear theory and a finite element modeling code, are used to analyze the warm forging of automotive transmission outer-race and predict the die wear condition.

1.7 Scope of the Thesis

The fin connector rod is designed in order to be used in guided munitions and developed by TÜBİTAK-SAGE. The scope of this study is analyzing that part for manufacturing by hot forging operation, using finite element modeling program.

Finite element modeling is beneficial analyzing technique before producing die and parts. In many cases, trial and error procedure is used to produce parts in forging. However, that causes material wastage, unsuccessful die filling, high energy, and money consumption. All parameters are vital in forging because forging process is related to the workpiece material and required force for plastic deformation. General information about the finite element modeling is considered in Chapter 2. Basic design considerations in order to find the forged part of the FCR are considered in Chapter 3.

In Chapter 4, the material distribution of the forged part is considered and the billet geometry is selected. Sequence designs of the fin connector rod are done and they are analysed by using finite element modeling in this chapter. Stresses and temperature distributions of the part at each operation are considered. The designed dies and the fixtures related to best forging case study is also mentioned in Chapter 4.

Chapter 5 gives information about the experimental study of the best forging sequence design of the fin connector rod. The information about the manufacturing dies and fixtures, forging operation order and required machining operation after forging is explained. All steps for manufacturing the fin connector rod are summarized in this chapter.

Today, conventional machining operations are used for manufacturing that part. In Chapter 6, forging operation is compared by machining technique and explained why forging is better method for producing the FCR by considering cost analysis. Conclusions and the future work about the FCR are mentioned in Chapter 7.

CHAPTER 2

FINITE ELEMENT METHOD

2.1 Nonlinear Analysis

The finite element method (FEM) is one of the effective approaches used in the solution of nonlinear problems as well as linear ones. Early development of the nonlinear finite element methodology was mostly influenced by the nuclear and aerospace industries. In the nuclear industry, nonlinearities are mainly due to the nonlinear high-temperature behavior of materials. Nonlinearities in the aerospace industry are mainly geometric in nature and range from simple linear buckling to complicated post-bifurcation behavior. Nonlinear finite element techniques have become popular in metal forming manufacturing processes, fluid-solid interaction, and fluid flow as well. In recent years, the areas of biomechanics and electromagnetism have seen an increasing use of finite elements in the solution of the relevant problems [12].

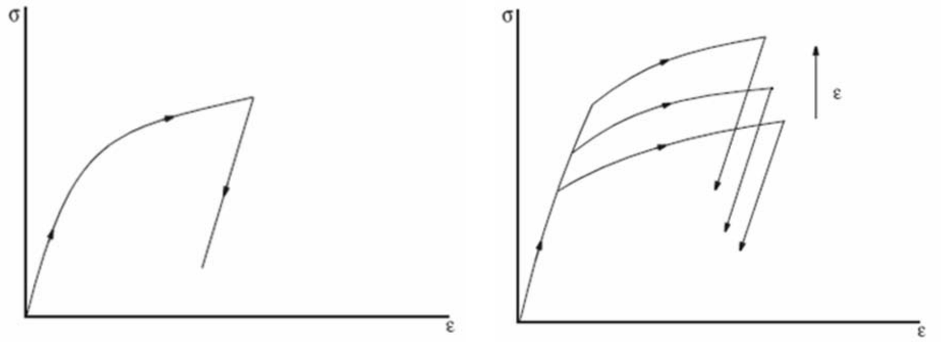
In general, a problem is said to be nonlinear if the force-displacement relationship depends on the parameters of the current state. In this sense, the generic expression of the force-displacement relation for a nonlinear problem can be written as,

$$\mathbf{F}=\mathbf{K}\,(\mathbf{F},\,\mathbf{u})\,\mathbf{u} \tag{2.1}$$

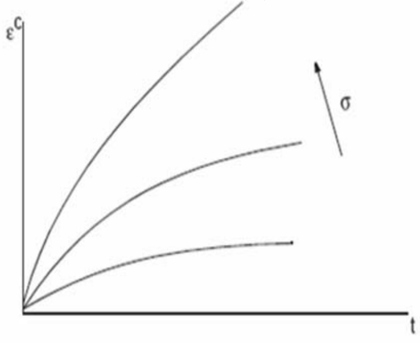
There are three sources of nonlinearity: material nonlinearities, geometric nonlinearities, and nonlinear boundary conditions.

2.1.1 Material Nonlinearities

Material nonlinearity results from the nonlinear relationship between stresses and strains. Considerable progress has been made in attempts to derive the continuum or macroscopic behavior of materials from microscopic backgrounds, but, up to now, commonly accepted constitutive laws are phenomenological. Difficulty in obtaining experimental data is usually a stumbling block in mathematical modeling of material behavior. A plethora of models exist for more commonly available materials like elastomers and metals. Other material model of considerable practical importance is composites, viscoplastics, creep, soils, concrete, powder, and foams. Figure 2.1 shows the elastoplastic, elastoviscoplastic, and creep behavior. Although the strain hardening is more commonly encountered, it may be necessary to consider strain softening and localization as well [12].



(a) Elastic-Plastic Behavior **(b) Elasto-Viscoplastic Behavior**



(c) Creep Behavior

Figure 2.1 Material Nonlinearity [13]

2.1.2 Geometric Nonlinearities

Geometric nonlinearity leads to two types of phenomena: change in structural behavior and loss of structural stability. For the large displacement small strain problems, changes in the stress-strain relation can be neglected, but the contributions from the nonlinear terms in the strain displacement relations should be considered [12, 13].

2.1.3 Nonlinear Boundary Conditions

There are three types of problems associated with nonlinear boundary conditions: contact, nonlinear support, and nonlinear loading.

Some examples of contact problems are the interface between the metal workpiece and the die in metal forming processes, pipe whip in piping systems, and crash simulation in automobile designs.

Springs and elastic foundations for the modeling of support conditions are the examples of nonlinear supports.

When the structure is deformed, the directions and the areas of the surface loads are changed resulting in nonlinear loading. For most deformed structures, such changes are so small that the effect on the equilibrium equation can be ignored. However, regarding structures such as flexible shell structure with large pressure loads, the effects on the results can be quite significant so that the surface load effects have to be included in the finite element equations [12, 13, 14].

2.2 Kinematics of Deformation

The kinematics of deformation can be described by means of Lagrangian and Eulerian formulations. The choice of one method over another can be dictated by the convenience of modeling physics of the problem, and integration of constitutive equations. [12, 15].

2.2.1 Lagrangian Formulation

The Lagrangian approach naturally describes the deformation of structural elements; that is, shells and beams, and transient problems, such as the indentation problem. This method can also be utilized in the analyses of steady-state processes such as extrusion and rolling. Shortcomings of the Lagrangian method are that flow problems are difficult to model and that the mesh distortion is as severe as the deformation of the object. However, recent advances in adaptive meshing and rezoning have alleviated the problems of premature termination of the analysis due to mesh distortions.

The Lagrangian approach can be classified in two categories: Total Lagrangian Method and Updated Lagrangian Method. In the Total Lagrangian Method, the equilibrium is expressed with the original undeformed state as the reference whereas the current configuration acts as the reference state in the Updated Lagrangian Approach [12, 13].

2.2.1.1 Total Lagrangian Procedure

The Total Lagrangian Procedure can be used for linear or nonlinear materials in conjunction with static or dynamic analysis. Although this formulation is based on the initial element geometry, the incremental stiffness matrices are formed to account for previously developed stress and changes in geometry. This method is suitable for the analysis of nonlinear elastic problems. The Total Lagrangian Approach is also useful for problems in plasticity and creep, where moderately large rotations but small strains occur [13, 15].

2.2.1.2 Updated Lagrangian Procedure

The Updated Lagrangian Approach is useful in the analysis of shell and beam structures in which rotations are large so that the nonlinear terms in the curvature expressions may no longer be neglected. The Updated Lagrangian Approach is also useful for large strain elasticity and plasticity analysis [14, 15].

In general, this approach can be used to analyze structures where inelastic behavior (for example, plasticity, visco-plasticity, or creep) causes the large deformations. The (initial) Lagrangian coordinate frame has little physical significance in these analyses.

2.2.2 Eulerian Formulation

In the analysis of fluid flow processes, the Lagrangian approach results in highly distorted meshes since the mesh connects with the material. Hence, an alternative formulation, namely Eulerian, is used to describe the motion of the body. In this method, the finite element mesh is fixed in space and the material flows through the mesh. This approach is particularly suitable for the analysis of steady-state processes such as the steady-state extrusion or rolling processes.

CHAPTER 3

FORGED PART DESIGN OF THE FIN CONNECTOR ROD

3.1 Basic Design Considerations

3.1.1 Machining Allowances

The design of a forged part involves the allocation of machining allowances, parting line location, draft, and radii. The machining allowance is considered for the surfaces that will be machined. Recommendations for machining allowances are given in Table 3.1.

Table 3.1 Machining Allowances for the Surface to Be Machined [16]

Diameter of the surface (mm)	**Length of surface (mm)**					
	0-63	64-160	161-250	251-400	401-1000	1001-2500
0-25	1.5	1.5	1.5	1.5	2.0	2.5
26-40	1.5	1.5	1.5	1.5	2.0	2.5
41-63	1.5	1.5	1.5	2.0	2.5	3.0
64-100	1.5	1.5	2.0	2.5	3.0	3.5
101-160	1.5	2.0	2.5	3.0	3.5	4.0
161-250	2.0	2.5	3.0	3.5	4.0	5.0
251-400	2.5	3.0	3.5	4.0	5.0	6.0
401-630	3.5	3.5	4.0	5.0	6.0	7.0

3.1.2 Parting Line Position

Parting line position is the line which divides top and bottom dies on forging. The location of parting line influences some major parameters as listed below [10].

- Ease and economy of die sinking
- Ease of die filling
- Formation of forging defects
- Ease of clipping
- Amount of draft required and hence forging weight
- Extent and detection of mismatch
- Ability to nest forgings
- Need to use die locks
- Forging tolerances

3.1.3 Draft Angles

Draft is necessary on almost all forgings, which have internal or external edges. It is necessary for easy removal of forging from die and in certain cases, it helps metal flow. Recommended draft angles on different locations (external, internal, and draft matching angle) of the forging are given in many publications and it is stated that the exact value of draft is function of many factors. The deeper the die cavity, the greater the draft is required to ensure release of forging [10]. Therefore, the depth of related impression is taken as a guide to take suitable draft in those publications. As the forging cools, it shrinks and a gap is formed between the outside surfaces of forging and die. Thus, outside draft is usually smaller than inside draft angles where the material shrinks onto bosses of the die. The draft is selected according to the location of internal or external surface of the part and the condition if ejector used is given in DIN standard 7523 and tabulated in Table 3.2 [10, 17].

Table 3.2 Draft Angles and Slopes [16]

INTERNAL DRAFTS			EXTERNAL DRAFTS		
PRES OR DROP FORGING		UPSET FORGING	PRES OR DROP FORGING		UPSET FORGING
Die half without ejector	Die half with ejector		Die half without ejector	Die half with ejector	
6 to 9° and 1:10 to 1:6	3 to 6° and 1:20 to 1:10	3 to 6° and 1:20 to 1:10	4 to 6° and 1:12.5 to 1:10	2 to 3° and 1:30 to 1:20	2 to 3° slope and 1:30 to 1:20

3.1.4 Corner and Fillet Radii

Corners on forging are sometimes difficult to fill with metal. Thus, fillet radii must be kept as large as possible and sharp corners must be heat up and cooled in a fast manner. The recommended edge radii for unmachined surfaces are shown in Table 3.3, Table 3.4, and Table 3.5.

Table 3.3 Corner and Fillet Radii [16]

Maximum height per half die (mm)	Maximum diameter/width of the forging (mm)								
	0-25	25-40	40-63	63-100	100-160	160-250	250-400	400-630	630-1000
0-16	3	3	4	4	4	5	5	-	-
16-40	3	4	5	5	5	6	6	8	10
40-63	-	6	6	6	6	8	8	10	12
63-100	-	-	8	8	8	10	10	12	16
100-160	-	-	-	10	10	12	12	16	20

Table 3.4 Internal Fillet Radii Selection [16]

Shoulder height per half die (mm)	**Maximum diameter/width of the forging (mm)**							
	0-25	25-40	40-63	63-100	100-160	160-250	250-400	400-630
0-16	4	5	6	4	10	12	14	16
16-40	6	8	10	12	14	16	18	20
40-63	-	12	14	16	18	20	22	25
63-100	-	-	18	20	22	25	28	32
100-160	-	-	-	25	28	32	36	40

Table 3.5 External Fillet Radii Selection [16]

Shoulder height per half die (mm)	**Maximum diameter/width of the forging (mm)**							
	0-25	25-40	40-63	63-100	100-160	160-250	250-400	400-630
0-16	3	4	5	6	8	10	12	14
16-40	4	5	6	8	10	12	14	16
40-63	-	6	8	10	12	14	16	2
63-100	-	-	12	14	16	18	20	25
100-160	-	-	-	18	20	22	25	32

3.2 Upsetting and Calculation of Total Required Volume for Billet Geometry

In order to manufacture the fin connector rod by forging, the complexity of the part requires upsetting first. Therefore, the billet material should be selected in an accurate diameter and length. The volume of the billet material should satisfy all the requirements given in the recommendation tables and also the geometry should satisfy the diameter of the section where the mass distribution is in its densest level.

Meyer [9, 18] suggests the equivalent mean diameter as the diameter of a cylinder that has the same volume and length as those of the tapers. Since buckling is dependent on the second moment of area of a section, it would seem preferable to use this as a means of determining an equivalent diameter for the calculations of upset ratio. Applying this equivalent mean diameter is then the forth root of arithmetic mean of the fourth power of the maximum and minimum diameters. This then allows a greater amount of material to be gathered in a single state for taper upsetting, as opposed to cylindrical upsetting [9].

For an upset requiring more than three diameters of stock length and for which the diameter of the upset is 1.5 times the diameter of the bar, the amount of unsupported stock length beyond the face of the die must not exceed one stock diameter. If, however, the diameter of the die cavity is reduced below 1.5 diameters, the length of the unsupported stock beyond the face of the die can be correspondingly increased. If the die cavity diameter is not greater than 1.25 times the diameter of the stock, then the amount of the stock beyond the face of the die can be increased to a maximum of 1.5 times the diameter of the bar. In this scene, Lange [18] has introduced the following limiting values:

$$l_0 \leq 2.5d_0 + 0.01d_0 \tag{3.1}$$

for free upsetting and

$$l_0 \leq 6.5d_0 + 0.01d_0 \tag{3.2}$$

for guided upsetting where, l_0 is length of unsupported stock and d_0 is bar diameter.

However, Meyer [18] proved that these limits are too high if buckling is to be avoided, and he suggested for free upsetting that $l_0 \leq 2.3d_0$ is more applicable. In tapered upsetting, it is necessary to determine an equivalent diameter in order to apply the rules for upset ratio limits.

Because of the less die cavity and the economy of long time, die life free upset forging is preferable. However, the analysis of a tapered upsetting is also done as an alternative sequence of manufacturing fin connector rod [9, 19].

The design rule of Gökler [11] requires the calculation of overall upset ratio, s

$$s = \frac{l_0}{d_0} = \frac{4V_T}{\pi d^2} \tag{3.3}$$

where, l_0 is the initial unsupported length, d_0 is bar diameter and V_T is the volume of the upset region including scale and flash allowances.

If the overall upset ratio is less then or equal to the upset limit, the particular upset region can be formed into the final shape in one operation. Conversely, if the overall upset ratio is greater than the upset limit, more than one operation is necessary to produce the final product, and tapered preforms are used in intermediate stages [11].

Using the CAD (Computer Aided Design) software program, the necessary design considerations are applied. Hence, it is easy to calculate to volume of the forged part whose geometry is indicated in Figure 3.1.

From the mentioned software, the total volume of the part is calculated as 112600 mm^3 for the material of AISI 4140 alloy steel.

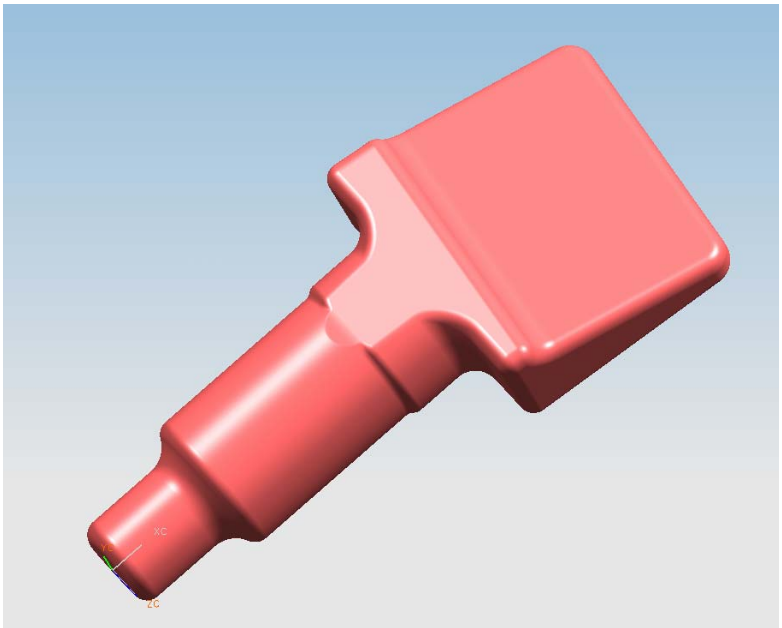


Figure 3.1 Forged Part Geometry

CHAPTER 4

SEQUENCE DESIGN OF THE FIN CONNECTOR ROD

4.1 Material Distribution of the Fin Connector Rod

Material distribution of the fin connector rod should be considered in order to decide the forging operation order and design the dies. To determine the forging operation of the part, the forged form of the fin connector rod should be analyzed. For this purpose the part is divided in sections along the x, y and z coordinates. Figure 4.1, Figure 4.3, and Figure 4.5 show the sectioning along the mentioned three axes. After dividing the part into sections, the volume of each section is shown on a graph to determine the volume distribution along a particular axis. Figure 4.2, Figure 4.4, and Figure 4.6 show the volume distribution of the fin connector rod along the x, y and z axes.

Determining the operation sequence by using the material distribution of the part is also beneficial for die life. The fewer cavities of dies to fill the material, the less press capacity required. If the operation order is designed by controlling the minimum metal flow, less punch load will be enough to plastically shape the material. It is known that less punch load increase the die life for mass production of a part comparing to high punch load respectively.

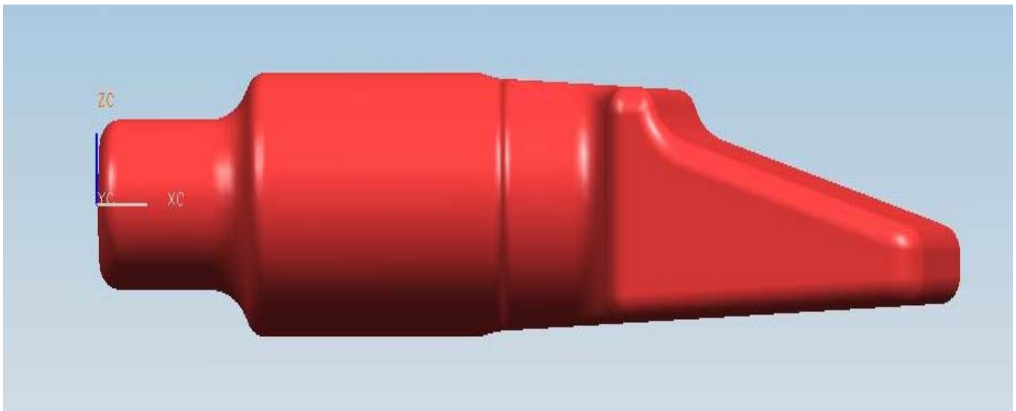


Figure 4.1 Equal Sections Along x Axis

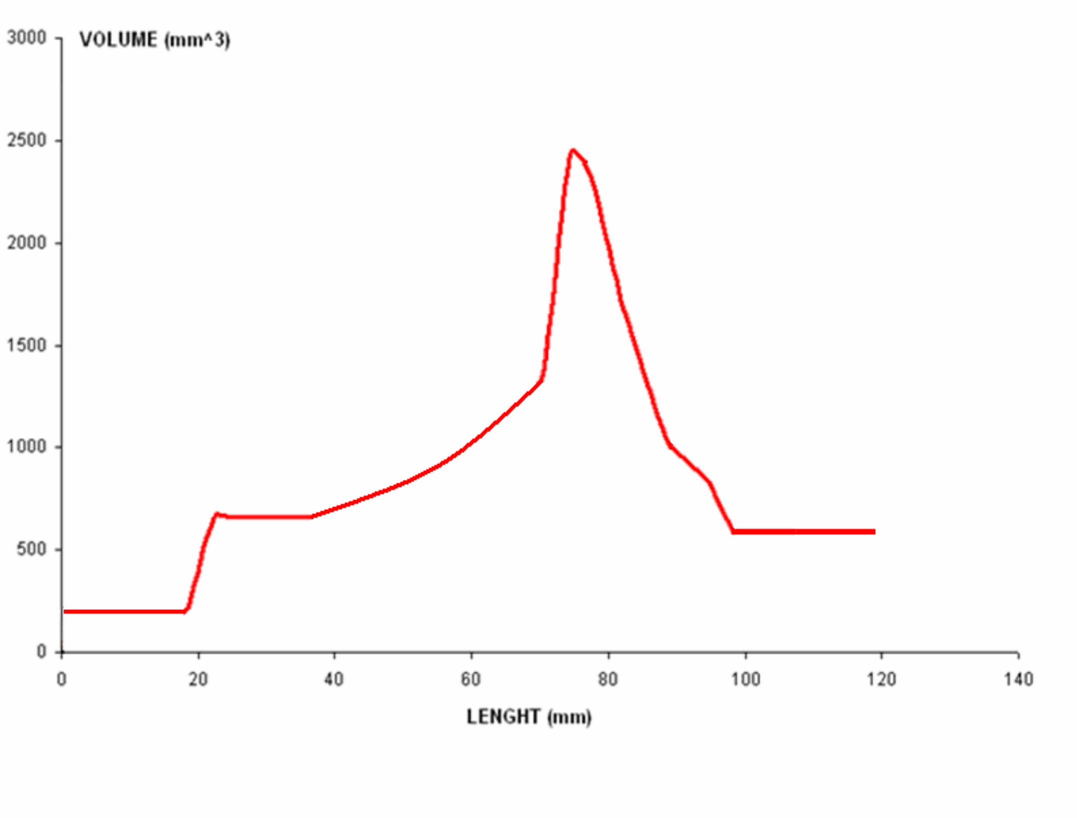


Figure 4.2 Volumetric Material Distribution of the Part Along x Axis

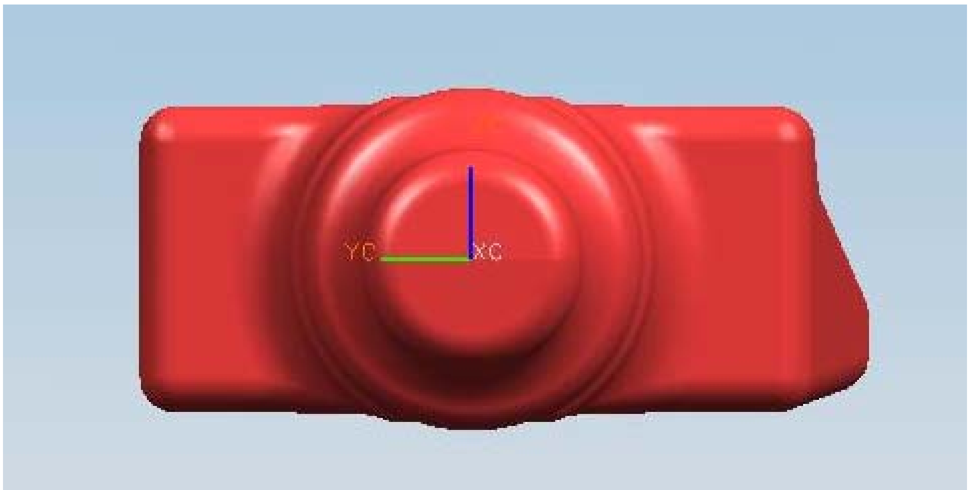


Figure 4.3 Equal Sections Along y Axis

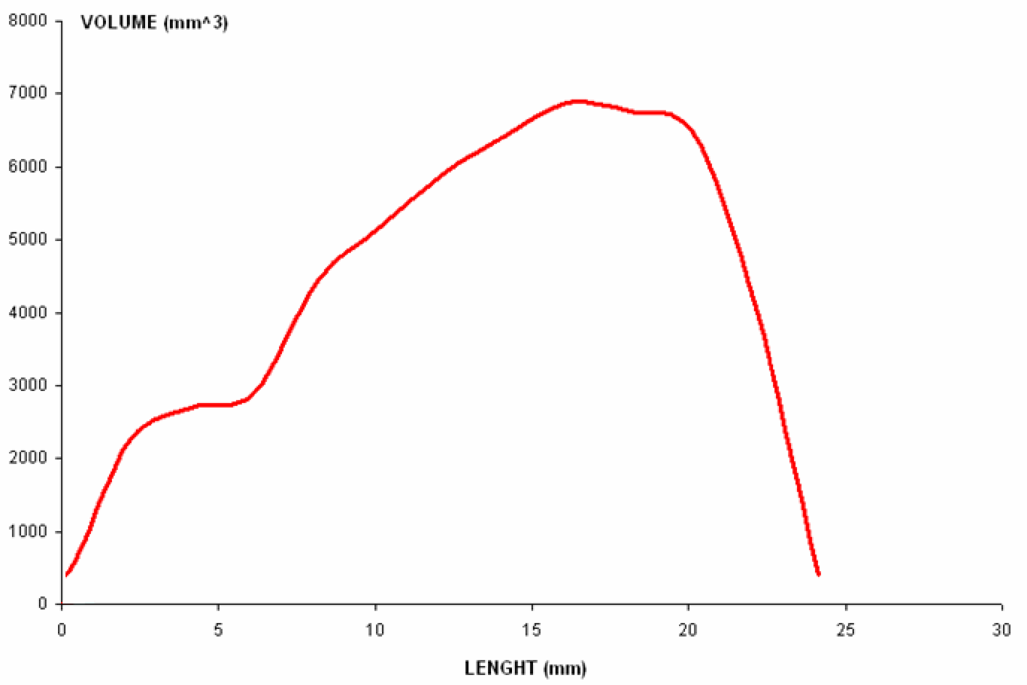


Figure 4.4 Volumetric Material Distribution of the Part Along y Axis

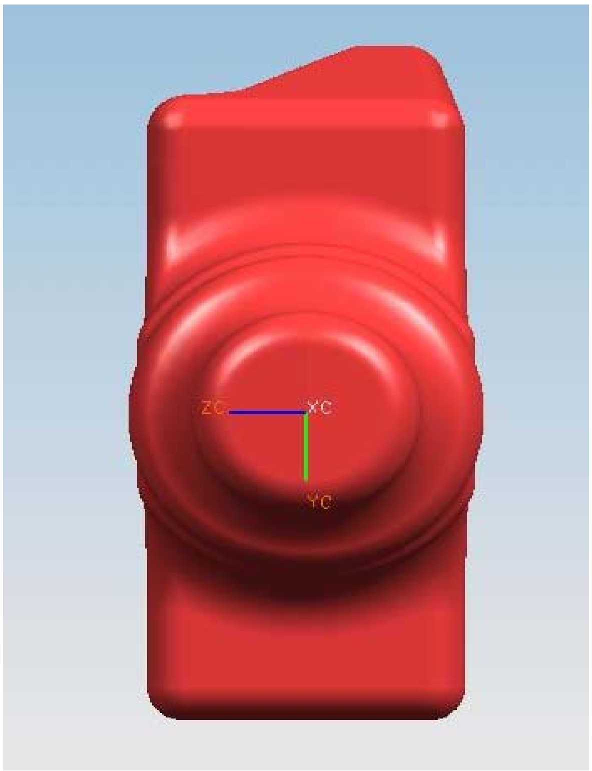


Figure 4.5 Equal Sections Along z Axis

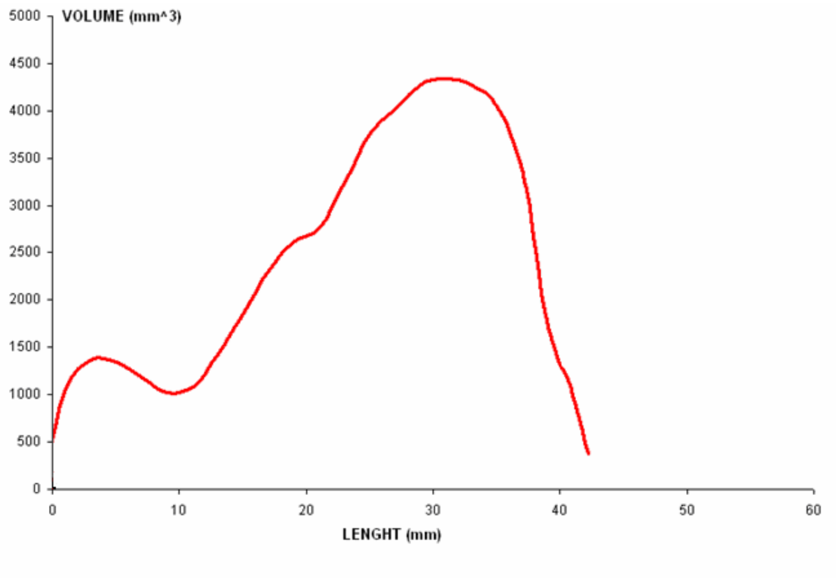


Figure 4.6 Volumetric Material Distribution of the Part Along z Axis

4.2 Die Design Procedure

Die design according to particular forging operation depends on forging geometry, production volume and expected die life. The general accepted outlines of die design can be found in publications [7, 16, 39] and summarized as follows:

1. At the parting line which is along the widest section of the forging, the mould cavity is kept 0.4 mm to 1.6 mm narrower than the finisher cavity.

2. Die cavity is designed deeper than the finisher cavity in order to compensate the reduction on the original dimension. During the finishing stage the material will be squeezed laterally toward the die cavity without additional shear at the die material interface.

3. The volume of the die cavity must be as large as the volume of the material in finisher cavity.

4. The die should have larger radii and fillets than finisher cavity to ease metal flow in the final operation.

5. Draft angles of the designed die shape must conform to the angles in the finished shape.

These general rules are considered for designing the dies and used in the sequence design of the fin connector rod.

4.3 Billet Dimension Selection

The final form of the fin connector rod is shown in Figure 4.7. Material distribution along the longitudinal axis is utilized in order to determine the billet diameter. In the given geometry, the cross-sectional areas with maximum volumes are at portion C as determined by Figures 4.2, 4.4 and 4.6. Portion C seems to be more capable to maximize metal flow with a less required load.

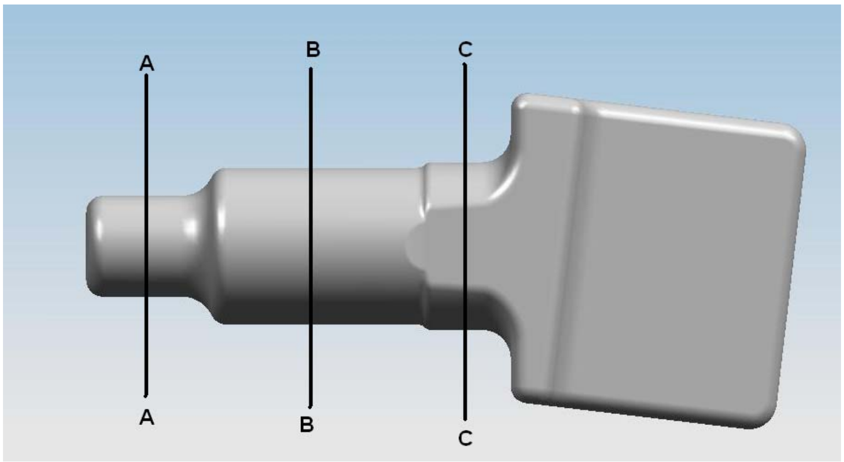


Figure 4.7 Main Portions of the Fin Connector Rod

The appropriate section C is selected for sequence design. Selected diameter of portion C is 30 mm. Considering DIN 668 (10.81) standards, a 32 mm diameter billet bar is selected. In DIN668 (10.81) standards, some available diameters of billets are given as Ø2, 2.5, 4, 8, 10, 12, 14, 18, 20, 25, 30, 32, 40 and 60 mm. Regarding the volume of the forged part as 112600 mm^3 length of the billet to forge can be calculated as 140 mm. The rod side of the part which is unforged length of the part is 74 mm. As a result, l_0 is 66 mm and d_0 is 32 mm. Since $l_0/d_0 \leq 2.3$ for the selected billet, the geometry can be forged in one operation by upsetting according to Gökler’s design rule [11].

4.4 Forging Sequence Design

The fin connector rod might be forged in many ways. However, the cost of manufacturing and the production time should be minimized before beginning mass production. In this thesis, the forgeability of the FCR is investigated with limited operations in two possible alternative designs named forging case studies. These case studies of the part are modeled by considering equal billet volume which is determined to obtain forged part. The finite element method is applied in order to determine the metal flow and temperature distribution in the deformed parts to find the most appropriate method.

4.4.1 First Forging Case Study

In the first forging case study, the billet material is planned to be forged by an upsetting operation in which an inclined form is obtained. Then, a preforming operation is planned to obtain the shape close to the desired geometry. In the third operation, it is expected to achieve the final form of the part. The planned operation sequence is given in Figure 4.8.

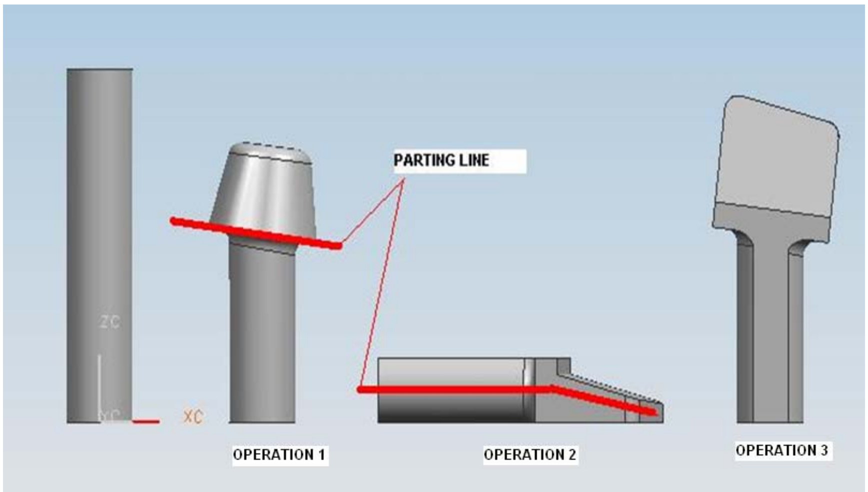


Figure 4.8 Forging Design of the First Case Study

a) Operation 1

At the beginning of the operation 1 of the first forging case study, the billet is placed into designed top and bottom dies. In the analysis 153569 nodes with 66523 elements are used for this operation. In this operation, it is expected to fill the top die cavity in an inclined form by upsetting operation. Figure 4.9 shows that the position of the billet in the upsetting dies.

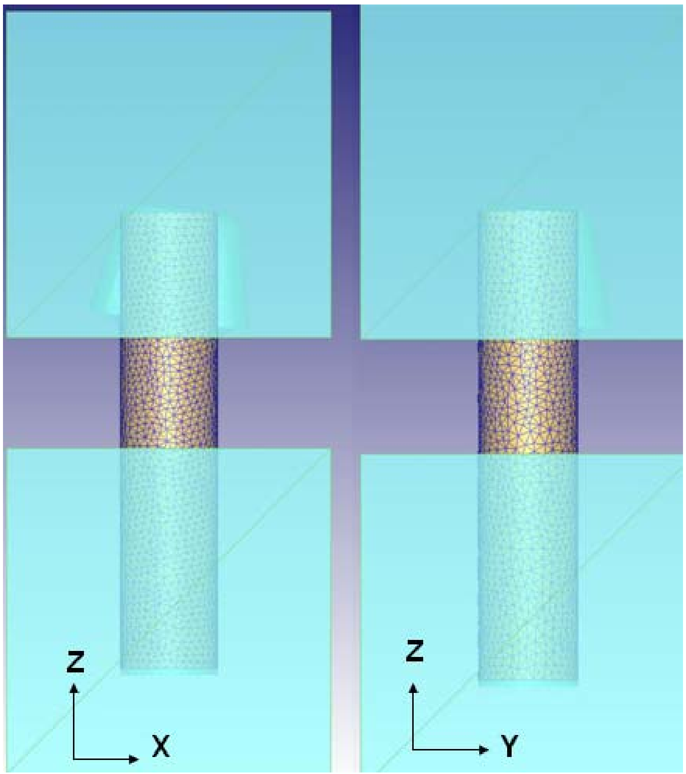


Figure 4.9 Position of the Dies and Billet in Operation 1

At the end of operation 1, it is observed that the desired geometry is not achieved. The top die is not totally filled with the billet material. Excessive flash is obtained before the die is filled with material. Stress distributions of the part are shown in Figure 4.10. Figure 4.10 (a) shows the position where the maximum equivalent stress is occurred at the end of the loading operation. It can be seen that the maximum stress is 101 MPa. Figure 4.10 (b) shows the stress distribution after unloading. Temperature variation of the forged part is also shown in Figure 4.11. Because of the unfilled die and excessive flash material, the second and third operations are not modeled.

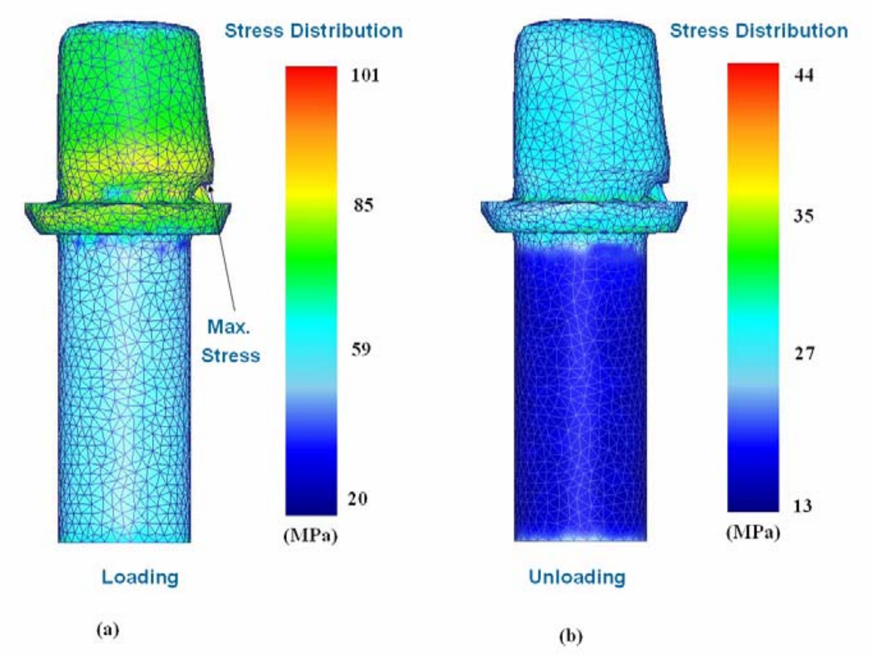


Figure 4.10 Stress Analysis of the First Case Study

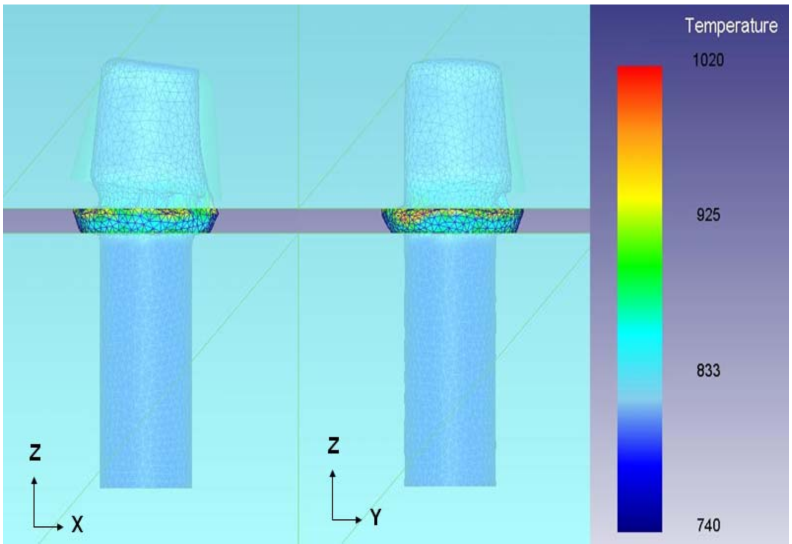


Figure 4.11 Temperature Distribution of the Operation 1

4.4.2 Second Forging Case Study

In this case study, a new operation sequence will be used for the production of the fin connector rod. At operation 1 the determined billet is forged by upsetting. This operation plays an important role for a uniform mass distribution of the part. In operation 1, the rod side of part is kept inside the bottom die. Then, billet is deformed with a flat die into desired geometry. In operation 2, the formed workpiece is forged into preform shape. After preforming operation, the workpiece is forged to obtain the last form of the fin connector rod in operation 3 which the desired form of the complex part is obtained. Finally, the last operation which is operation 4 helps cut the flash of the fin connector rod.

The geometrical and mechanical results of previous operation are used before next operation in the finite element analysis program. In other words, the finite element results of the strain hardened part is used in the next operation. These operation order and the designed dies are shown in Figure 4.12 and Figure 4.13.

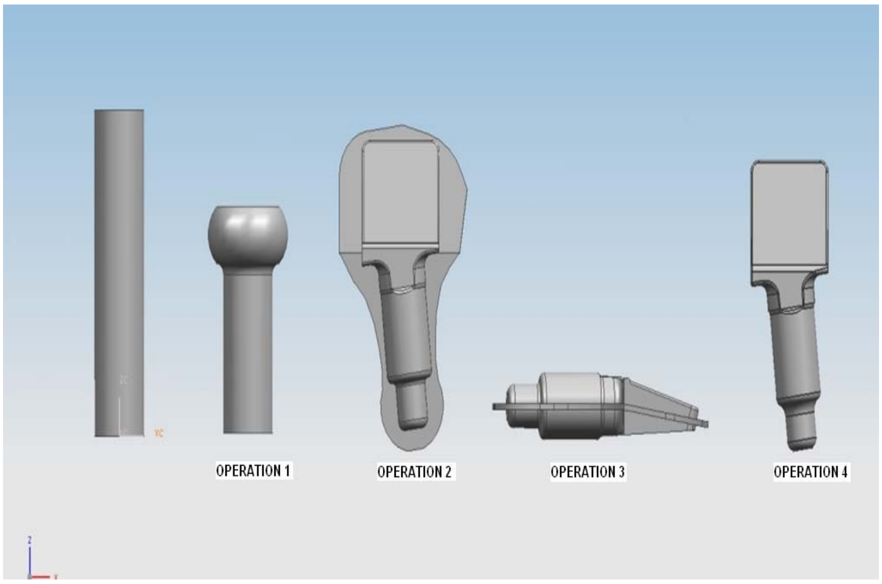
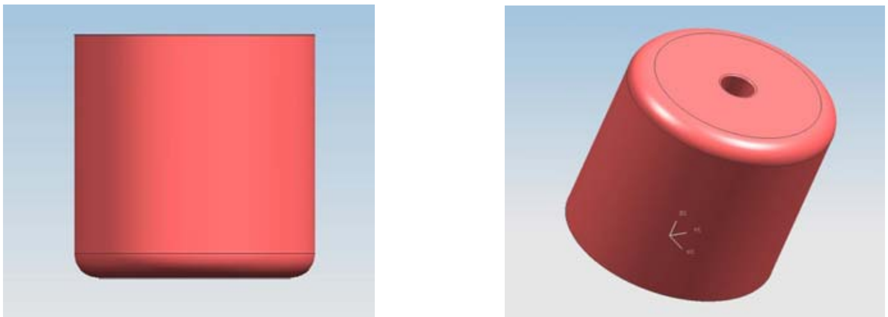
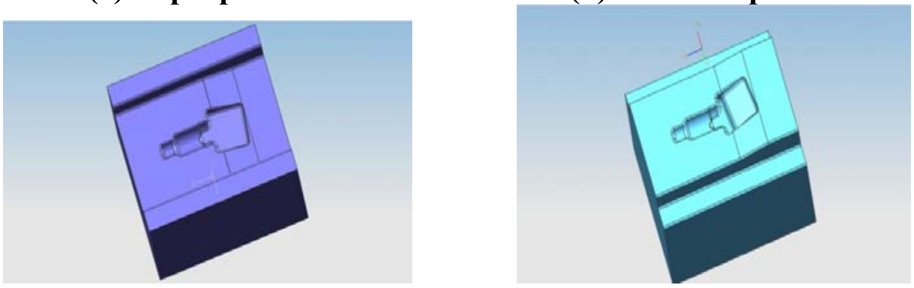


Figure 4.12 Forging Design of the Second Forging Case Study

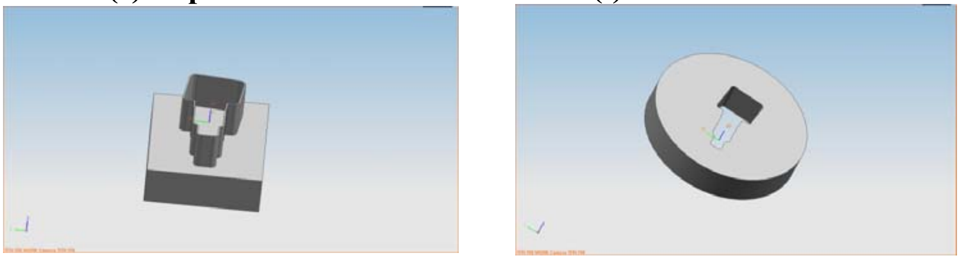


(a) Top Upset Die **(b) Bottom Upset Die**



(c)Top Preform Die **(d) Bottom Preform Die**

(e) Top Finish Die **(f) Bottom Finish Die**



(e) Top Trim Die **(f) Bottom Trim Die**

Figure 4.13 Designed Dies

a) Operation 1

At the beginning of the operation 1 of the second forging case study, the billet is placed into designed top and bottom dies. The aim of this operation is to achieve the desired upset part and to analyze the stress and temperature distribution of the forged part. Billet is placed into cavity of the bottom die.

The position of the billet and the dies before finite element analysis is shown in Figure 4.14. In the finite element analysis of the operation, 252012 nodes with 89823 elements are used.

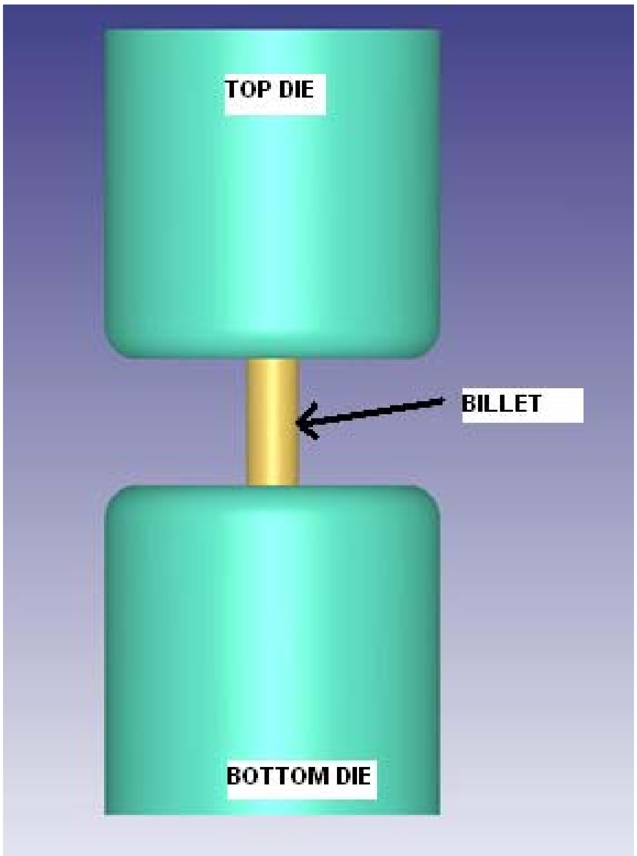


Figure 4.14 Position of the Dies and Billet in Operation 1

At the end of the operation 1 of the second forging case study, the maximum equivalent stress is obtained at the end of loading operation and it is shown in Figure 4.15 (a). It can be seen that the maximum stress is 94 MPa It is observed that the desired geometry is achieved. The stress distribution after unloading the dies is shown in Figure 4.15 (b).

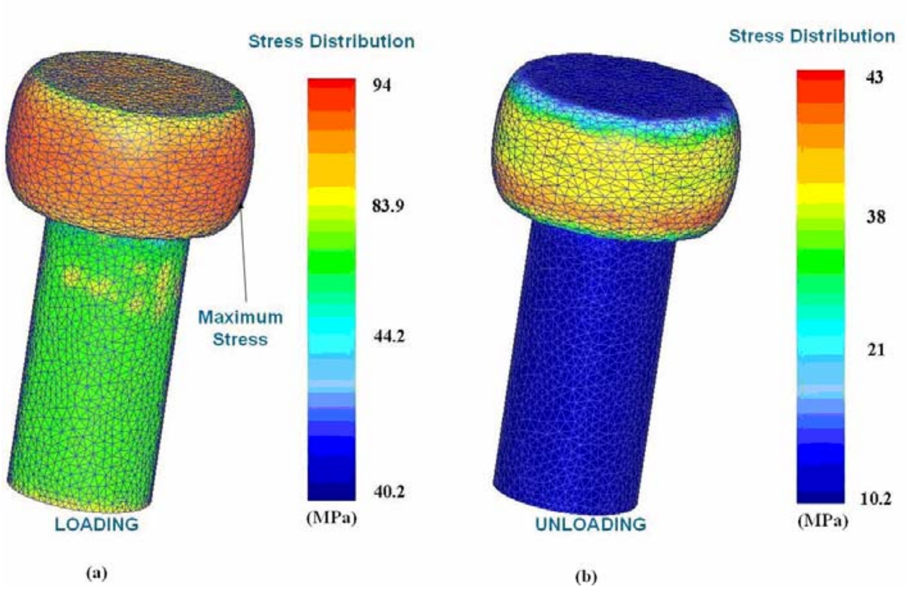


Figure 4.15 Stress Analysis of the Operaion 1

The temperature distribution of the first operation of the second case study is also shown in Figure 4.16.

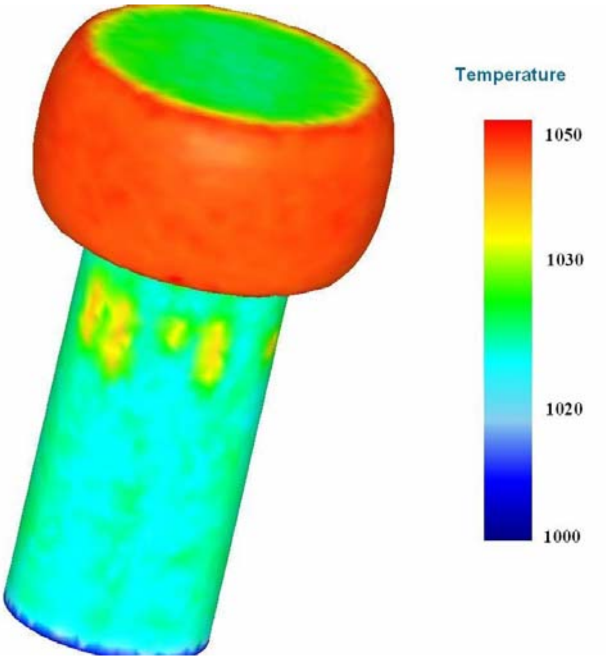


Figure 4.16 Temperature Distribution of the Operation 1

a) Operation 2

In operation 2, the product of the operation 1 is placed into the dies. Finite element program considers the new number of elements and nodes using remeshing process in operation 2. In the operation 2, 325465 nodes and 95024 elements are used. Figure 4.17 represents the product of the operation 1 and the preformed dies at the beginning of the forging operation.

At the end of the analysis, the material adequately filled the die cavity. The stress distribution of the operation 2 and the position of maximum equivalent stress are shown in Figure 4.18 (a) at the end of the loading stage. The maximum equivalent stress is obtained 105 MPa in loading. The stress distribution after unloading is shown in Figure 4.18 (b). The figure indicates that the maximum equivalent stress on the part is acceptable for the material at current temperature. The temperature distribution of the part is shown in Figure 4.19.

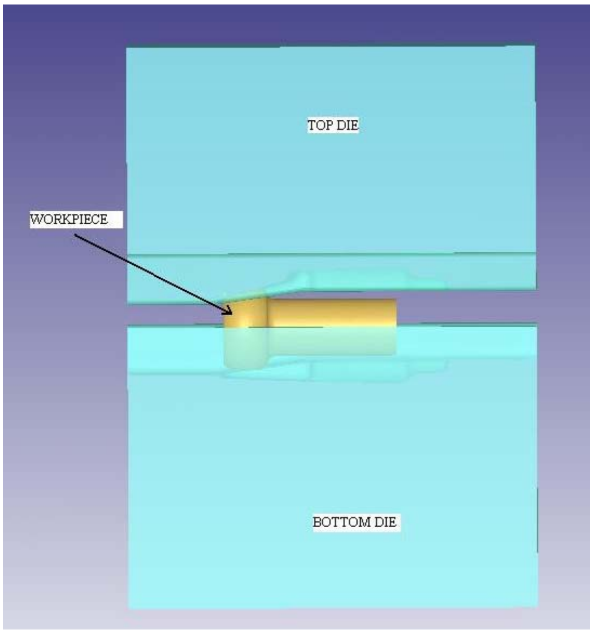


Figure 4.17 Position of the Dies and Workpiece in Operation 2

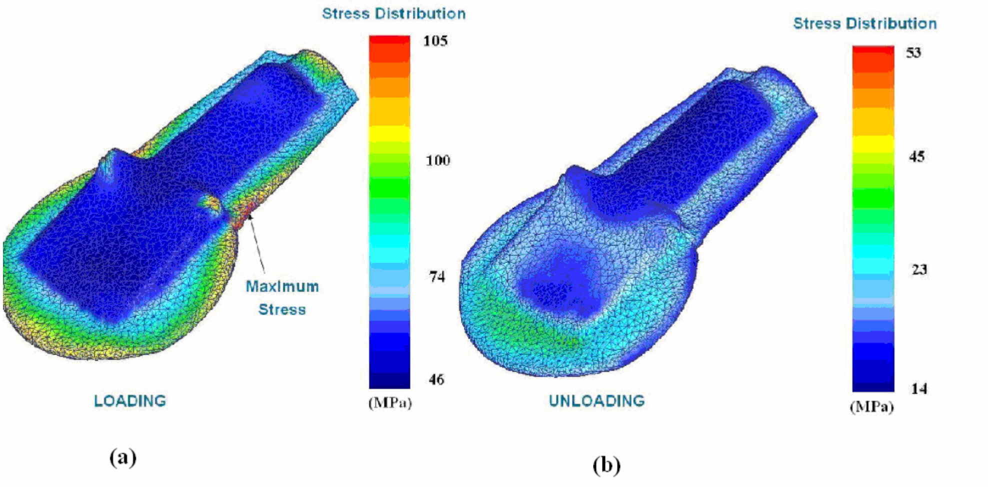


Figure 4.18 Stress Analysis of the Operation 2

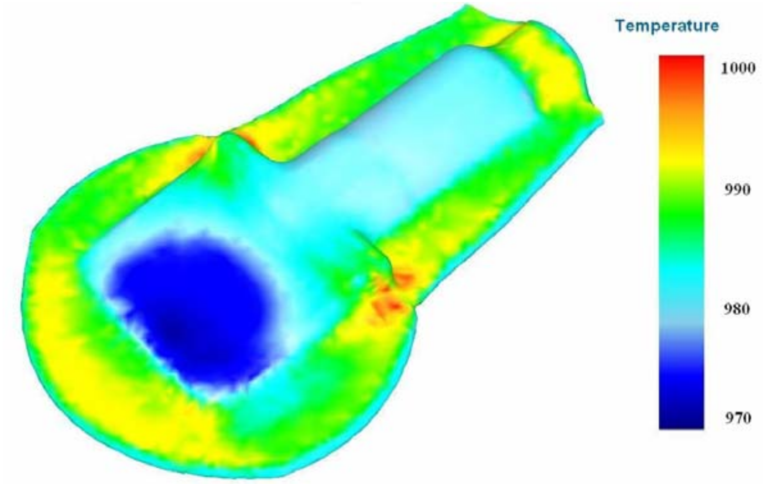


Figure 4.19 Temperature Distribution of the Operation 2

c) Operation 3

In operation 3, preformed part is forged to final geometry of the part. Since preformed workpiece did not totally fill the cavity of the dies in this operation the final form of the part will be obtained. Figure 4.20 represents the position of the finish dies and preformed part.

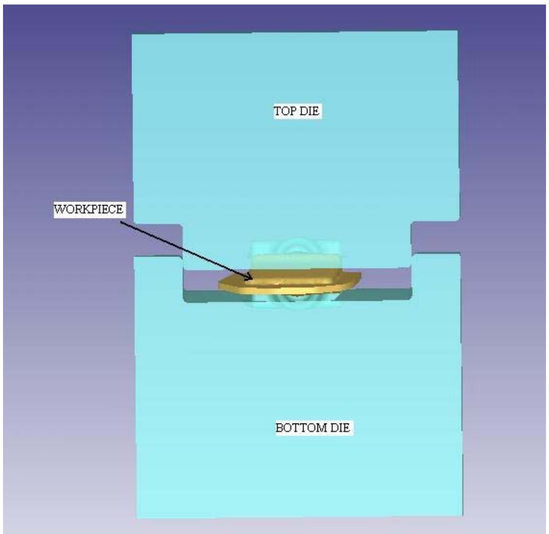


Figure 4.20 Position of the Dies and Workpiece in Operation 3

The obtained stress distributions after loading and unloading are shown in Figure 4.21. At the end of the loading in operation 3, it is observed that the maximum equivalent stress is reached and its magnitude is 110MPa. The position of the maximum stress is also shown in Figure 4.21 (a). The stress distribution after unloading is shown in Figure 4.21 (b). The cavity of dies is totally filled with the material in operation 3. The maximum equivalent stress at the given temperature range is acceptable.

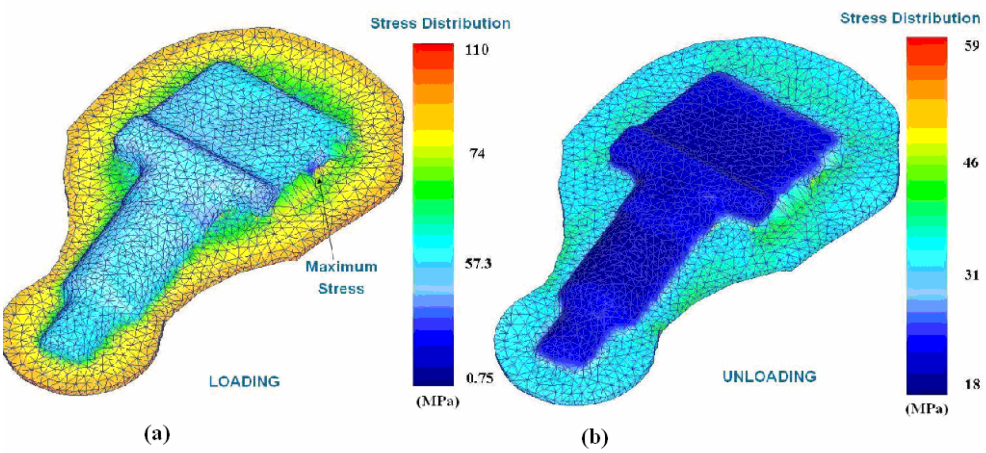


Figure 4.21 Stress Analysis of the Operation 3

Temperature distribution of the operation 3 is shown in Figure 4.22.

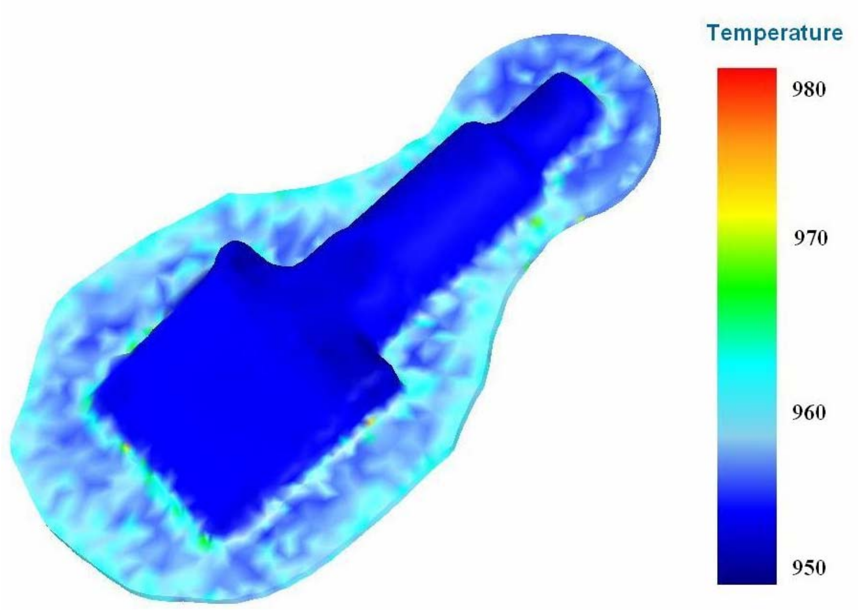


Figure 4.22 Temperature Distribution of the Operation 3

With the second forging case study, the forged part geometry of the FCR satisfies the specified design considerations. It is applicable to continue operation 4 for this case study.

d) Operation 4

In the trimming operation, the flash on the forged part is to be cut. The designed dies and workpiece are shown in Figure 4.23.

In the finite element analysis, it is found that the maximum forging load is attained as 866 ton in the second forging case study. Experimental study of this case study is done by considering the maximum forging load on the part.

At the end of the second forging case study, it is observed that the desired geometries are obtained successfully. The material has almost same dimensions of the desired forged part. In this method, the machining operation after forging is minimized and the amount of excess material is very low.

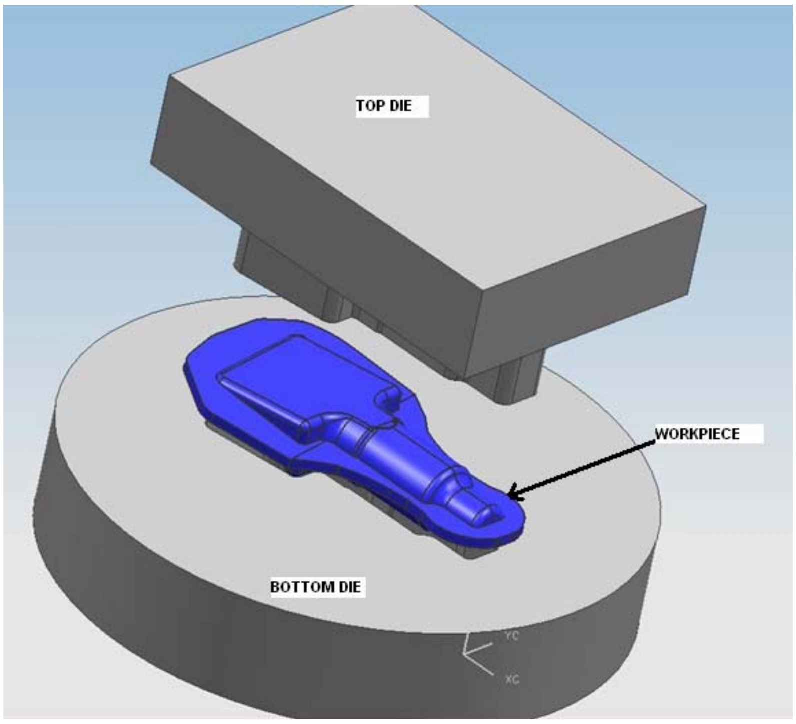


Figure 4.23 Dies and Workpiece Position of Trimming Operation

4.3 Secondary Operations

In order to have the finished part of the FCR, forged part of the second forging case study should have some machining operations. The rod side of the part will be machined in turning operation whereas the head side of the part will be machined in milling operation. However, to machine the forged part in the CNC machine tools, fixtures are required. The fixtures for machining are designed and shown in Figure 4.24 and Figure 4.25.

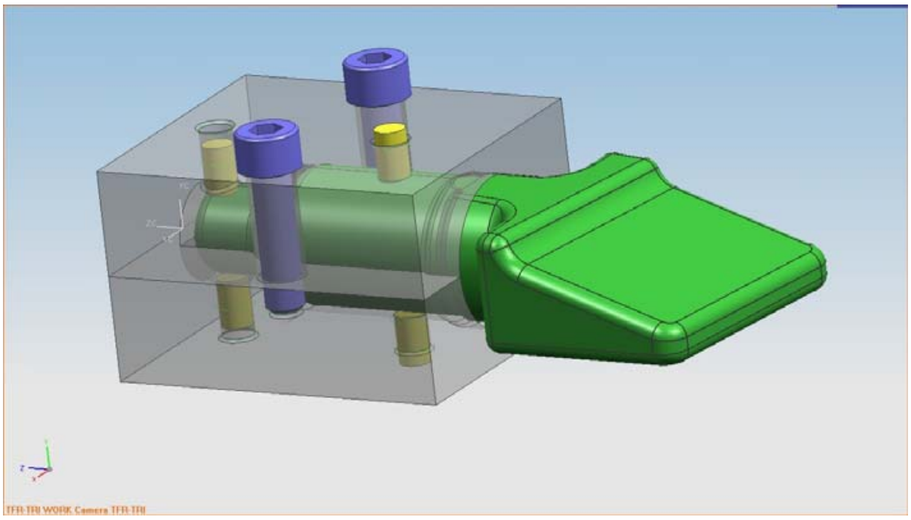


Figure 4.24 First Manufacturing Fixture of the FCR

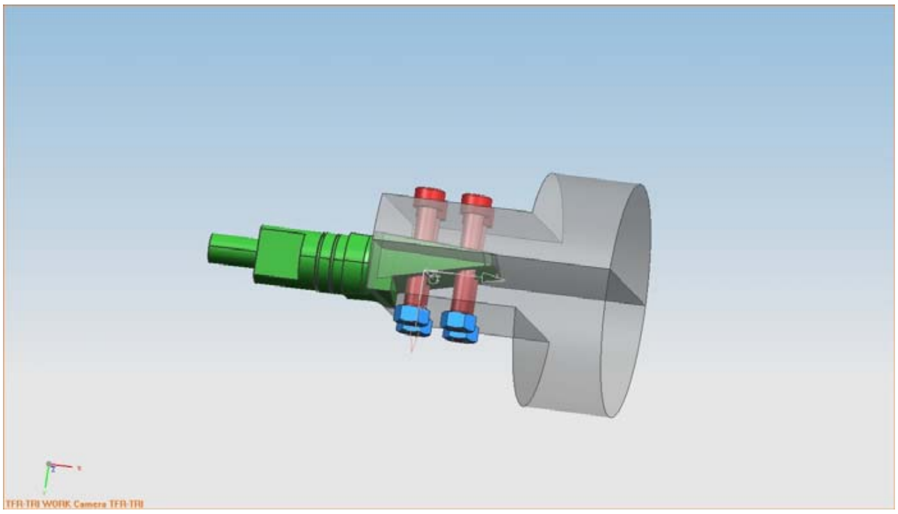


Figure 4.25 Second Manufacturing Fixture of the FCR

CHAPTER 5

EXPERIMENTAL STUDY

5.1 Manufacturing Dies and the Fixtures

By using the results of the finite element analysis of the fin connector rod, the second forging case study is selected.

The designed dies according to design order, are manufactured by using CAM (Computer Aided Manufacturing) codes of the UNIGRAPHICS 5.0 program. There are three main parameters which are feed rate, depth of cut and spindle speed. These parameters are optimized in TÜBİTAK-SAGE’s manufacturing engineering department and postprocessed for machining operation. Machining of the dies is done in AKSAN Steel Forging Company. Machining simulation of the die is shown in Figure 5.1. Selected material of the dies is AISI 2714 forging steel which is applicable for forging of St 4140 and material of the fixture is St 44 [44].

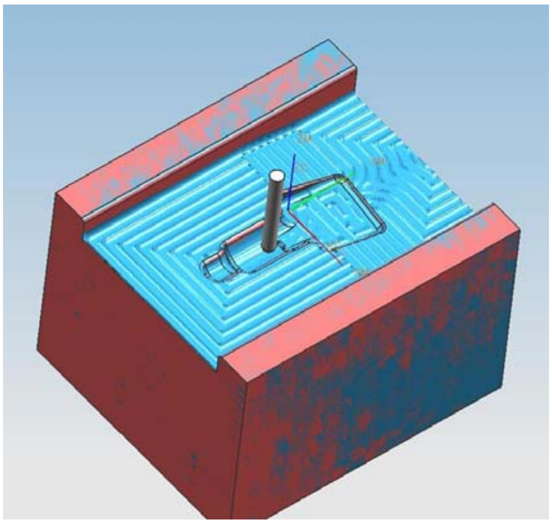


Figure 5.1 Machining Simulation of the Die

Manufacturing of the fixtures is also done by using CAM module of the 3D modeling program in TUBİTAK-SAGE. Figure 5.2 shows the manufactured dies and Figure 5.3 shows the manufactured fixtures.

(a) Bottom Die of Operation 1 **(b) Top Die of Operation 2**

(c) Bottom Die of Operation 2 **(d) Top Die of Operation 3**

(e) Bottom Die of Operation 3 **(f) Trimming Dies**

Figure 5.2 Manufactured Dies

(a) First Manufactured Fixture of the FCR **(b) Second Manufactured Fixture of the FCR**

Figure 5.3 Manufactured Fixtures

5.2 Forging Operation

Billet, dies, induction machine for heating, presses, thermal and geometric measuring devices are ready before forging. Additionally a LPG (liquid petroleum gas) tank with flame gun for heating the dies and a tong for holding the heating billet are prepared. A 1000 ton capacity of a mechanical press is selected for manufacturing of the fin connector rod in AKSAN.

Initially, the inspected and accepted dies are mounted into the press machine carefully, since any misalignment during setup operation may damage the dies. Then, required billets are measured before forging. Sample billet dimensions are given in Table 5.1.

Table 5.1 Dimensions of the Sample Billets

Billet Number	**Diameter**	**Length**
1	31.98	139.9
2	31.95	140.1
3	32.02	140.1

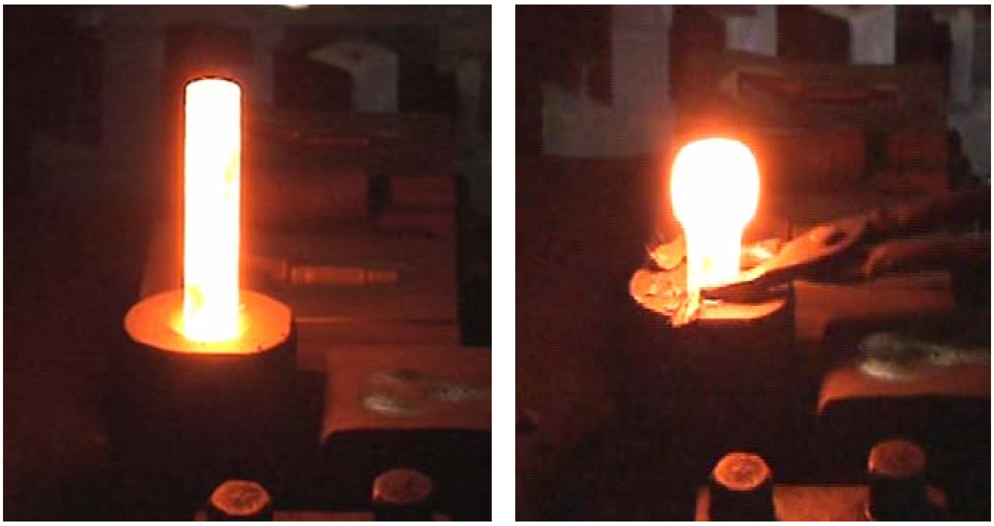
Table 5.1 Cont'd

4	32.01	139.9
5	31.93	139.8
6	31.95	140.1
7	31.97	139.9
8	31.98	140.3
9	32.01	140.1

After the set-up of the dies has been completed, selected billets are placed into induction machine for heating to 1000-1050°C. Dies and the other tools are heated to 300-310°C with an LPG heater flame gun at the same time. Figure 5.4 represents the heating operation of the dies.

Figure 5.4 Heating Dies

In the first operation, which is upsetting, the billet is placed on the die set in a vertical position. Cavity of the bottom die covers the rod side of the fin connector rod and the top die freely falls onto billet with a desired stroke to shape the part. Figure 5.5 shows the upsetting operation of the FCR.



(a) Before Upsetting **(b) After Upsetting**

Figure 5.5 Upsetting Operation

Hot upset part is placed into preform dies immediately in a horizontal position. The reference of positioning is done by considering parting line position of the preform dies. The part before the last forming operation is shown in Figure 5.6.

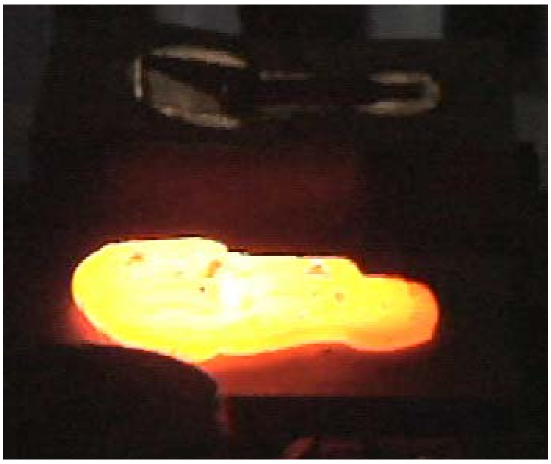


Figure 5.6 Preformed Workpiece

Then, the preformed part is forged into last form in operation 3 in order to obtain the precise geometry of the forged part. The preformed part is placed into finish dies in horizontal position and forged by ram stroke of the machine.

Finally, having the precise geometry of the fin connector rod, the obtained flash after last forging operation is cut by the trimming operation. Top and the bottom trimming dies are placed into simple press and the workpiece is placed into bottom die in a horizontal position. Top die freely falls onto bottom die with a defined trajectory to trim the flash. Experimental study of the trimming operation is shown in Figure 5.7. This operation is the last operation of forging the FCR.

(a) Before Trimming **(b) After Trimming**

Figure 5.7 Trimming Operation

5.3 Machining of the Forged Part

After forging, the forged part of the FCR is ready for machining operation using designed fixtures in CNC machines. All the machining operations are done in TÜBİTAK-SAGE. Figure 5.8 indicates the position of the forged part inside the first fixture before milling operation and Figure 5.9 shows milling operation of the part in the CNC machine tool by using postprocessing module of the 3D modeling program.

Figure 5.8 Forged Part is Placed into First Fixture

Figure 5.9 Machining of the Part in Milling Operation

After milling operation, the rod side of the FCR is machined by a turning machine. The second fixture helps for fixing the FCR on the turning machine. The position of the fixture and the part are shown in Figure 5.10.

After completing all machining operations, the dimensional measurement of the fin connector rod is done with CMM (Coordinate Measuring Machine) and there is no geometrical failure found.

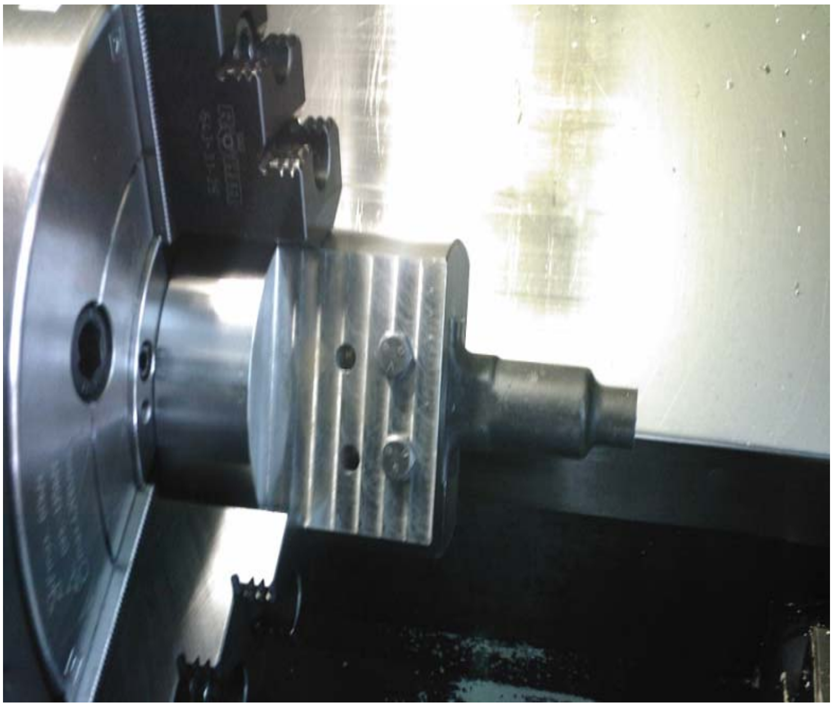


Figure 5.10 Machining of the Part in Turning Operation

5.4 Wastage Material Calculation

Initial billet mass is selected 0.88 kilogram. After forging and machining operations, the mass of the part which is shown in Figrure 5.11 is measured 0.45 kilogram. Total material loss of forging operation is 0.43 kg. However, current machining operation requires a raw material about 2.60 kilogram so that the total loss material in machining is approximately 2.15 kilogram. By comparing two methods, 1.72 kilogram material saved per part in forging operation.

Figure 5.11 Weight of the Final Part

5.5 Hardness Test

In order to determine the strength of the part, hardness test has been done in TUBİTAK-SAGE's quality control department The surface hardness of the part is measured as 36-38 HRC (Hardness Rockwell-C). The measured value satisfies the requirements of the fin connector rod. Figure 5.12 shows the hardness test of the part.

Figure 5.12 Hardness Test of the Part

CHAPTER 6

ECONOMIC ANALYSIS OF MANUFACTURING THE FIN CONNECTOR ROD

6.1 Importance of Cost Estimation

Product manufacturing involves the conversion of material into finished goods using labor and equipments. Having a precise idea about the cost of manufacturing, a product is very critical factor of competition. The objective is to minimize the cost, maximize the profit, and maintain the competitive edge. Cost estimation is the evaluation and analysis of the cost of process operation [20].

Manufacturing operations involve many cost elements that require analyzing. An estimate is an attempt to predict the future of production. The accuracy of the project and product cost estimations can often determine the ultimate success or failure of the company. Attempting to estimate without detailed cost information or wrong manufacturing process selection can easily give two results: loss of the business or wining of the order but having to perform the work at a loss. If the cost estimate is too high, other firms may give lower prices and the business will be lost. If the cost estimate is too low, the job will be gained but money will be lost during manufacturing. Therefore, a right good quality cost estimates will always be helpful to the company.

In many firms, the business of cost estimation is considered in the domain of the financial department. However, the cost estimation of the products extends to every department of the company and especially into the manufacturing engineering department. In today's business environment with the current automated cost estimation approaches, the engineers can also play an active and decisive role in cost estimation [21, 22].

6.2 Cost Estimation Approach of Current Manufacturing Operation of the Fin Connector Rod

Production costs and production rates are of vital interest to the manufacturing engineering division. Although in practice, a high production rate would probably mean low production costs, it should be pointed out that these two factors must be considered separately and that the manufacturing conditions giving the maximum production rate will not be identical to those conditions giving the minimum cost of production [26, 29].

Analysis of production costs and production rates can be a complicated subject, and in many cases the analysis will apply only to the particular operation in question. However, experience gained over the years has led to certain empirical rules or guiding principles for choosing the optimum cutting conditions for a given machining operation, and it is the objective to illustrate how these principles can be used.

The production time is defined as the average time taken to produce one component, and the production cost is identified as the total average cost of performing the machining operation on a component using a CNC machine tool. In general, the production of a component involves several machining operations using a variety of machine tools [30].

Manufacturing of the FCR by machining requires different size of raw material when comparing forging. A calculated and required raw material dimensions of the FCR used in machining operation is given in Figure 6.1.

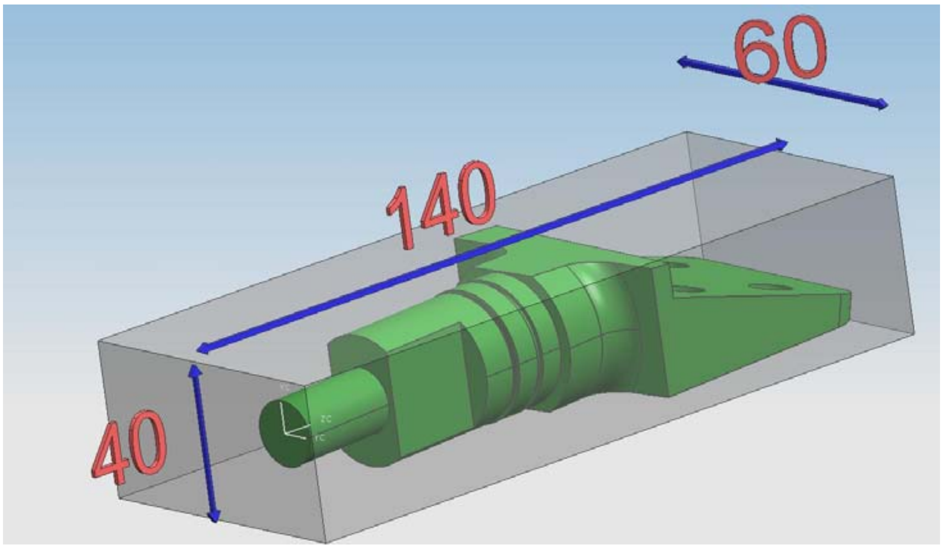


Figure 6.1 Required Volume to Produce the FCR in Machining

Total Volume = 140x 40x 60 =336000 mm^3 material is required. The project also requires 5000 product of the FCR and all cost calculations are done by considering that number of part.

Assuming the appropriate tool and cutting fluid are chosen for the machining of a batch of components, the only cutting conditions to be determined are the cutting speed and feed at a given depth of cut [29]. For the purposes of this discussion, it is necessary to explain that feed is the distance moved by the tool relative to the workpiece in the feed direction for each revolution of the tool or workpiece. Confusion may arise in certain multipoint tool operations such as milling where the feed settings on the machine refer to the relative speed between the tool axis and the workpiece in the feed direction [26, 31].

6.2.1 Operation Order and the Cost of the Fin Connector Rod

In machining operation, only a CNC milling machine tool is used. The material of the part is placed into machine tool in horizontal position before beginning to machining the head side of the part. The CAM codes of the part are postprocessed by using 3D modeling program. After finishing the head side of the part, the workpiece is rotated 90° with respect to machine tool and it is fixed in order to continue machining the rod side of the FCR. Single machining tool seems easy to produce the part. However, fixing and rotating operations takes time of the operator. The high precise geometry of the part should be produced in a good repeatable condition during mass production. In the machining process of the part, 3.6 kilogram of the raw material is reduced to 0.66 kilogram which is not so beneficial method when considering the initial raw material volume.

After machining operation the part is sent for heat treatment process in order to have the required hardness on the part. The expected hardness should be 36-42 HRC.

Fin connector rod has so many complex angles on the part geometry. Even if the machining operation finishes the required dimensions accurately, heat treatment operation results distortion on the part. Producing the parts in this operation order, about 90% of the parts are not accepted in the quality control department of TUBİTAK-SAGE because of the geometrical failure on the part.

The calculated production cost and the offer of producers are considered together and the cost of the part is **$ 80/ part**. In this cost estimation, some major parameters are considered and they are operator wage cost, machine usage cost, production cost, tool cost, secondary operation cost, production time, tool changing and resetting time.

Because of the inefficient production order, the fin connector rod should be manufactured in different production technique and the results of the goods should satisfy the requirements of the product in mass production of the project with low cost and high production rate.

6.3 Cost Estimation Methods of Forging

There are four kinds of cost estimation methodologies used throughout the industry.

- Subjective estimation
- Estimation by analogy (comparative estimation, top-down estimation)
- Statistical estimation
- Bottom-up estimation (synthetic estimation, estimation by engineering methods, grass roots estimation)

In the subjective estimation method, the estimator obtains the price by relying completely upon own memory and judgment without referring to the systematically collected data. This is an unreliable and unsatisfactory method of cost estimation. Although it is an unrecommended method, it is widely used in the industry as a quick method to check the price to give the customer a rough order magnitude of the price [23]. In the estimation by analogy method, the particular product is compared with the formal cost and technical data records of an old product. Allowances are made for any differences in material, weight, size, energy consumption, complexity, and other factors to derive the product cost. The basis for the cost estimate is the similarity that exists between the known item and the proposed part. Estimation by analogy method is also named as top-down estimation method and comparative estimation method. The major disadvantage in estimation by analogy is a higher degree of judgment required [24]. The analogous system approach places heavy emphasis on the opinions of the cost estimators. Uncertainty in a cost estimate using analogy is due to the subjective evaluations made by the technical staff and the cost estimators during the determination of the cost impacts of the differences between the old and new products. Considerable experience and expertise are required to identify and deal with convenient analogies and make adjustments for required differences. Estimation by analogy takes less time; therefore, it is widely used in the industry as a check on the other methods and in the early cost estimation. For the forging industry, if there are analogous products available for comparative evaluation, analogy method can be used as a fast and early cost estimation method, especially for the cases when estimation time availability is too short [22]. The statistical estimation method involves collecting relevant historical data, usually at a convenient level of detail and relating it to the product to be estimated through the use of mathematical techniques. The objective is to find a functional relationship between the changes in costs and the factors upon, which the cost depends. The important bases of the statistical estimation methodology are the cost estimation relationships. Each of the cost estimation relationships defines the cost as a function of the physical or operational parameters, like the speed, lot size, weight, complexity, horsepower, etc. This method may also utilize the statistical techniques ranging from simple graphical curve fitting to complex correlation analysis. Generally, a detailed statistical study and the analysis of the related cost items are required to derive a formula to express the total product cost. If a statistical formula can be established, it is fairly simple to use. However, these methods generally, capture the costs at a very high level, without going into too much detail.

In the bottom-up estimation method, the aim is to break down the business into its smallest tasks, based upon the best available information. The product cost is broken into small manageable cost items. The cost estimator specifies each task, equipment usage cost, necessary tool cost, material cost, labor cost, secondary cost etc. Then, the costs are assigned to elements at the lowest level of detail and then summed up to form the overall product cost. Bottom-up estimation method, is also named as synthetic estimation, engineering estimation and grass roots estimation [22]. Bottom-up estimation can be either broad or detailed depending on the time available to the estimator and the required accuracy or the importance of the cost estimate. With full details and information, the bottom-up estimation method can give very accurate estimates. The work element and the cost items of a product or project and their interrelationships can be analyzed at successive levels of detail in the form of a work break down structure. The work break down structure is a management technique for subdividing a total job into its component elements in a product-oriented hierarchy that identifies all elements of a product or project and their major/minor relationships. Forming of work break down structure is the first step in bottom-up method of cost estimation. The work break down structure is developed from the top to down in successive level of details. The job is divided into its major work elements. The major work elements are then divided to develop higher level and so on. All work elements like, product material cost, labor cost etc. and their interrelationships must be shown in the work break down structure. The preparation of the work break down structure is essential in ensuring the inclusion of all work elements, eliminating the errors like duplications and overlaps between the work element, showing the cost items level of details and giving an overall cost perspective about the product. With this technique, it is started at the lowest level of definable work within the work break down structure, e.g. milling a die. The direct material costs are estimated. The labor hours required to complete the work are estimated from the engineering specifications and the labor costs are estimated usually using the company or general industry standards. Tunç [22] has attempted to develop an early cost estimation of forging software program based on bottom up approach. The cost estimation of the fin connector rod is done by using this cost analysis approach.

6.4 Forging Cost Estimation of the Fin Connector Rod

The cost of forging process depends on many factors such as material, die, labor, equipment, inspection, heating and overhead costs etc. These charges may vary from plant to plant and also type of product [25]. In order to observe and calculate the manufacturing of the fin connector rod by forging, some major and minor cost items should be investigated. The items that form up forging cost can be grouped as:

- Forging material cost
- Forging equipment cost
- Forging die cost
- Forging labor cost
- Secondary operation cost

6.4.1 Forging Material Cost

In the forging process, it is convenient that the material cost is the cost of material required per forging including the waste material [22, 23]. This will include the following:

- Net weight of the forging
- Waste material due to scale loss
- Waste material due to flash, saw cut, tong hold loss

The weight of the forging including the waste material is called forging weight. Material cost is the most important cost item in forging cost estimation as it comprises about half of the total forging cost. For estimation of waste material weight due to scale loss is the recommendation of Bruchanow and Rebelski [22, 23, 24].

Briefly, the forging mass of the FCR is calculated to be 0.88 kilogram of AISI 4140 steel. The raw material cost is \$3 / kilogram. Material cost is **\$2.64/part**.

6.4.2 Forging Equipment Cost

During the manufacturing of the fin connector rod by forging process, some machines are required. There are heating furnace, a required capacity of press or hammer and the presses for trimming. In a cost estimation process, all equipment costs should be considered. The equipment usage cost may include the set up cost, operating cost, maintenance, and repair costs.

The setup cost is generally reflected to unit forging cost on time basis considering the setup time and the production batches with greater quantity of forgings, the setup cost is smaller per unit forging.

In the experimental study of producing fin connector rod, forging equipment cost is calculated by AKSAN and given as **$2.17/part** [28].

6.4.3 Forging Die Cost

Forging die cost includes the cost of designing and manufacturing the forging dies and tools. Forging die cost per forging is the cost of the forging dies and other tools divided by the quantity of the forgings. The cost of the tooling includes,

- Cost of die material,
- Cost of design, and generating CNC codes,
- Cost of machining the dies,
- Cost of heat treatment.

Material of the dies is selected according to type of material to forge. Also, the amount of products is necessary for the die life. In the forging process, the number of the required dies is also necessary.

Cost of the die machining can be found by multiplying the machining time with the hourly usage cost of the used machines one by one and then adding all of the machine usage costs. The hourly usage cost of a machine is a value that should include the energy expenses, maintenance cost, depreciation cost, cutting tool cost, etc. [25, 26, 27].

In the manufacturing of the fin connector rod, design of the dies is done according to forging die design standard.

All the CAM codes of the dies are post processed in TÜBİTAK-SAGE and given to AKSAN forging company for manufacturing the dies. The cost of the manufacturing process of the dies is calculated considering the total production number of the part and it is founded **$0.65/part** [28].

6.4.4 Forging Labor Cost

For forging industry, the general procedure to find forging labor cost starts with computing or assuming the unit manufacturing time. The unit manufacturing time in the forging includes, time for cropping the billets, time for heating, preforming, forging, and trimming operations. Once the time spent in the forging is estimated, the forging workers cost should be charged to the particular forging product. The number of the workers in the forging is multiplied by the forging time and this result is also multiplied by the labor cost per unit time [22, 29].

Overall labor cost of the fin connector rod manufacturing might be calculated considering above information. However, it is not so easy to estimate the labor cost per part. Thus, some uncertain labor cost parameters are learned from the company where the experiment is done. Labor cost of the manufacturing the FCR by forging is **$2.1/part** [28].

6.4.5 Secondary Operation Cost

The cost for secondary operations is the cost due to machining, cleaning, testing, sandblasting operations. Secondary operation costs are based on forging weight. In this general cost estimation, the forging weight is taken as a basis for reflecting the secondary operations cost [22, 29].

Manufacturing the fin connector rod requires machining operations with fixtures. The secondary operation cost of the part is calculated as **$1.04 /part.**

Considering all the cost factors of forging operation, calculation of the FCR by forging can be done. Briefly the costs of the fin connector rod by forging are given.

Material cost is	$ 2.64 / part
Equipment cost is	$ 2.17 / part
Die cost is	$ 0.65 / part
Labor cost is	$ 2.1 / part
Secondary operation cost is	$ 1.04 / part

The total forging cost is **$ 8.6/part.**

6.5 Comparison of Manufacturing Techniques of the Fin Connector Rod

The unit part production of each operation is done. According to unit part costs, the cost graph for 5000 parts can be drawn. Figure 6.2 represents the comparison chart of the manufacturing techniques.

The figure clearly shows that the manufacturing the fin connector rod by forging is feasible when comparing the machining process. Approximately, after the production of 55 parts, forging operation costs less. The project requires 5000 FCR parts. The table indicates that more than $350,000 can be saved during the project.

When considering not only the production cost, but also time consumption, forging is beneficial manufacturing method of the fin connector rod.

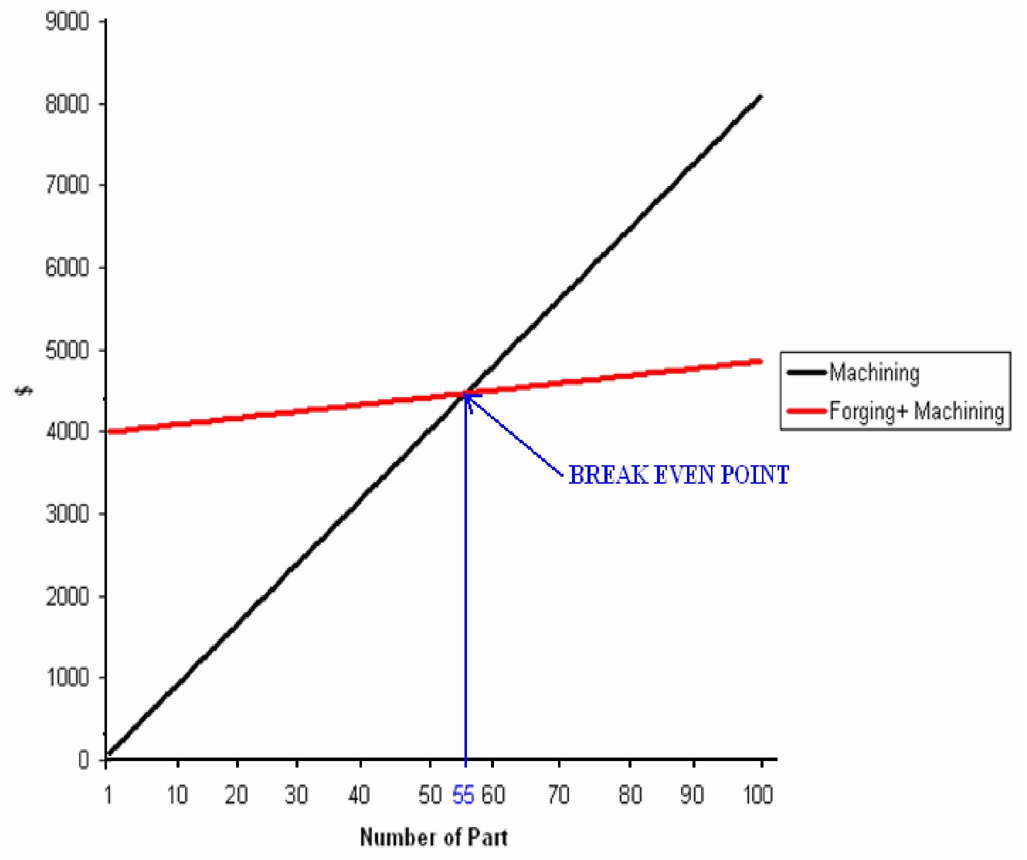


Figure 6.2 Production Cost Comparison of the Methods

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this study, manufacturing of the FCR by hot forging operation is accomplished. Finite element method is utilized to determine the operation sequence by comparing different alternative approaches. In the simulations, the particular fin connector rod is analyzed for a temperature range of 1000-1050°C and the dies are assumed as rigid at 300°C.

By using finite element method, two forging sequences have been designed for manufacturing the FCR. It is observed that, only one of the sequences is successful for the manufacturing of the part and this sequence consists of four operations which are upsetting, preform forging, final forging and trimming operation. The part is manufactured successfully by using the particular sequence. A single upsetting stage has been applied by considering material distribution of the part. In the preforming operation a rough geometry of the part is obtained. The precise geometry of the part is achieved by final forging operation. Finally, trimming operation is applied to remove the flash material of the part.

In this study, the following conclusions have been acquired:

1. The fin connector rods are successfully produced by forging operation using the numerically determined operation sequence.

2. It is observed that, the mass production of the part by forging operation is convenient and advantageous to have a high material strength with low cost compared to current manufacturing method based on machining.

3. It has been demonstrated that, the proposed design of precision dies have been successfully implemented in real-life application.

7.2 Future Work

The following may be suggested as future work:

- The dies can be modeled as deformable bodies to obtain the stress and strain distribution that are developed on the dies.
- By the die analysis, die material can be changed to have longer die life.
- The number of alternative forging methods can be increased to have a better approach and product quality.
- The cylindrical end of the part can be produced by the extrusion method.
- Finite element analysis results can be compared by using different finite element codes.
- Other forgeable ferrous materials can be used for the manufacturing of the fin connector rod.

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APPENDIX A

INFORMATION ABOUT DEFORM SOFTWARE

A.1 Deform Software Program

DEFORM is an engineering software that enables designers to analyze metal forming, heat treatment, machining and mechanical joining processes on the computer rather than the shop floor using trial and error. Process simulation using DEFORM has been instrumental in cost, quality and delivery improvements at leading companies for two decades. Today's competitive pressures require companies to take advantage of every tool at their disposal. DEFORM has proven itself to be extremely effective in a wide range of research and industrial applications.

DEFORM was initially applied to hot forging applications in the 1980's. Applications cover the entire range of forged products. Axisymmetric (round) parts can be simulated, including turbine disks, flanges, upset tubes, shafts and more are routine applications. Three-dimensional applications include gears, crankshafts, connecting rods, pistons, control arms, tracks, yokes, medical implants and more. DEFORM makes a significant improvement in development time and cost [43].

A.2 Finite Element Theory of Deform

Computer analysis of metal flow is based on the idea that material follows the path of least resistance. The bulk material is subdivided into simply shaped areas using nodes & elements and single element behavior is relatively simple and based on material stress strain curves.

The behavior of the entire workpiece is calculated based on the assembled behavior of individual elements. After a completed calculation, the shape of the workpiece is updated, and the calculation repeated and at each step, contact with other objects is checked and modified.

The fundamental assumption of metal forming simulation is that material flows into a shape which follows the path of least resistance. DEFORM works by finding the velocity distribution in a deforming workpiece which represents the lowest work rate.

A part can be divided into nodes and elements and an element represents a region of material. Figure A.1 shows elements and nodes of a part. A node represents a material point and an element corners are defined by nodes. The movement of a node defines the change in shape of the associated elements [43].

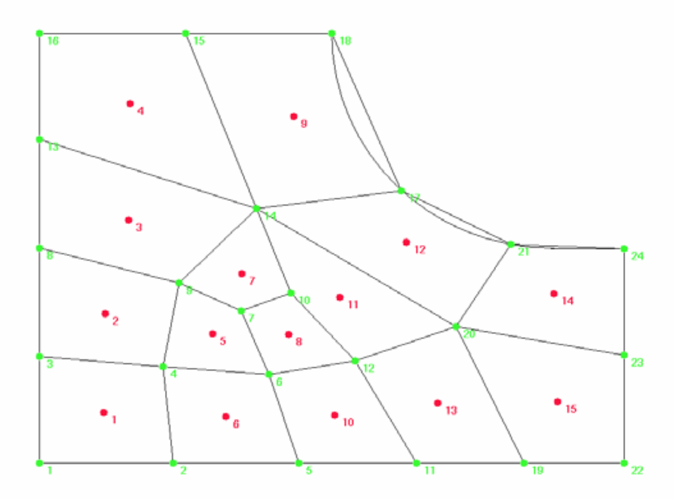

Figure A.1 Nodes and Elements [43]

The velocity of each node is assumed (initial guess), and force & energy required to deform each element is calculated.

All individual element behaviors are assembled into a “global” behavior, and the velocity of each node corresponding to minimum energy is calculated. Result of a single step calculation is a velocity at each node point. Next incremental shape is derived by moving nodes in the calculated direction for a very short time interval.

Contact is calculated at nodes and element faces always form a straight line between nodes. Figure A.2 shows the contact at nodes and element faces.

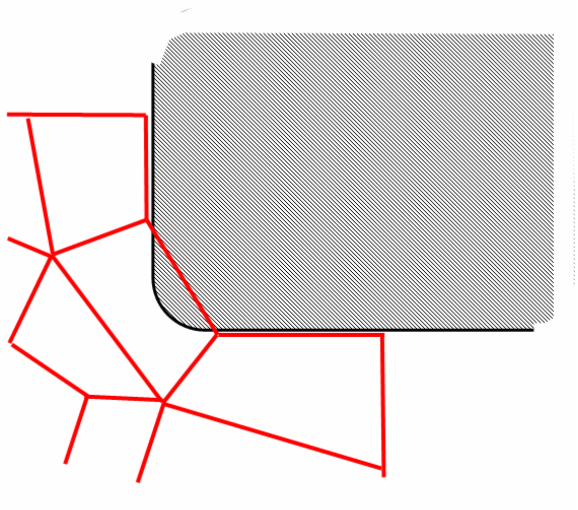

Figure A.2 Contact and Element Faces [43]

Complete shape evolution is calculated by incrementally calculating a series of small deformation steps. Temperature calculations are “coupled” with deformation calculations to track temperature in each node. Steps are saved to a file on the computer and they are available for viewing after calculations are completed.

APPENDIX B

FEATURES OF AISI 4140

B.1 Some Operational Features of AISI 4140

This is one of the chromium, molybdenum, manganese low alloy steels noted for toughness, good torsional strength and good fatigue strength.

Machinability

Machinability of this alloy is well in the annealed condition. In the heat treated and quenched condition machining is best limited to finish grinding.

Forming

As with all the low alloy steels forming may be done by conventional methods with the alloy in the annealed condition. These alloys have good ductility, but they are tougher than plain carbon steel and thus usually require more force, or pressure, for forming.

Welding

Weldable by all of the conventional methods. Note that welding with the alloy in the heat treated condition will affect the mechanical properties and a post weld heat treatment may be needed.

Heat Treatment

This alloy is hardened by heating to 850°C and quenching in oil. It is best to normalize the alloy by heating at 1200°C for a long enough time to permit thorough heating, followed by air cooling, prior to the hardening treatment.

Annealing

Annealing is available at 800°C followed by slow furnace cooling.

Aging

Not applicable to this alloy.

Tempering

Tempering temperatures range from 300°C to 900°C depending upon the hardness level desired. The lower the tempering temperature the greater the hardness of the alloy.

Composition

The composition of St 4140 is given in Table B.1.

Table B.1 Composition of AISI 4140 [44]

ELEMENT	WEIGHT%
C	0.38-0.43
Mn	0.75-1.00
P	0.035 (max)
S	0.04 (max)
Si	0.15-0.30
Cr	0.8-1.10
Mo	0.15-0.25

Figure B.1 represents the stress-strain curve of the material at different temperatures. Figure B.2 shows the forging temperature-forging pressure graph and Figure B.3 shows the upset reduction-forging pressure of AISI 4140.

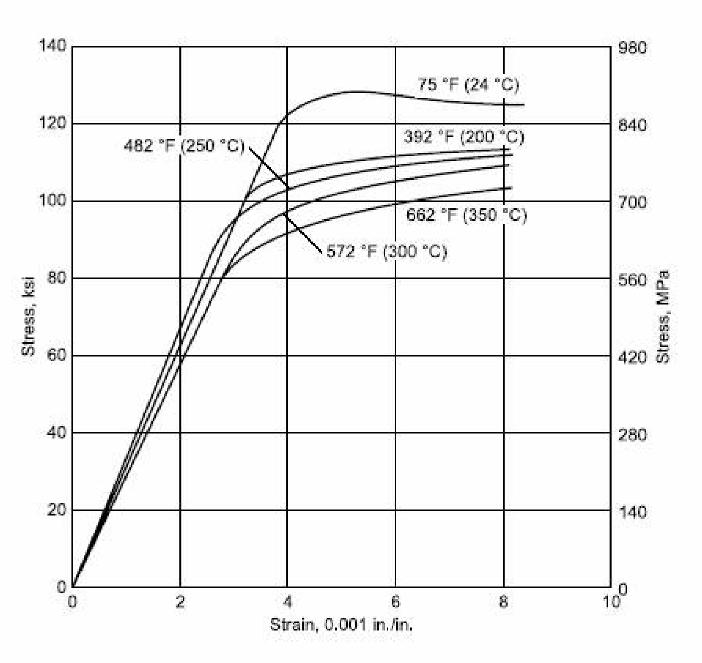

Figure B.1 Stress-Strain Curve of AISI 4140 [44]

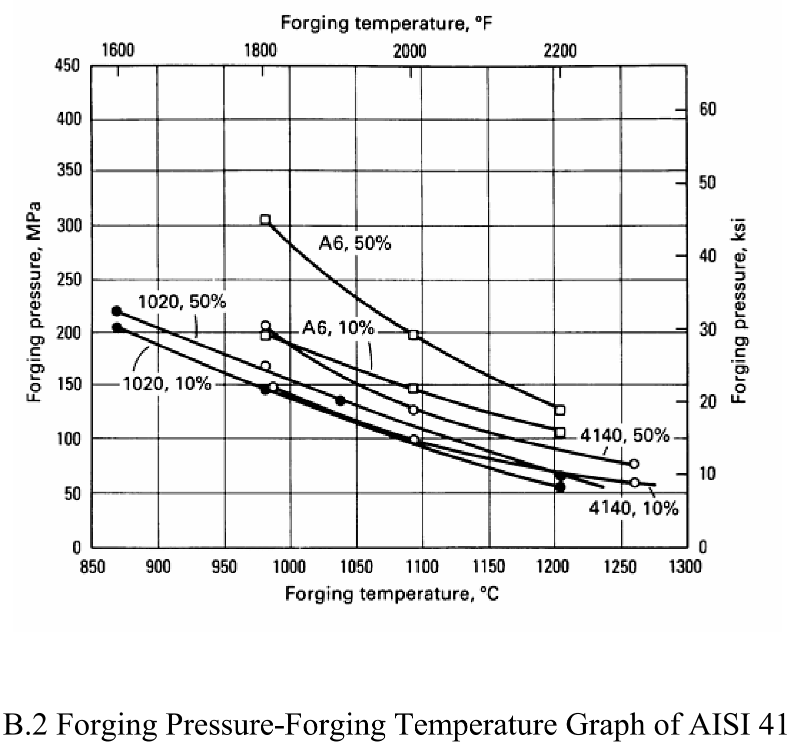

Figure B.2 Forging Pressure-Forging Temperature Graph of AISI 4140 [44]

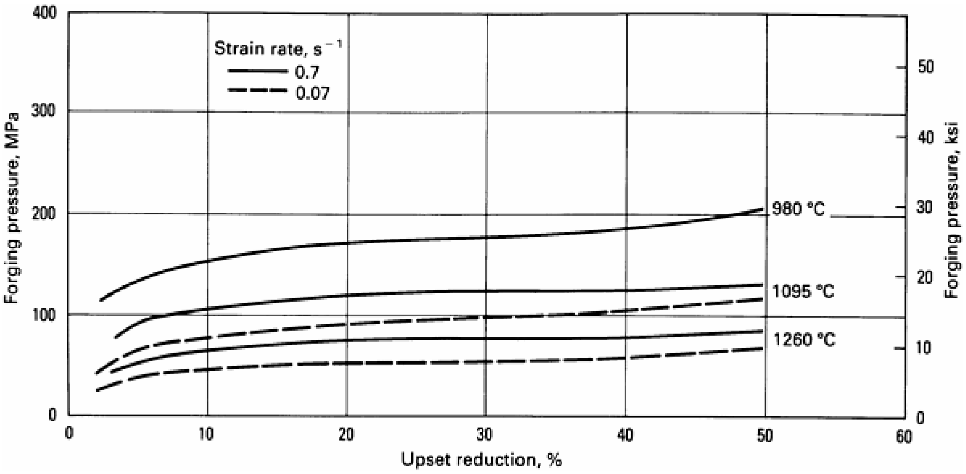

Figure B.3 Upset Reduction-Forging Pressure Graph of AISI 4140 [44]