ANALYSIS OF FORGING FOR THREE DIFFERENT ALLOY STEELS

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ABSTRACT

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Forging is a manufacturing process which is preferred among the others in that, the final product shows more enhanced properties. The properties of the final product are directly related with the material used in the forging process. Main parameters such as forging temperature, number of stages, preform design, dimensions of the billet, etc. may be affected by the forging material.

Alloys are one of the main areas of interest in the forging industry. The use of alloy steels may bring superior properties, especially in terms of strength and forgeability.

In this study, three different alloy steels, which are hot forged in industry have been examined. The flow of the material, stress distribution, die filling and the effects of the process parameters on the forging have been investigated. Three industrial forging parts; M20 and M30 eye bolts and a runner block have been studied. Finite Volume Analysis of the forging process has been performed for carbon steels;

C45 and C60 and alloy steels; a stainless steel X20Cr13, a heat-treatable alloy steel, 42CrMo4 and a bearing steel, 100Cr6. The results of the simulations have been compared with the findings of the experiments carried out in a forging company. It has been observed that numerical and experimental results are in good agreement.

Keywords: Alloy Forging, Hot Forging, Forging Parameters, Closed-Die Forging, Finite Volume Analysis.

ÖZ

ÜÇ FARKLI ALAŞIMLI ÇELİK İÇİN DÖVME ANALİZİ

CİVELEKOĞLU, Barış

Yüksek Lisans, Makina Mühendisliği Bölümü

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Dövme, ürünün daha üstün özellikler göstermesi bakımından, diğerlerine göre tercih edilen bir üretim metodudur. Ürünün özellikleri, dövme işleminde kullanılan malzemeyle doğrudan ilişkilidir. Dövme sıcaklığı, işlem sayısı, ön form tasarımı, başlangıç malzemesinin boyutları vb. gibi ana değişkenler, kullanılacak malzemeden etkilenebilir.

Alaşımlar, son yıllarda dövme endüstrisinin en çok uğraştığı alanlardan biri olmuştur. Alaşımlı çelik kullanımı, özellikle mukavemet ve dövülebilirlik bakımından daha üstün özellikler getirebilir.

Bu çalışmada, endüstride sıcak olarak dövülen üç farklı alaşımlı çelik incelenmiştir. Malzemenin akışı, gerilme dağılımı, kalıpların malzeme ile dolması ve işlem parametrelerinin dövme üzerine etkileri araştırılmıştır. Üç endüstriyel dövme parçası; M20 ve M30 gözlü civatalar ve bir bilyalı yatak üzerinde çalışılmıştır. Karbon çelikleri; C45 ve C60, paslanmaz bir alaşımlı çelik; X20Cr13, bir ıslah çeliği;

42CrMo4 ve bir rulman çeliği; 100Cr6 için dövme işleminin Sonlu Hacim Analizi yapılmıştır. Sayısal analiz sonuçları, bir dövme firmasında yapılan deneylerin bulgularıyla karşılaştırılmıştır. Sayısal ve deneysel sonuçların uyum içinde olduğu gözlemlenmiştir.

Anahtar Kelimeler: Alaşımlı Çelik, Sıcak Dövme, Dövme Parametreleri, Kapalı Kalıpta Dövme, Sonlu Hacim Analizi.

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INTRODUCTION

1.1 Forging

Forging is a process in which a piece of metal is shaped to the desired form by plastic deformation of a simple starting form such as bar, billet, or ingot. In metal forming industry, forging has a special place in that, it reduces the required machining operations, gives the opportunity to produce complex parts with the desired directional strength, refining the grain structure and developing the optimum grain flow, which imparts desirable directional properties such as tensile strength, ductility, impact toughness, fracture toughness and fatigue strength. The final product has structural integrity meaning that it has no internal voids and porosity, having uniform mechanical properties and predictable response to heat treatment [1].

Forging has advantages over machining and casting in terms of the material properties resulting from the orientation of grains in the finished product. In forging, directional alignment is oriented in the maximum strength direction which also yields ductility and impact and fatigue resistance. In machining, end grains are exposed, leaving the part more liable to fatigue and more sensitive to stress corrosion cracking. In casting, grain flow and directional strength are not observed as a characteristic of the operation.

Table 1.1 Common Applications for Forgings [1]

• Aerospace, Aircraft Engines Airframe and auxiliary equipment • Guided missiles and space vehicles • Automotive • Construction, mining and materials handling equipment • Ball and roller bearings • Electric power generation and transmission • Industrial and commercial machinery and equipment • Hand Tools • Industrial tools • Internal combustion engines	• Mechanical power transmission equipment • Oil field machinery • Plumbing fixtures, valves and fittings • Pumps and compressors • Railroad equipment and spikes • Rolling, drawing and extruding equipment and tools for nonferrous metals • Ship and boat building and repairs • Steam Engines and turbines • Steel works, rolling and finishing mills • Metalworking and special industry machinery

The wide range of alloys and sizes, combined with excellent mechanical and physical properties has made forgings the design choice for nearly all product areas. The most common application areas are shown in Table 1.1.

1.1.1 Types of Forging Operations

Forging can be carried out at room temperature, called cold, or at elevated temperatures, called warm or hot forging, depending on the temperature. The temperature ranges are given in Table 1.2 in terms of the homologous temperature, which is the ratio of the testing temperature to the melting point temperature, T/T_m, where T_m is the melting point of the workpiece material and both are expressed in degrees Kelvin. The homologous recrystallization temperature for metals is about 0.5 [2].

Table 1.2 Homologous Temperature Ranges for Various Processes

PROCESS	**T / Tm**
Cold Working	< 0.3
Warm Working	0.3 to 0.5
Hot Working	> 0.5

There are mainly two types of forging operations called open and closed die forging according to the type of the die set. Forging may be performed by placing a workpiece between two flat or curved plates, which is called open-die forging. Full control of the geometry of the forging is not satisfied and in general, large forgings are produced with this kind of operation. The initial shape of a forging in a forging sequence is also given between open dies so as to prepare the part for a preforming or a final step.

In impression or closed-die forging, while the workpiece is being upset between the closing dies, it acquires the shape of the die cavities. In most hot forging operations, the temperature of the workpiece materials is higher than that of the dies. The main objective of the closed die forging is to ensure adequate flow of the metal in the dies in order to obtain the desired finished part geometry without any defects and with prescribed properties.

There are several types of forging machines that may be used for the open die, impression die and cold forging processes. Some of the forging presses are shown in Figure 1.1. They vary in factors such as the rate at which energy is applied to the workpiece, and the capability to control the energy. Each type has distinct advantages and disadvantages, depending on the number of forgings to be produced, dimensional precision, and the alloy being forged.

Hydraulic presses have a constant low speed and are load limited. Large amounts of energy can be transmitted to the workpiece by a constant load available throughout the stroke.

Mechanical presses are stroke limited and they are basically crank or eccentric types, with the speeds varying from a maximum at the center of the stroke to zero at the bottom. The force available depends on the stroke position and becomes extremely large at the bottom dead center.

Hammers derive their energy from the potential energy of the ram, which is then converted to kinetic energy; thus they are energy limited. The speed are high, therefore the low forming times minimize cooling of the hot forging, allowing the forging of complex shapes, with thin and deep recesses.

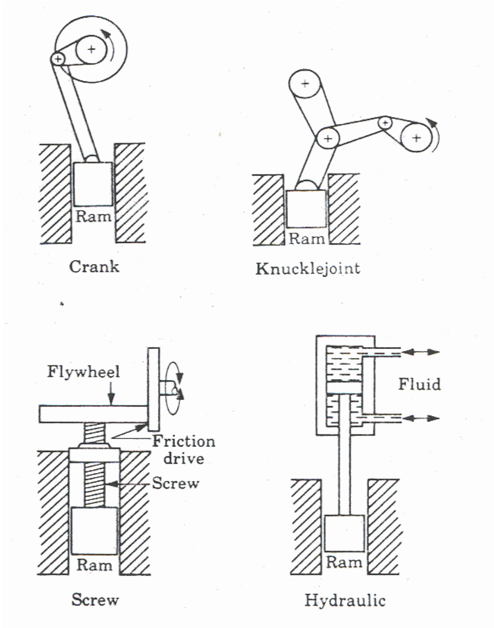


Figure 1.1 Schematic Illustration of Various Types of Presses Used in Forging [2]

Screw presses derive their energy from a flywheel. The forging load is transmitted through a vertical screw. These presses are energy limited and can be used for many forging operations.

The choice of the forging process, for any product, depends on many factors, in terms of material and weight of the workpiece, the size, quality, and quantity of the forging required.

1.1.2 Forging Design Parameters

In a general bulk forming process, the key areas of interest should include [3],

- workpiece material : shape and size, chemical composition and microstructure, flow properties under processing conditions, thermal and physical properties
- dies or tools : geometry, surface conditions, material and hardness, surface coating, temperature, stiffness and accuracy
- interface conditions : surface finish, lubrication, friction, heat transfer.
- work zone : mechanics of plastic deformation, material flow, stresses, velocities, temperatures.
- equipment used : speed, production rate, force and energy capabilities, rigidity and accuracy.

The control of the above parameters helps the manufacturer to predict the characteristics of the final product.

Forging process has several design parameters which are specific to itself in terms of; the selection of presses, forging and die materials, temperature, forging sequence, preforms that help the final product to have the desired material properties and geometrical shape, the parting plane, dimensions of dies such as gutter and flash clearances, and the location of impressions. As it is in nearly all bulk forming operations, cost is also a very important factor that influences the selection of the above parameters. One has to predict several factors to optimize a forging operation.

One very practical method by which a scientific approach to improving forging technology can be applied is to maintain accurate and detailed records of forging variables. This kind of information then can be used to select forging practices for alloys and parts to be forged in the future.

1.1.3 Forging Defects

Defects in forgings can be caused by excess material, thick webs, small radii, grain flow pattern and the anisotropy of the forged part.

Excess material in the web of a forging may buckle during forging and develop laps. If the web is thick, the excess material flows past the already forged portions and develops internal cracks, indicating the importance of properly distributing material and controlling the flow in the die cavity. Also, as a result of oversized stock, the material at the center of the part flows past the filled regions as the deformation continues as seen in Figure 1.2 [2].

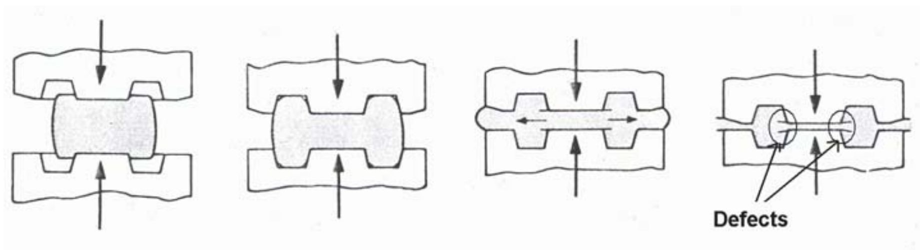


Figure 1.2 Internal Defects Because of an Oversized Billet in Forging

The various radii in the die cavity can significantly affect formation of defects. In Figure 1.3, the material follows a large corner radius better than a small radius. With small radii, the material can fold over itself and produce a lap, called cold shut.

Although it may not be considered a flaw, another important aspect of quality in a forging is the grain flow pattern. At times the grain flow lines reach a surface perpendicularly, exposing the grain boundaries directly to the environment. They are known as end grains.

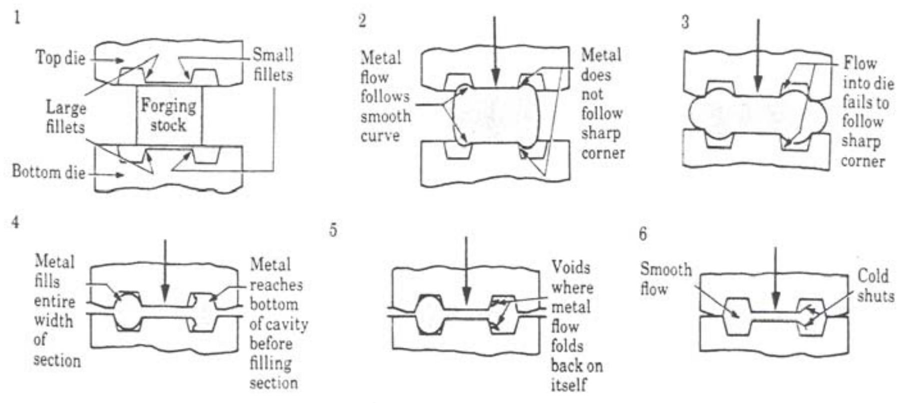
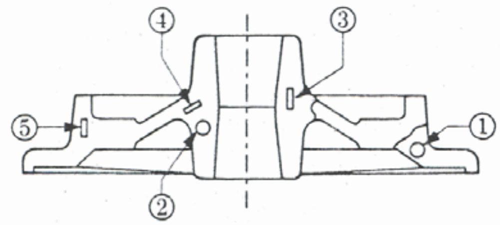


Figure 1.3 Effect of Fillet Radius on Defect Formation in Forging. On The Right Side of Drawings Small Fillets are Shown Causing Defects [2]

In service, they can be attacked by the environment and develop a rough surface and act as stress raisers. For critical components, end grains in forgings can be avoided by proper selection of the original workpiece orientation in the die cavity and by control of material flow.

Because the metal flows in various directions in a forging, and because of temperature variations, the properties of a forging are generally anisotropic. As Figure 1.4 shows, strength and ductility vary significantly in test specimens taken from different location and orientations in a forged part.

Residual stresses should also be considered in the design stage. The sustained tensile stress at the surface of a forging that contributes to stress corrosion cracking is the total of applied and residual stresses. When the residual stress constitutes a significant percentage of the total stress, it should be reduced or eliminated. Common sources of residual stresses include quenching, machining, and poor fit in the assembly. Each can be suitably modified to reduce or eliminate residual stresses.



Specimen location	Yield strength, psi	Ultimate tensile strength, psi	Elongation, %
1.	26,500	41,200	20.0
2.	23,000	39,400	17.7
3.	13,800	38,000	18.6
4.	25,400	40,400	16.2
5.	17,100	37,500	14.0

Figure 1.4 Mechanical Properties of Five Tensile Test Specimen Taken at Various Locations and Directions in an AZ61 Magnesium Alloy Forging [2]

Hydrogen-stress cracking is another defect, which occurs as a result of hydrogen in the metal in combination with tensile stresses, or stresses that have tensile components. Hydrogen-stress cracking cannot occur if hydrogen is prevented from entering the steel, or if hydrogen that has entered during processing or service is removed before permanent damage has occurred. During forging, steels develop a surface scale and a decarburized surface layer, both of which are removed by grit blasting and machining. Unless the steel is acid pickled, there is no possibility of hydrogen pickup. Many of the critical parts made from steel forgings are protected by a coating of cadmium.

1.1.4 Forging Design Optimization

In order to optimize forging parameters, process should be simulated to assure filling of dies and to avoid flow induced defects such as laps and shuts, process temperature should be predicted to control mechanical properties of the forging part together with friction conditions and die life, and also grain flow and microstructure should be predicted. For the prediction of these parameters several methods are being used in the industry, one of which is to establish a preliminary die design and select process parameters by using experience based knowledge.

In hot-forging dies, thermomechanical loading is large enough to produce stresses beyond the yielding point, especially at critical regions of stress concentration, such as geometrical irregularities of the surface. Another reason for a non-homogeneous distribution of stress and its rise beyond the yielding point is a non-optimal design of preform for the final forge. This causes the accumulation of plastic strain and, therefore, accumulation of damage in the critical areas of the die. The investigation of hot ductility for die steel makes possible the application of damage mechanics to the die fracture, and calculation of the level of damage introduced into the die after every forging cycle. By changing the preform design, the level of damage can be minimized, and an optimal preform shape that gives the longest die life can be found.

The most important design consideration in a forging sequence is therefore the preform design. With the correct selection of number and shape of the preforms, die life should be improved, material should be flown through the intended direction, required load should be reduced and the process time should be decreased.

Lapovok et al. described the steps of preform optimization including the following sequence [4];

- Choose the main geometrical parameters defining the form of the preform, and plan the mathematical experiment by prescribing the variation of these parameters.
- Determine the form of preforms according to every set of selected geometrical parameters in the plan of the mathematical experiment.
- Choose the criteria for preform optimization (e.g. die life).
- Solve the plasticity boundary problem for every set of selected geometrical parameters in the plan of the mathematical experiment.
- Define the discriminating function which depends on the main geometrical parameters (e.g. the die life as a function of the geometrical parameters of the preform), and investigate its extremum to determine the optimal parameters

1.2 Forging Materials

Virtually all metals have alloys that are forgeable, giving the designer the full spectrum of mechanical and physical properties of ferrous and non-ferrous alloys. The most common forging alloys include:

- Carbon, microalloy and alloy steel forgings account for the greatest volume of forgings for a very wide range of applications.
- Stainless steels are widely used where resistance to heat and corrosion are required

- Aluminum forgings are used in applications where temperatures do not exceed 150°C, and where weight of the component is an issue.
- Copper, brass and bronze forgings offer excellent corrosion resistance with high thermal and electrical conductivity.
- Iron, nickel and cobalt high temperature alloy forgings are preeminent for applications of cyclical and sustained loads at high temperatures.
- Titanium forgings are used where high strength, low weight and excellent corrosion resistance, combined with moderate heat resistance, are required.
- Magnesium forgings offer the lowest density of any commercial structural metal, at operating temperatures similar to aluminum.

In this study, several alloy steels will be investigated. Special emphasis will be given on types of steels on the following pages.

1.2.1 Steels

Steel may be defined as iron in a modified form, artificially produced, containing a certain amount of carbon and other constituents and possessing a hardness, strength, elasticity, etc., which vary with chemical composition and thermal treatment.

Steels can be classified by a variety of different systems such as:

- The composition, such as carbon, low-alloy or stainless steel,
- The manufacturing methods, such as open hearth, basic oxygen process, or electric furnace methods,
- The finishing method, such as hot rolling or cold rolling,

- The product form, such as bar plate, sheet, strip, tubing or structural shape,
- The deoxidation practice, such as killed, semi-killed, capped or rimmed steel,
- The microstructure, such as ferritic, pearlitic and martensitic,
- The required strength level, as specified in ASTM standards,
- The heat treatment, such as annealing, quenching and tempering, and thermomechanical processing,
- Quality descriptors, such as forging or commercial quality.

There are hundreds of steels that range in carbon content from approximately 0.06% to 1.5%. Many contain metallic alloying elements, such as manganese, chromium and molybdenum, ranging from trace amounts to approximately 9%. Virtually all can be readily forged. There are two groups within the general classification of steels: carbon steels, and alloy steels.

1.2.1.1 Carbon Steels

As defined in ASTM standards, carbon steel is a steel that conforms to a specification that prescribes a maximum limit, in mass percent, of not more than: 2.00 for carbon and 1.65 for manganese, but does not prescribe a minimum limit for aluminum, boron, chromium, cobalt, columbium, molybdenum, nickel, tungsten, vanadium, or zirconium. Popular carbon grades include DIN C15, C45, and C60. Carbon grades are used extensively in applications which require machining, welding, forging or induction hardening.

1.2.1.2 Alloy Steels

In general, alloy steel is used when more strength, ductility or toughness is required than can be obtained in a carbon grade. In addition, alloy grades should be used where properties such as corrosion resistance, heat resistance and low-temperature impact values are required. Microalloyed steels, which are carbon products with very low ranges of elements (such as vanadium, niobium and/or titanium), and stainless steels may be classified as alloy steels. Detailed information about alloy steels will be given in Chapter 2.

1.2.2 Material Selection

The selection of material for a forging part requires a balance between factors such as strength versus toughness, stress-corrosion resistance versus weight, manufacturing cost versus useful load-carrying capacity, maintenance cost versus production cost, heat treatment versus using special alloys. An efficient design aims to produce a part from the minimum amount of material with the lowest loads on dies. The material is first examined for toughness and strength, then qualified for stability to temperature and environment. Selected materials are then analyzed for producibility and economy at the last step. To obtain data for material properties, failure analyses offer useful data. Failure of a component can occur during operation within the design stress range. Lack of proper orientation of a critical design stress with the preferred grain flow may cause failure.

Failure may also occur because of deterioration of material properties with time and service conditions. Failure analyses may help to understand the causes of unexpected failure, such as grain growth, inclusions of nonmetallic impurities, grain flow folding from improper forging practice, lack of a wrought metallurgical structure and from the unintentional production of stress raisers by machining to a very sharp fillet or by poor fit in assembly [5].

The strength to density ratio is one of the most important parameters in material selection. It resembles the strength per unit weight of parts, which are used mostly in aerospace applications where low weight and high strength is a major requirement. In Figure 1.5, strength-density ratios of several aerospace-forging alloys tested at room temperature are shown.

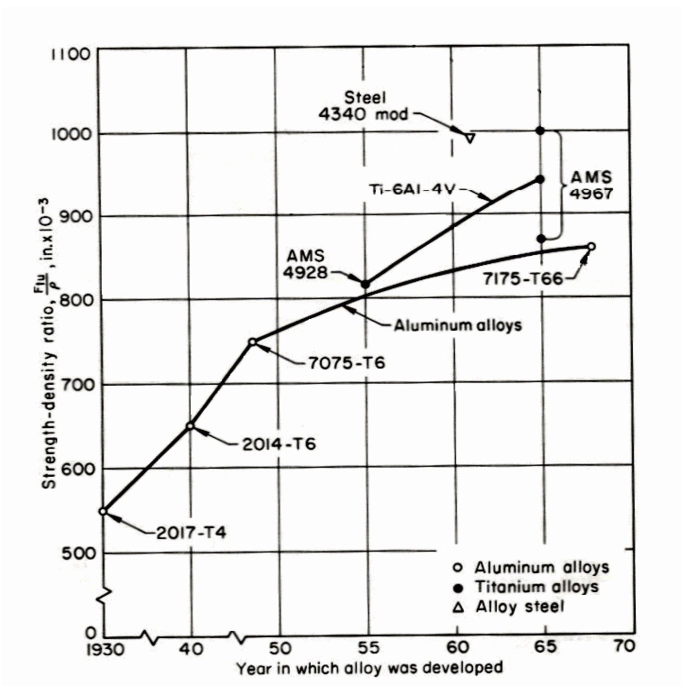


Figure 1.5 Room Temperature Strength-Density Ratios of Aerospace Materials [5]

In order to select the most appropriate material, one has to have information on the material and the process specifications. Material specifications define material properties or requirements. However, they often include one or more sections on processing such as heat treatment, forging operations, and inspection. Processing specifications may include sections on materials. As a result, material and process specifications are closely related. The tests contained in the material specifications are intended to provide correlation with the behavior material in real life use. Room temperature laboratory fatigue and fracture-toughness testing does not reflect the effects of operating conditions of environment and temperature on the reliability and life expectancy of forged components. Most test data have been of limited usefulness because of a lack of direct correlation with service conditions.

1.3 Simulation of Forging

In the design of forging operations, information is necessary such as material flow in the dies, level of die fill, defects, strain, stress, temperature distribution in the work pieces and the dies, and working force. In the subsequent heat treatment operations, information on combination of microstructure, residual stresses and dimensional accuracy in the final product are also very important. Such information may be obtained by numerical simulation [6].

On the other hand, the information obtained from the simulation of forging is also very important for the subsequent heat treatment process because the residual stress from the forging process does influence the results of heat treatment.

Many approaches have been developed in the field of closed-die forging to integrate the use of numerical simulation techniques and CAD programs based on empirical rules in the form of expert systems or intelligent knowledge-based systems. One of these approaches was adopted at the University of Birmingham in developing an expert system for upset forging die design which combined the results of many years research into the design based on empirical guidelines and finite element metal forming simulation [7].

Various CAD/CAE packages are being used in the industry and for the academic studies so as to obtain the necessary information stated above. Some of these packages are briefly introduced below:

FORGE2 and FORGE3 are software packages developed through a joint research program, involving major companies such as Snecma, Peugeot, Pechiney, Safe Ascometal and the Ecole des Mines de Paris, a leading French university. FORGE2 is dedicated to the simulation of hot, warm and cold forging of axisymmetric parts and parts with high length-to-width ratios such as cylinders, impacts, extrusions, axles, shafts, gear blanks, rings, fasteners and wire drawing, aircraft disks, blades, wheels, bearing cages, and railway wheels. FORGE3 examples of fully three-dimensional parts include steering knuckles, crankshafts, twin connection rods, lower arms, constant velocity joints, bevel gears, aircraft landing gears, fan blades, engine mountings, and wing components.

QFORM3D is used for the simulation of hot, warm and cold forming processes. The software predicts material flow defects, identifies the temperature distribution, assesses the load and consumption of energy for the deformation. It features a direct interface to Pro/Engineer (PTC), Solid Works (Solid Works Corp.), TFlex CAD (Top Systems), Solid Edge (Unigraphics) and Mechanical Desktop (AutoDesk), speeding up the operation considerably. The software generates a finite element mesh on the die and workpiece surface and inside automatically, restructuring it in the solution process, as required.

DEFORM™-3D is a process simulation system designed to analyze the three-dimensional flow of complex metal forming processes. Based on the finite element method, DEFORM™ has proven to be accurate and robust in industrial applications. The simulation engine is capable of predicting large deformation material flow and thermal behavior with precision. The software simulates material flow, die fill, forming load, tool stress and defect formation in cold, warm and hot forming processes.

MSC. Patran is an open-architecture, general software, 3-D mechanical computer aided engineering software package with interactive graphics providing a complete CAE environment. It enables direct access to geometry from many CAD systems for creating finite element models. MSC.Patran finite element system permits the user to directly access model geometry and to quickly develop finite element meshes. It can perform thermal, fatigue, and composite laminate analyses.

MSC.Superform is a simulation tool for the simulation of bulk forging processes and manufacturing tools. MSC.SuperForm features integrated 2-D and 3-D thermally coupled analysis, damage analysis, simulation of forming tools, integrated material database, and press kinematics. MSC.SuperForm's graphical user interface is designed specifically to meet the demands of the bulk forging industry. The simulation software uses a fully automated remeshing technology based on material deformation and die geometry. Using the improved meshing technology, MSC.SuperForm can simulate various machining operations.

MSC.SuperForge is a new software application for the computer simulation of industrial forging processes. It combines a Windows graphical user interface with a robust solution procedure to provide unprecedented accuracy and speed in forging simulations. It is the first "meshless" forging simulation tool available on the market, and is utilized by leading forging companies and suppliers around the world to simulate the forging of a wide variety of practical industrial parts. MSC.SuperForge provides forging process engineers with detailed insight into the forging process, including material flow, die fill, flash regions, laps/folds and die loads. Unlike a traditional finite element mesh, which distorts while attempting to follow the deformation of material, the finite volume mesh in MSC.SuperForge defines a fixed frame of reference through which the workpiece material simply flows.

1.4 Previous Studies

In a study, a bevel gear forging preform design is altered to improve the product quality and to secure the effective material flow. In this study, it has been shown how an improvement can be made through an improved design using finite element simulation [8].

Caporalli, Gileno and Button studied on an expert system for hot forging design. A software interfacing MS Visual Basic v.5.0 and SolidEdge v.3.0 was used to design flashless hot forged parts. The dimensions of the billet were calculated from the volume of the final forging. The best shape and dimensions of the preform were defined from the results of simulations with FEM program ANSYS [9].

In his paper, Lapovok described an approach to improve hot-forging die life by minimization of damage accumulation and optimization of preform design. He observed an improvement in the die life of a gear-annulus forging, using simulations as a tool and distribution of equivalent plastic strain as an objective function. He used a damage accumulation formula and optimized the geometrical parameters of the forged part [4].

Matlock, Krauss and Speer considered the processing approaches for the production of direct-cooled forging steels with emphasizing features that control strength and toughness. They stated that medium-carbon, direct-cooled microalloyed forging steels replace the quenched-and-tempered steels to realize cost savings associated with controlled cooling after forging instead of conventional quenching and tempering heat treatment of low alloy steels [10].

The microstructure of a medium carbon microalloyed steel and the influence of thermomechanical treatment conditions on the final austenite grain size have been studied. It was found that the strain rate can be as important as the strain to influence the final microstructure and therefore the mechanical properties of the final product [11].

A system for quantifying and comparing the sensitivity of a thermomechanical finite element analysis of forging to variations in different input parameters is reported by Snape et al. Since the number of parameters makes it impractical to investigate all of them, they have restricted the investigations to the parameters that define the flow stress of the forged steel, heat transfer and friction at the die-workpiece interface. They investigated the response of five results which are maximum generalized strain, maximum load, forging work, final die fill and the complexity factor, to input variations [12].

Zhao et al. developed a finite element based sensitivity analysis method for preform die shape design in forging, by controlling the deformation uniformity. In the optimization problem, it is considered to minimize the effective strain variation within the final forging through optimizing the preform die shape, so as to obtain a more uniform deformation within the final forging. The sensitivity of the objective function is calculated by the accumulated sensitivities of the nodal coordinates and the elemental effective strain to design variables throughout an entire simulation [13].

A sensitivity analysis based preform die shape design for flashless forging operations was proposed by Guoqun Zhao, Ed Wright and Ramana V. Grandhi [14]. They represented the preform die shapes by cubic B-spline curves. They studied on an optimization problem in which they tried to minimize the zone where the realized and desired final forging shapes do not coincide. They concentrated on two-dimensional problems and left the determination of the initial size of the stock as a future work.

Taylan Altan has proposed a computer aided sequence design system consisting of a computer program, a CAD program and a commercial Finite Element program. The aim of the study was not to develop a computer system to automate a forming sequence design, but to develop computer aided tools to assist the designers. They built a sequence library using the reference works and the industrial practices. Finite element simulations were used to optimize the process variables and die design to reduce the process development effort and cost [15].

Altan et. al. [16], summarized the flow stress data from the literature and showed that forging stresses vary considerably among materials and with temperature and strain rate.

1.5 Scope of the Thesis

Forgeability and strength are important material properties in forging. Poor forgeability may cause rupture before the die has been filled. High flow stress may result in underfilling of the die. Each material has different flow and forgeability characteristics. However, sufficient number of comparative studies have not been encountered in the literature.

This study aims investigating forging of specific alloys. The forging sequence will be investigated and the effects of material selection on the processes will be observed. Pro/ENGINEER is used for 3D modeling of the parts and simulations are performed by using MSC.Superforge. Case studies will be performed by using the parts made of different alloy and carbon steels. The results of the forging experiments, which have been carried out in the forging company, will be compared with the computer simulations.

In Chapter 2, characteristics of alloy steels are provided. In Chapter 3, the design considerations in forging process are given. In Chapter 4 and 5, case studies realized for industrial forgings are presented. Finally, conclusions and suggestions for future works are discussed in Chapter 6.

CHAPTER 2

ALLOY STEELS

2.1 Introduction

Alloy steel is defined in ASTM standards as a material that conforms to a specification that requires one or more of the following elements, by mass percent, to have a minimum content equal to or greater than: 0.30 for aluminum; 0.0008 for boron; 0.30 for chromium; 0.30 for cobalt; 0.06 for columbium (niobium); 0.40 for copper; 0.40 for lead; 1.65 for manganese; 0.08 for molybdenum; 0.30 for nickel; 0.60 for silicon; 0.05 for titanium; 0.30 for tungsten (wolfram); 0.10 for vanadium; 0.05 for zirconium; or 0.10 for any other alloying element, except sulphur, phosphorus, carbon, and nitrogen.

Engineers have demanded steels with higher and higher tensile strength, together with adequate ductility. This has been particularly so where lightness is desirable, as in the automobile and aircraft industries. An increase in carbon content met this demand in a limited way, but even in the heat-treated condition the maximum strength is about 700 MPa above which value a rapid fall in ductility and impact strength occurs and mass effects limit the permissible section.

Heat-treated alloy steels provide high strength, high yield point, combined with appreciable ductility even in large sections. The use of plain carbon steels frequently necessitates water quenching accompanied by the danger of distortion and cracking, and even so only thin sections can be hardened throughout. For resisting corrosion and oxidation at elevated temperatures, alloy steels are essential.

With the exception of the high-alloy maraging steels, all the commercially significant alloy steels are strengthened by conventional quench hardening. Alloying elements are added to prevent or retard the formation of nonmartensitic microconstitutents during quenching. The maximum attainable strength level is determined by the carbon content. In order to improve the ductility and toughness of hardened steel, it is reheated (tempered) for a relatively short time at a moderate temperature.

Steels containing alloying elements in high amounts can be transformation hardened by air-cooling instead of liquid quenching.

The standard alloy steel grades are found in the AISI and SAE 1300 through 9800 series. They are listed in many AISI publications and in the ASM and SAE Handbooks [1]. Modifications of these types are also used in special applications. As a rule, these standard grades are specified when more strength, ductility and impact toughness are required than can be attained in carbon steels. They are also specified when specific properties such as wear resistance, corrosion resistance, heat resistance and special low temperature impact properties are required. Some alloy steels are formulated for special treatments such as carburizing or carbo-nitriding.

2.2 Effect of Alloying Elements

The principal alloying elements added to steel in widely varying amounts either singly or in complex mixtures are manganese, nickel, chromium, molybdenum, vanadium, tungsten, silicon, copper, cobalt and boron.

The effect of the alloying element in the steel may be one or more of the following:

- The alloying element may go into solid solution in the iron, enhancing the strength. Effect of alloying element additions on hardness after nitriding with a base composition of; 0,25% C, 0,30% Si, 0,70% Mn is shown in Figure 2.1.
- Hard carbides associated with Fe, C may be formed.
- It may form intermediate compounds with iron, e.g. FeCr (sigma phase), Fe, W.
- It may influence the critical temperature range.
- It may alter the carbon content of the eutectoid.
- It may alter the “critical cooling velocity”.
- Combinations of elements can be chosen so that the volume change and the risk of quench cracking is reduced.
- It may have a chemical effect on the impurities.
- It may render the alloy sluggish to thermal changes, increasing the stability of the hardened condition and so producing tool steels which are capable of being used up to 550°C without softening and in certain cases may exhibit an increase in hardness.
- Certain elements such as chromium, Aluminum, silicon and copper tend to produce adherent oxide films on the surface of the steel, which increase its resistance to corrosion and oxidation at elevated temperatures.

- Creep strength may be increased by the presence of a dispersion of fine carbides, e.g. molybdenum.

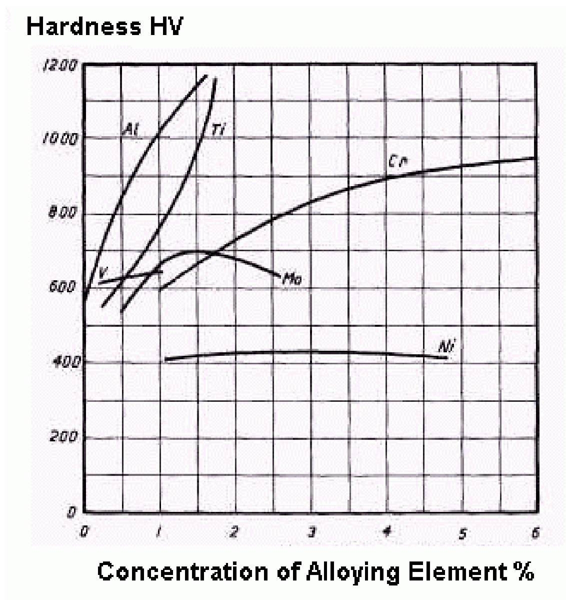


Figure 2.1 Hardening Effects of Alloying Elements in Solid Solution After Nitriding [17]

The effects of the alloying elements may be summarized as follows:

Manganese: All commercial steels contain 0,3-0,8% manganese, to reduce oxides and to counteract the harmful influence of iron sulfide. There is a tendency to increase the manganese content and reduce the carbon content in order to get a steel with an equal tensile strength but improved ductility. If the manganese is increased above 1,8% the steel tends to become air hardened, with resultant impairing of the ductility. Up to this quantity, manganese has a beneficial effect on the mechanical properties of oil hardened and tempered 0,4% carbon steel. The manganese content is also increased in certain alloy steels, with a reduction or elimination of expensive nickel, in order to reduce costs. Manganese increases hardenability by lowering transformation points and causing transformations to be sluggish.

Nickel: The addition of nickel acts similarly to increasing the rate of cooling of a carbon steel. Steels with 0,5% nickel are similar to carbon steel, but are stronger, on account of the finer pearlite formed and the presence of nickel in solution in the ferrite. When 10% nickel is exceeded the steels have a high tensile strength, great hardness, corrosion resistance, but are brittle.

Chromium: Chromium steels are easier to machine than nickel steels of similar tensile strength. The steels of higher chromium contents are susceptible to temper brittleness if slowly cooled from the tempering temperature through the range 550/450°C. These steels are also liable to form surface markings, generally referred to as "chrome lines".

Molybdenum: Additions of 0,5% molybdenum have been made to plain carbon steels to give increased strength at boiler temperatures of 400°C, but the element is mainly used in combination with other alloying elements. Molybdenum is also a constituent in some high-speed steels, magnet alloys, heat-resisting and corrosion-resisting steels. It may inhibit the grain growth.

Vanadium: It has a beneficial effect on the mechanical properties of heat-treated steels, especially in the presence of other elements. Chromium-vanadium (0,15%) steels are used for automobile axles, coil springs, torsion bars and creep resistance. Vanadium increases strength while retaining ductility, and promotes fine grain structure.

Tungsten: Tungsten raises the critical points in steel and the carbides dissolve slowly over a range of temperature. When completely dissolved, the tungsten renders transformation sluggish, especially to tempering, and use is made of this in most hot-working tool ("high speed") and die steels. Tungsten refines the grain size and produces less tendency to decarburization during working. Tungsten is also used in magnet, corrosion- and heat-resisting steels.

Silicon: Only three types of silicon steel are in common use-one in conjunction with manganese for springs; the second for electrical purposes, used in sheet form for the construction of transformer cores, and poles of dynamos and motors, that demand high magnetic permeability and electrical resistance; and the third is used for automobile valves. It contributes oxidation resistance in heat-resisting steels and is a general purpose deoxidizer.

Copper: It lowers the critical points, but insufficiently to produce martensite by air cooling. The resistance to atmospheric corrosion is improved and copper steels can be temper hardened.

Cobalt: It decreases hardenability but sustains hardness during tempering. It is used in gas turbine steel, magnets and as a bond in hard metal.

Boron: Boron is added to previously fully killed, fine-grain steel to increase the hardenability of the steel. The yield ratio and impact are definitely improved, provided advantage is taken of the increased hardenability obtained and the steel is fully hardened before tempering. In conjunction with molybdenum boron forms a useful group of high tensile bainitic steels. Boron is used in some hard facing alloys and for nuclear control rods.

Classification of alloying metals according to their effect in the steel is difficult, because the influence varies so widely with each addition depending on the quantity used and other elements present. A useful grouping, however, is based upon the effect of the element on the stability of the carbides, and the stability of the austenite.

2.3 Classification of Alloy Steels

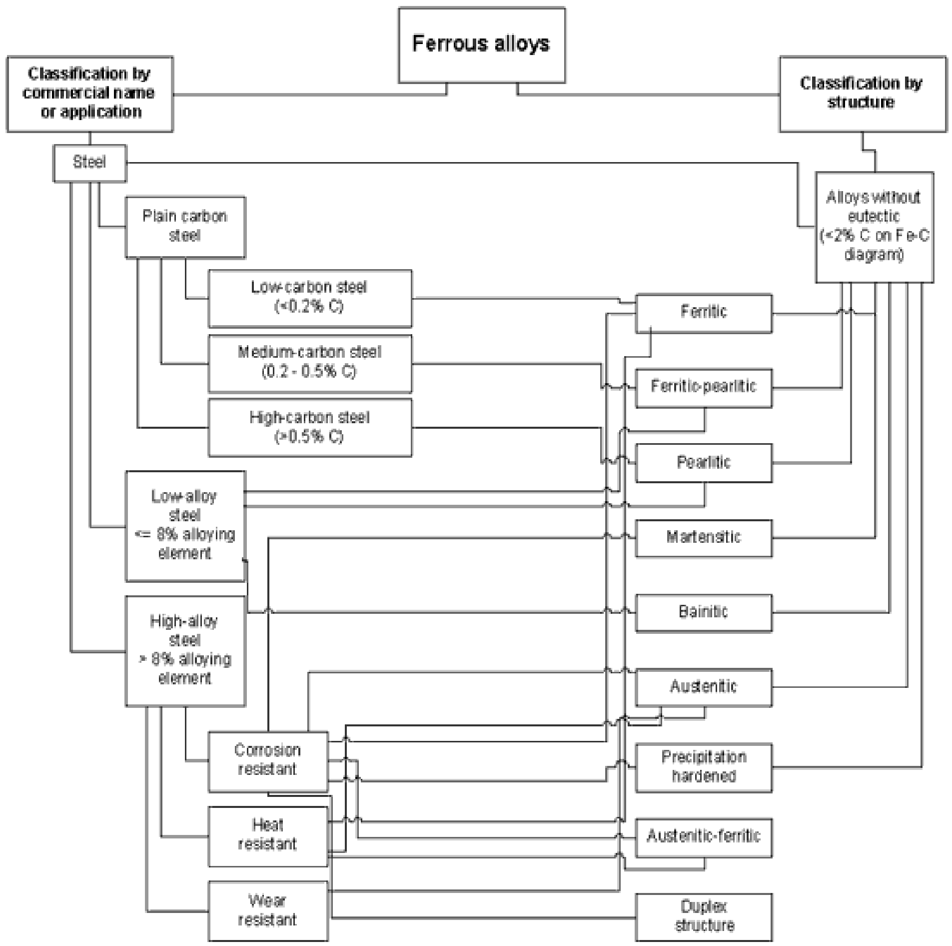


Figure 2.2 Classification of Ferrous Alloys [17]

Steels can be categorized by composition, strength, formability, hardenability, weldability, corrosion or oxidation resistance etc. A general classification is given in Figure 2.2.

There are two general categories of alloy steels: the high-strength-low-alloy (HSLA) types, which rely largely on chemical composition to develop the desired mechanical properties in the asrolled or normalized condition, and the constructional alloy steels, in which the desired properties are developed by thermal treatment [18].

Stainless steels may also be classed as alloy steel, the main alloying elements being Nickel and Chromium. According to applications, alloy steels may be divided into four classes:

(1) Structural steels, which are subjected to stresses in machine parts.
(2) Tool and die steels.
(3) Magnetic alloys.
(4) Stainless and heat-resisting steels.

2.4 Strengthening Mechanisms in Alloy Steels

There are some alternative procedures for improving the strength of alloy steels by influencing the microstructure:

(1) *Grain refinement*, which increases strength and ductility. This can be developed by severely reducing the time after the finishing of forging at some low temperature of austenite stability or by rapid heating, coupled with a short austenitising period. Fine grain is produced in 9% Ni steel by tempering fine lath martensite.

(2) *Precipitation hardening* by carbide, nitride or intermetallic compounds.

(a) By secondary hardening, e.g. 12% Cr steel with additions.

(b) Age hardening a low carbon Fe-Ni lath martensite supersaturated with substitutional elements, e.g. maraging.

(c) Age hardening of austenite, e.g. stainless steels. Phosphorus and titanium are common additions. Stacking faults are often associated with fine carbide precipitates, and strength can be raised by increasing the number of stacking faults (i.e. lower fault energy.

(d) Controlled transformation 18/8 austenite steels in which transformation to martensite is induced by refrigeration or by strain.

(3) *Thermomechanical treatments,* such as deformation of austenite prior to or during the transformation, and deformation after the transformation of austenite.

2.5 Material Selection in Forging

In selecting the optimum alloy, first of all, the alloy must have the ability to be forged; that is, it must be sufficiently forgeable so that the product can be manufactured. Some alloys are relatively easy to forge and may be used to make components with very intricate features. Grades that are more difficult to forge require distinct design approaches.

On the other hand, the alloy must be able to achieve the required properties so that the product can meet service requirements.

The forging process, particularly development of grain flow, produces significant effects on material properties. In addition, there is a wide range of available heat treatments, particularly for steel alloys. Arriving at the optimum material, processing and heat treatment from the available matrix requires a balance of product design, forging and materials expertise.

Carbon steels are selected in nearly all manufacturing areas. Microalloyed steels serve as an alternative for their high strength and uniform hardness without heat treatment. Alloy steels have improved mechanical properties versus carbon steels. Stainless steels are less forgeable than alloy and carbon steels and they are used in areas where high temperature properties and corrosion resistance are required. There are ferritic, austenitic and martensitic stainless steel types having different characteristics; ferritic stainless steels have excellent corrosion resistance, good ductility, and they can be worked cold or hot. Austenitic stainless steels are highly resistant to acids and they have good toughness at cryogenic temperatures. Martensitic stainless steels are magnetic and they can be hardened and tempered.

Other than steels, there are various alloys in terms of aluminum, copper base, titanium, magnesium and high temperature alloys. Aluminum alloys can be very easily forged into precise, complex shapes. They have low density and good corrosion resistance. They are used mostly in aerospace, automotive, defense industries and sporting accessories. Copper base alloys have excellent corrosion resistance and forgeability. They are used in leak proof fittings, plumbing fixtures, gears, bearings, pumps, value bodies, and non-sparking applications. Titanium is a high strength alloy having a low weight, high service temperatures and excellent corrosion resistance. Aerospace, chemical processing and prosthetics are some of the areas of use. Magnesium has a low density and low modulus of elasticity. It is used where minimum weight is required at relatively low service temperatures. High temperature alloys have good corrosion and oxidation resistance. They are used in gas turbine components.

CHAPTER 3

FORGING DESIGN CONSIDERATIONS

3.1 Introduction

The applications of alloy steels in forging require several design considerations affecting the number of stages, forging temperature, preform design, dimensions of dies and billet, etc. Alloy steels have a wide area of use in forging industry since they bring superior properties to the final product. Strength and forgeability are the main parameters of the forging materials that affect the process.

3.2 Forgeability

Forgeability is defined as the tolerance of a metal or alloy for deformation without failure, regardless of forging-pressure requirements. Forgeability evaluations at a particular temperature do not necessarily define the ease with which a metal can be forged in impression dies under process conditions. In forging operations, temperatures of the workpiece usually differ as a result of die chilling and because of energy absorption causing heating. A metal having a wider forging temperature range may be easier to forge than the one, which withstands equal amounts of deformation without rupture [19].

Forgeability of a metal can be determined by several tests in terms of hot-twist, upset, notched-bar upset, hot impact tensile, tension and compression tests [19]. Compression tests are expected to provide values more useful for estimating forging pressures. Based on known correlations of test values with forging performance, the hot-twist test is particularly useful for evaluating the forgeability of carbon, low-alloy, and stainless steel. Tension tests provide data on ductility, which agree to some extent with the forgeability of metals at cold-working temperatures.

The most important metallurgical variables influencing forgeability are the composition and purity with the grain size of the material and number of phases present. In general, the forgeabilities of metals and alloys increase with increasing temperature. However, there are various distinct behaviors exhibited by different alloy systems. Improving the forgeability of an alloy by increasing the forging temperature may lead to reduced forgeability because of grain growth and the accompanying brittle grain boundary condition. Besides these metallurgical factors there are some mechanical factors that influence forgeability such as strain rate and stress distribution. Carbon and low-alloy steels are forged better at higher deformation rates. In general, metals exhibiting low ductility at cold-working temperatures show reduced forgeability at increasing strain rates, and metals exhibiting high ductility at cold-working temperatures are not affected by increasing strain rates as much. In Figure 3.1, the influence of forgeability and flow strength on die filling is shown.

Types of stresses applied to the metal during deformation contribute to the variations in forgeability. The workpiece is exposed to a combination of compressive, tensile, and shear stresses. Tensile and shear stresses cause ruptures in general. It is necessary to provide compressive support to those portions of a less forgeable metal that are normally exposed to the tensile and shear stresses.

INCREASING FLOW STRENGTH OR FORGING PRESSURE →

DECREASING FORGEABILITY ↓

GOOD	1030 (Carbon Steel) 4340 (Alloy Steel) H11 (Tool Steel) 6061 (Al Alloy)	TYPE 304 (Stainless) Ti - 6Al - 4V	MOLYBDENUM 16 - 25 - 6 (Stainless)
MODERATE	AZ 80 (Mg Alloy) 7075 (Al Alloy)	A - 286 (Stainless) INCO 901(Ni Alloy) 17 - 7PH (Stainless) Ti - 5 Al - 2.5Sn	WASPALOY (Ni Alloy) Ti - 13V - 11Cr - 3Al N 155 (Ni - Cr - Co Alloy)
FAIR	1130 (Alloy Steel) RESULFURIZED STEELS	TYPE 321 (Stainless) 15 - 7Mo (Stainless)	RENE 41(Ni Alloy) HASTELLOY C (Ni Alloy) HASTELLOY B (Ni Alloy)

Figure 3.1 Influence of Forgeability and Flow Strength on Die Filling [19]

For less forgeable materials, there are some methods for improving forgeability. Firstly, the multiple-stage upsetting dies may be used, each permitting 20-25 % reduction for progressively increasing diameters of the billet material. Secondly, Vee-Flat dies are an alternative to flat dies in that they change the stress distribution, shifting the maximum stress to the mid-radius positions. Starting materials with coarse grains and having center porosity may gain forgeability using this die type.

3.3 Grain Size

Grain size significantly influences the mechanical properties of metals. Large grain size is in general associated with low strength, hardness, ductility, and particularly in sheet metals result in a rough surface appearance after being stretched. Grain size may be measured by counting the number of grains in a given area or the number of grains that intersect a given length of a line randomly drawn on an enlarged photograph of the grains taken under a microscope on a polished and etched specimen.

Strain, strain rate and temperature are assumed as important technological parameters influencing the grain size. The optimal trajectories of thermomechanical parameters can be defined by using an appropriate optimal control algorithm based on a grain size evolution model and stable regions of thermomechanical parameters to ensure consistency in the properties and microstructures of forgings of difficult-to-deform materials [20].

There are several variables influencing the microstructure development. Shape design variables are one of the most important parameters as investigated by Gao and Grandhi [21]. The shape of initial billet affects the forming processes, such as influencing the distribution of strain, strain rate and temperature, then further influencing the microstructural behavior. In theory, it is best to obtain a uniform/fine grain size and a large recrystallized volume fraction. They concluded that; for Waspaloy, the recrystallization occurs in a small temperature range and a complete recrystallization does not happen in most areas during non-isothermal forging process.

Since forging is a multistage operation with a strong relationship between the stages, theoretical prediction of microstructure evolution and mechanical properties of the final product is difficult. In order to gain a full understanding, one has to combine experimental results with the thermal–mechanical–microstructural model of a forging sequence.

3.4 Preforming

Decision on the preform shape is the most important step in a forging when less forgeable materials are used and a high quality in both the dimensions and the properties is required. In forging of carbon or low-alloy steel, the preform should not have any flash. In addition to this, for any type of material, the preforms should be deformed without flash, since the formed flash before the final forging cannot be used in the filling of the dies, and considered as scrap.

There are many studies on the determination of the optimum die profile in the literature using computer aided design and analysis techniques [14], [15], [22], [23].

3.5 Parting Plane

Parting plane is the plane having the maximum cross-sectional area along the forging direction. Parting plane placement determines whether the grain flow that is required and specified for the forging will be obtained. After locating the parting plane, the depth and position of the impressions in the dies are fixed. The principal grain flow direction within the forging will be parallel to the principal direction of service loading provided that the parting plane is placed properly. A planar parting plane is given in Figure 3.2.

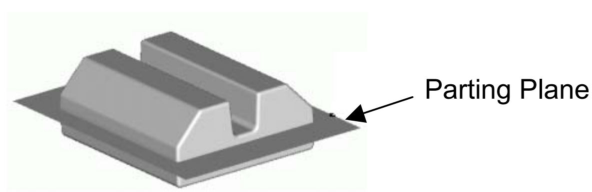


Figure 3.2 A Planar Parting Plane

3.6 Draft

Draft refers to the angle or taper on the sides of a forging that is necessary for releasing the forging from the dies. The location of draft is determined by the location of the parting line. The forging has its maximum spread at the parting plane regardless of whether the draft is intentionally applied or is normally part of the design. Ideally, drafted forgings should remove from dies in the first instant of separation at the interface.

Workpieces are to be designed with no taper on vertical sides with respect to the forging direction meaning zero draft. This requires special forceful means for ejection from die cavities. Workpiece is then removed from the die by mechanical means, by “strippers” that pull and “knockout pins” that push. In such situations several features are added to the forging in order not to harm the piece as in Figure 3.3.

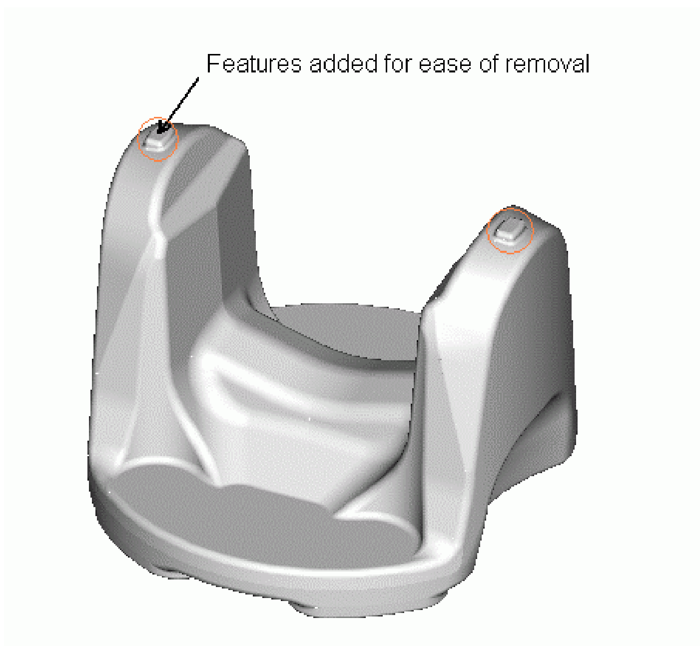


Figure 3.3 Addition of the Features to a Forging Model for Ease of Removal and not to Harm the Part

Zero-draft has the advantage of eliminating the machining operations after forging. However, the more common practice with forgings of steel, heat resisting alloys, and titanium is to finish machine for improved surface, and the forgings are designed with draft. The significance of cut grain and any end-grain exposure is up to what quality is required in the forging [5].

In Figure 3.4, types of draft are shown. In steel forgings, inside draft is generally greater than the outside draft, because the outside surface shrinks away from the die during cooling and permit removal of the forging.

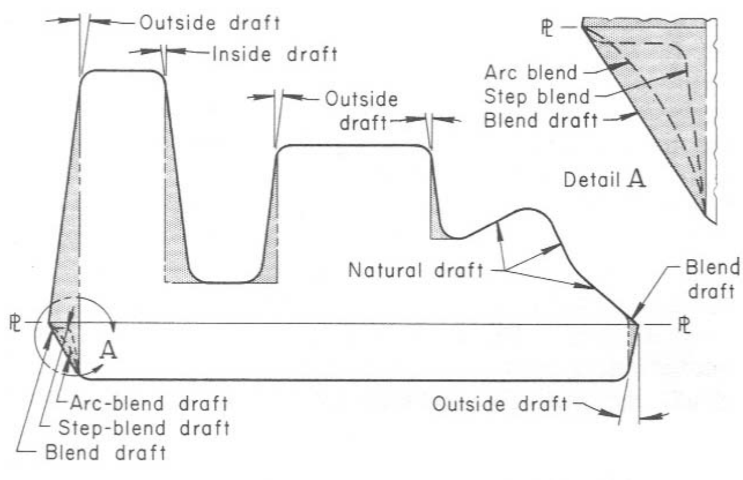


Figure 3.4 Types of Draft [5]

3.7 Flash

Some of the material flows radially outward and forms a flash. Because of its high length-to-thickness ratio, the flash is subjected to high pressure. The pressure in turn means high frictional resistance to material flow in the radial direction in the flash gap. Since high friction encourages the filling of the die cavities, the flash has a significant role in the flow of material in impression-die forging. Furthermore, when the operation is performed at elevated temperatures, the flash cools faster than the bulk of the workpiece because of its high surface-to-thickness ratio. Thus the flash resists deformation more than the bulk does and helps fill the die cavities.

For the parts having holes, the design should include webs in order not to give damage to dies. The web of a forging is relatively thin, plate-like element placed in the hole and can be considered as an inner flash. The remaining web section of the part can be removed after the forging by trimming it on a press or by machining. Recommended values for these features can be found in the related DIN standard [24].

There are several methods in determining the flash geometries and National Association of Drop Forgings (NADF) recommendation is one of them which is given in Table 3.1, in terms of forging weight versus flash weight per unit length of the parting line.

Table 3.1 Recommendation of NADF for Flash Mass per Unit Length of the Parting Line [25]

Forging Mass (kg)	Flash Mass (kg/cm of periphery)
Less than 0.450	0.0047
0.450 - 2.273	0.0063
2.273 - 4.545	0.0098
4.545 - 6.818	0.0130
6.818 - 11.364	0.0168
11.364 - 22.727	0.0223
22.727 - 45.455	0.0324
45.455 or above	0.0477

Forging is referred as flashless forging when the space between dies is filled with no flash. The design of flashless forging processes is more complex than the design of conventional closed die forging with flash. Therefore, in order to accelerate the development of the manufacturing process as well as to reduce the development costs, new design methods must be developed and applied [26]. Flashless forging shows much less forging load than that for conventional forging. Trimming process is also eliminated. However a major advantage of the closed-die forging with flash is that the volume of the preform can vary within a wider range than for flashless forging, which makes it easier to continuously manufacture products with the same quality.

3.8 Temperature

In hot forging operations, temperature is a very important design consideration in that; it directly affects the properties of the materials. Temperature variations are influenced by the surface area of contact between dies and forging, the part thickness or volume, die temperature, the amount of heat generated by deformation and friction, and the contact time under pressure. In the hot-working temperature range, deformation occurs by breakdown of grain into subgrains through dislocation movement, grain-boundary shearing and migration, and fine slip [27].

Changes in temperature during closed-die forging can have quite different effects in load requirements and in metal flow for different materials. The forging temperatures and reductions must be controlled to prevent grain growth. The amount of reduction is important, because deformation heating of the workpiece influences the effective temperature. The temperatures should be low enough to prevent recrystallization during working; short periods above the recrystallization temperature (on the order of 10 minutes) can usually be tolerated [27].

For alloys that need control of forging temperature within a narrow range in order to develop desirable microstructures and properties, isothermal forging may be a good solution. The process is named isothermal, because the tools and the stock are at the same temperature at the beginning of forging and the low strain rates and long dwell times minimize temperature changes. Isothermal forging is advantageous in that, chilling, which limits permissible reductions is eliminated. Also, heat is distributed or extracted uniformly from all locations of a forging, which helps to stay in the required temperature range. While it is always desirable to keep the temperature difference between the dies and the workpiece as small as possible, it must be considered that, the dies cannot be heated higher than the tempering temperature of the die material, because exceeding the tempering temperature causes the die to become softer. As a result, dies may fail.

CHAPTER 4

CASE STUDY ON EYE BOLTS

4.1 Introduction

In this study, metric 20 and 30 eye bolts, which are forged from alloy steels and titanium in industry, have been investigated. A forging model of the eye bolt is given in Figure 4.1.

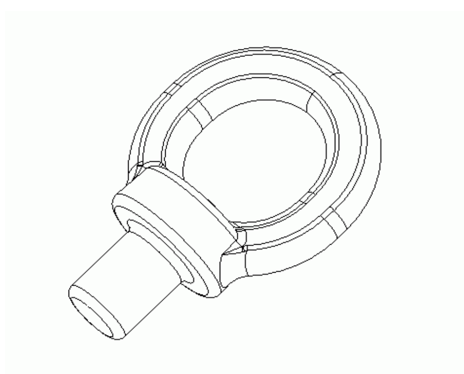


Figure 4.1 Forging Model of a High Tensile Eye Bolt

These types of eye bolts are used for lifting purposes. They have a short threaded shaft and are ideal for through-bolting fiberglass or metal.

DIN 580 standards specify the dimensions and the safe carrying capacities for various metric lifting eye bolts, with two types of loading configurations. When installing male lifting eye bolts, it is important to ensure that the face is in firm contact with the mating face. Side loads across the eye plane are not permitted for safety reasons. To get the maximum lifting capacity from an eyebolt, the load should be lifted straight upwards. Eye bolts are selected based on the load weight and the angle of the pull on the bolt as shown in Figure 4.2.

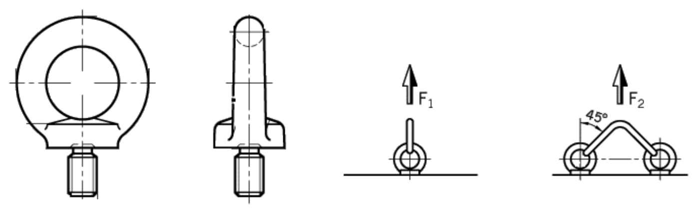


Figure 4.2 A Lifting Eye Bolt with Two Loading Configurations [28]

4.2 Forging Practice for Eye Bolts

Several metric series of eye bolts are being forged in industry. In this study, the forging processes of M20 and M30 are observed in AKSAN Steel Forging Company [29]. The process sheet of the forging for M20, which is forged from 42CrMo4, is given in Table 4.1.

To mount the die pairs appropriately on the forging press, necessary mounting features are machined on the die blocks as seen in Figure 4.3 (a). Dies are heated approximately to 275 °C to extend the die life by decreasing the thermal fatigue. When the necessary temperature is reached on the dies, lubrication is applied on the die cavity surfaces. Billets are placed in the induction furnace for heating.

Table 4.1 The Process Sheet of Forging M20 Eye Bolt [29]

Op #	Operation	Equipment
1	Crop the bar to length of 80 - 81 mm with the stock diameter of 40 mm	Cropping Tool
2	Heat the stock up to 1100^{o}C	100 KW Induction Heater
3	Check the temperature	Optical Pyrometer
4	First Preform: Upset the stock. After the upsetting operation, the height should be 30-32 mm and diameter should be 67-69 mm	10 MN Mechanical Forging Press
5	Second Preform: Place the stock to the die and lengthen the stock. After the operation length should be 95-98 mm, depth should be 30-32 mm, width should be 45-46 mm	10 MN Mechanical Forging Press
6	Final Forging: Adjust the dies such that the flash thickness is 3.5 mm and web thickness is 5 mm	10 MN Mechanical Forging Press
7	Place the forged product on the hole trimmer and trim the hole	1 MN Mechanical Trimming Press
8	Place the finished part on the trimmer and trim the flash	1 MN Mechanical Trimming Press

After the billet is taken out from the furnace, the heated billet is placed between the first pair of dies and the other stages of process are subsequently applied to forge and trim the part in the test run. The upper and lower dies are adjusted to obtain the required geometry and a more uniform flash distribution and prevent misalignment.

(a) (b)

Figure 4.3 (a) Finish Die Used for the Forging of M20 Eye Bolt and (b) The Final Product

4.3 Forging Simulation of M20 Eye Bolt

Simulations are performed by using MSC.Superforge, which is a commercial finite volume analysis package. Five different materials are used in the simulations which are a heat-treatable steel: 42CrMo4, carbon steels C60 and C45, a stainless steel: X20Cr13 and a bearing steel: 100Cr6. Material properties are taken from the MSC.Superforge database. The die material is also selected from the database as H-13, which is the commonly used die material. The open dies are used in the simulations of the upsetting and the flattening operations and the closed die is used in the final stage. Plastic shear friction model is used with 0.3 as the interface friction factor [12]. The element size used in the modeling of the workpiece is taken as 2 mm.

10 MN mechanical press is used in the numerical analysis as used in the particular forging company. In the program, the press is represented as given in Figure 4.4 with crank radius, (R) of 125 mm, rod length (L) of 665 mm and rotational speed (ω) of 90 rpm.

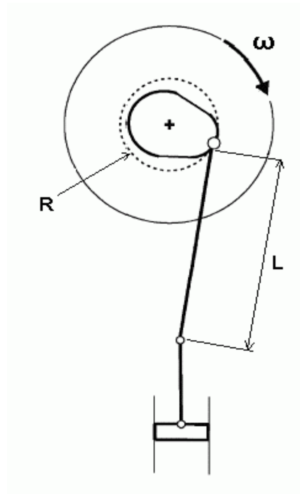


Figure 4.4 Input Parameters for the 10 MN (1000 tonf) Mechanical Press

In the first step, the stock with the length of 81 mm and the diameter of 40 mm is deformed between flat dies so that the height is reduced to 31 mm. As a result of the simulation, the diameter of the deformed shape becomes about 66 mm. In the second step, the upset part is rotated 90º and it is flattened between flat dies. At the end of this step, the parts dimensions become approximately 87 x 31 x 46 mm. The geometries of the part at the subsequent stages are given in Figure 4.5.

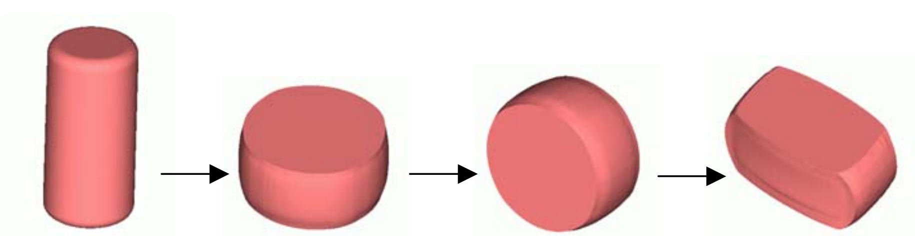


Figure 4.5 Upsetting and Flattening Stages of M20 Forging

The part is then placed between the final forging dies. The thicknesses of the flash and the web are 3.5 and 5 mm respectively. The geometries of the part, before and after the final stage are presented in Figure 4.6.

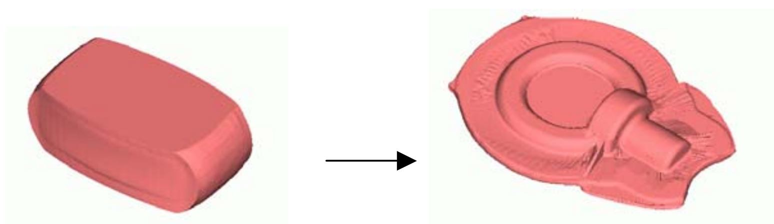


Figure 4.6 The Final Forging Stage of the Operation

The first set of simulations has been performed for three different materials with different initial workpiece temperatures. Die loads and die fill are examined in each simulation sequence.

The temperature of the dies are taken as 275 °C, which is the intended value of AKSAN forging company and the ambient temperature is assumed to be 25 °C. A carbon steel C45, a stainless steel X20Cr13 and a heat-treatable steel 42CrMo4 are used as the materials to be forged. In Superforge, the dies are taken as rigid and heat transfer is allowed between dies and the workpiece. The maximum die loads are given in Table 4.2.

It is observed that, the die loads decrease as the temperature increases, as expected. At different temperatures, the minimum die loads are obtained for different materials. For example, while at 800 ºC, X20Cr13 has the lowest die load, at 900 ºC and 1000 ºC, C45 and at 1100 ºC, 42CrMo4 are most forgeable as seen in Table 4.2.

Table 4.2 Maximum Die Loads in Forging Various Steels at Different Temperatures

Material / Temperature °C	Carbon Steel C 45 (DIN 1.0503)	Stainless Steel X20Cr13 (DIN 1.4021)	Heat-Treatable Steel 42CrMo4 (DIN 1.7225)
1100	7,135 x 10^6 N	7,208 x 10^6 N	6,370 x 10^6 N
1000	7,200 x 10^6 N	7,319 x 10^6 N	7,405 x 10^6 N
900	7.825 x 10^6 N	8,109 x 10^6 N	8,338 x 10^6 N
800	8.513 x 10^6 N	8,220 x 10^6 N	8,662 x 10^6 N

For the three steels, a sharp increase is observed at die loads as temperature increases. The workpiece should be heated above this critical temperature. For instance, for the stainless steel, X20Cr13, the forging temperature should be higher than 900 ºC, looking at the die load results.

4.4 Experimental Study of M20 Eye Bolt

Five different materials have been forged for the testing purposes. These materials are C45, C60, X20Cr13, 42CrMo4 and 100Cr6. Practically, forming temperature ranges of the selected materials proposed by AKSAN company and the average test temperatures measured by using a portable pyrometer are as given in Table 4.3 [29]. Die surface temperature for the die set was measured as 130 ºC. Although the preheat surface temperature of the dies has been planned as 275 ºC, unfortunately the die surface temperatures are observed below this value due to unavoidable time interval for successive testing of different materials and the time limitations coming from the forging company. The ambient was at 20 ºC.

Table 4.3 Temperature Ranges for Selected Materials in AKSAN [29]

Material	Temperature ºC (proposed range)	Test Temperature ºC
C45	1150-1230	1100
C60	1180-1250	1150
X20Cr13	1100-1200	1180
42CrMo4	1150-1230	1150
100Cr6	1150-1230	1150

For testing purposes, cylindrical billets which are 40 mm in diameter and 80 mm in length are cut. Then these are heated up to the forging temperatures in an induction heater and forged by using the 10 MN (1000 tonf) mechanical press. It should be also noted that the width of the flash region on dies which is observed in AKSAN during the test and given in the technical drawings, are different.

The photographs of the forged products for the five experiment materials are shown in Figure 4.7.

The part is then inspected macroscopically for examining the flow defects that may occur during forging. The procedure and the results of this inspection are given in Appendix.

Figure 4.7 The Steps of the Forging Process of M20 Eye Bolt with Different Materials (a) C45 (b) C60 (c) X20Cr13 (d) 42CrMo4 (e) 100Cr6

4.5 Forging Simulation of M20 Eye Bolt Using the Test Data

In the second set of simulations, the measured values of the temperatures in the testing of M20 eye bolt in the company have been entered in the simulations. For comparison with C45, the simulations of C60 and 100Cr6 have also been performed with 1100 ºC as the initial billet temperature. The results for the die loads are obtained as given in Table 4.4. In Figures 4.8 through 4.14 die load versus time graphs of the simulations of C45, C60, X20Cr13, 42CrMo4 and 100Cr6 are presented respectively.

Table 4.4 Simulation Results using the Test Data

Material	Temperature ºC	Max.Die Load ($x10^6$ N)
C45*	1100	6.808
C60*	1150	6,424
C60**	1100	6,505
X20Cr13*	1180	6,895
42CrMo4*	1150	5,748
100Cr6*	1150	5,657
100Cr6**	1100	5,713

* temperature value input for the test data

* * temperature value input for comparison purpose

When the maximum die loads of C45 in the first set are compared with the second set results, it is seen that loads are higher in the first one. The reason of this difference is due to the flash region, which is wider in the second case.

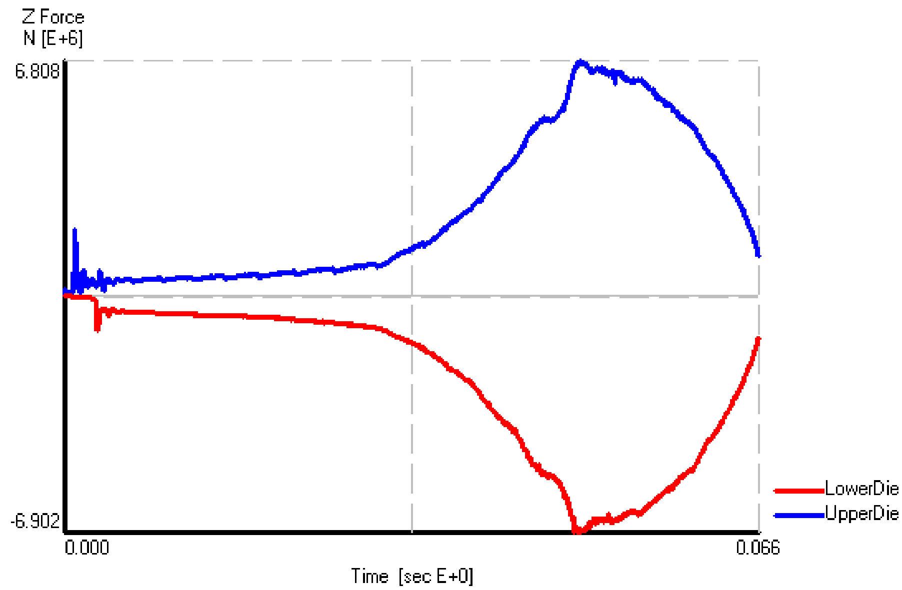


Figure 4.8 Die Load vs. Time Graph of C45 at 1100 ºC

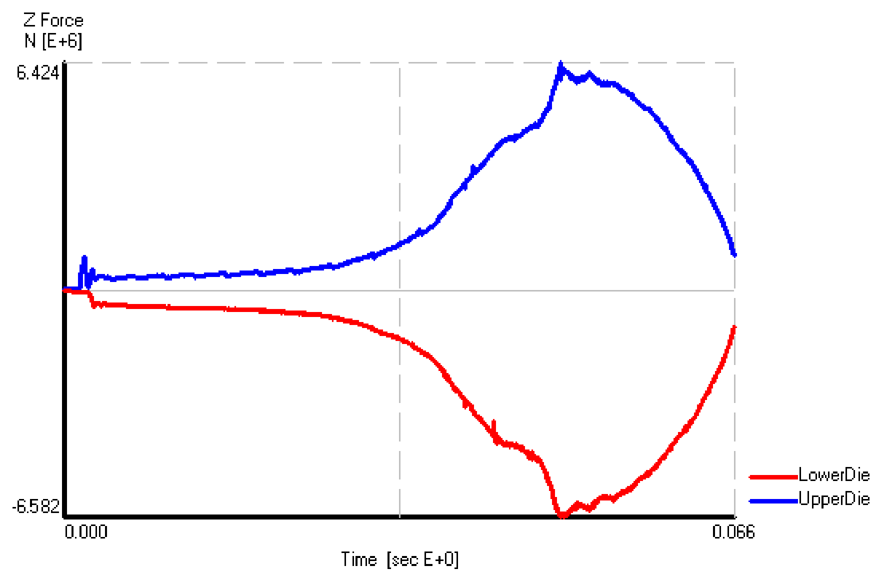


Figure 4.9 Die Load vs. Time Graph of C60 at 1150 ºC

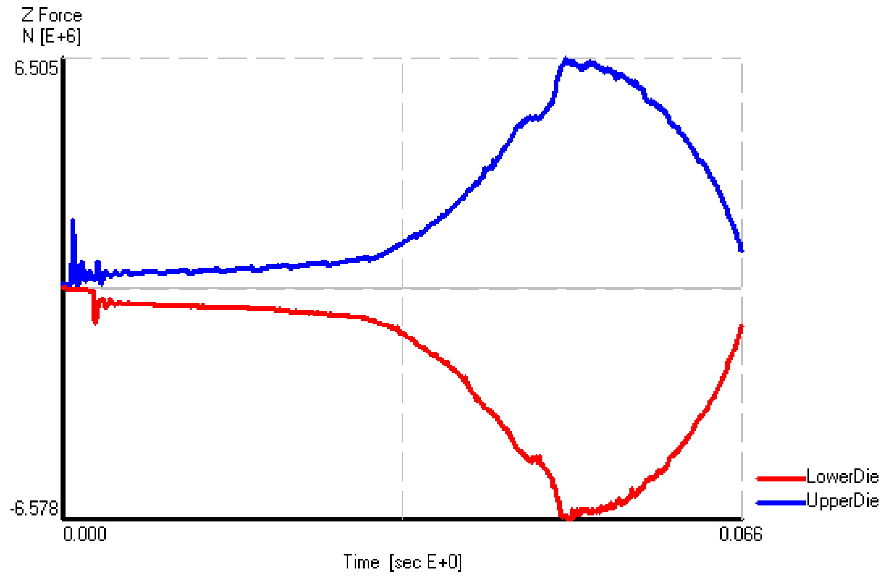


Figure 4.10 Die Load vs. Time Graph of C60 at 1100 ºC

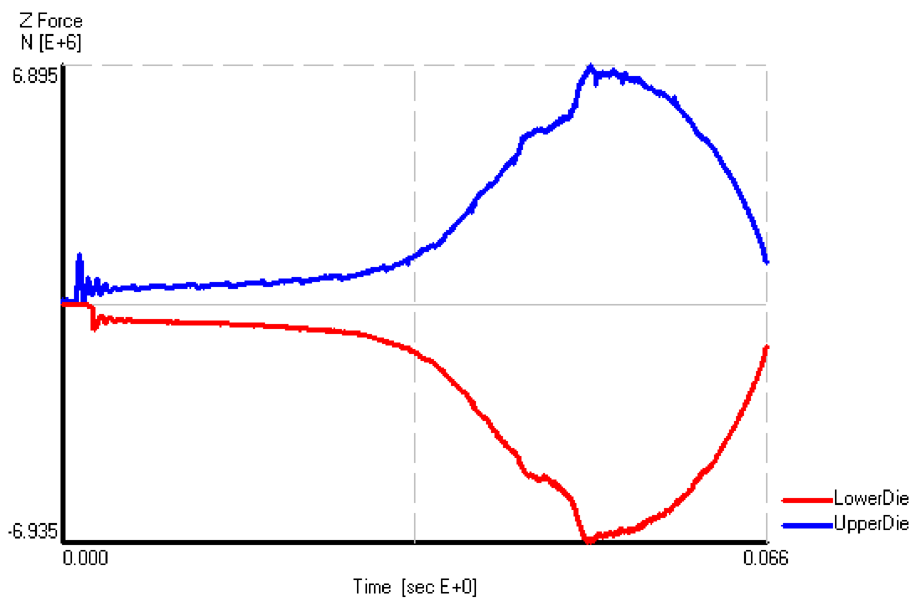


Figure 4.11 Die Load vs. Time Graph of X20Cr13 at 1180 ºC

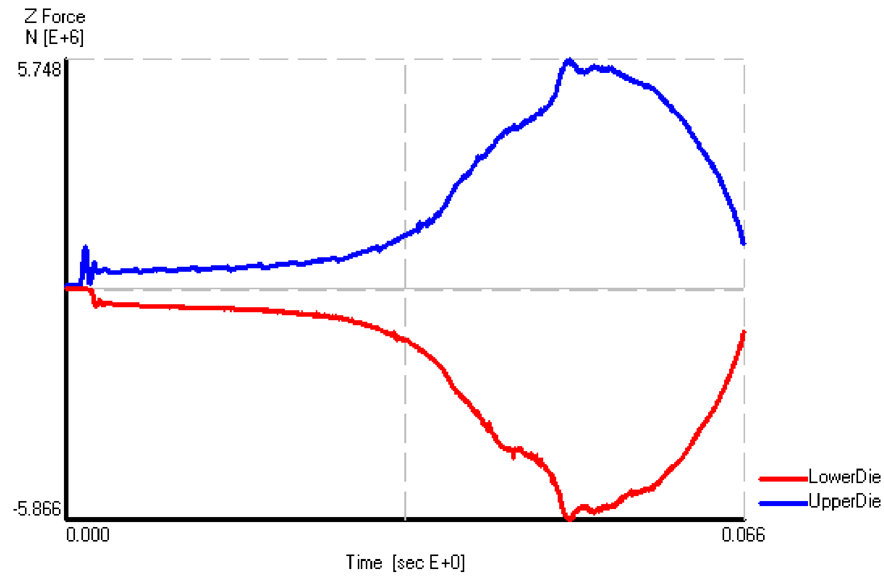


Figure 4.12 Die Load vs. Time Graph of 42CrMo4 at 1150 ºC

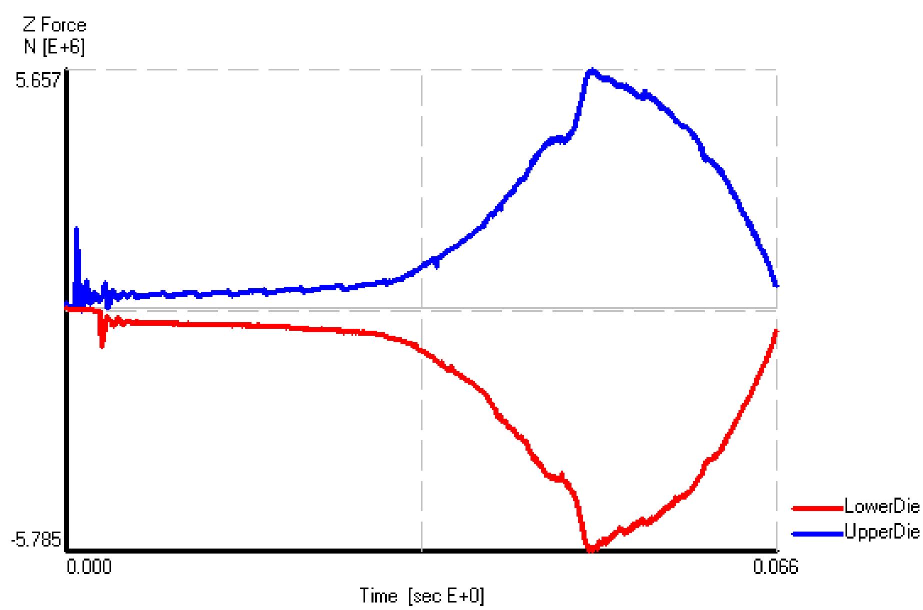


Figure 4.13 Die Load vs. Time Graph of 100Cr6 at 1150 ºC

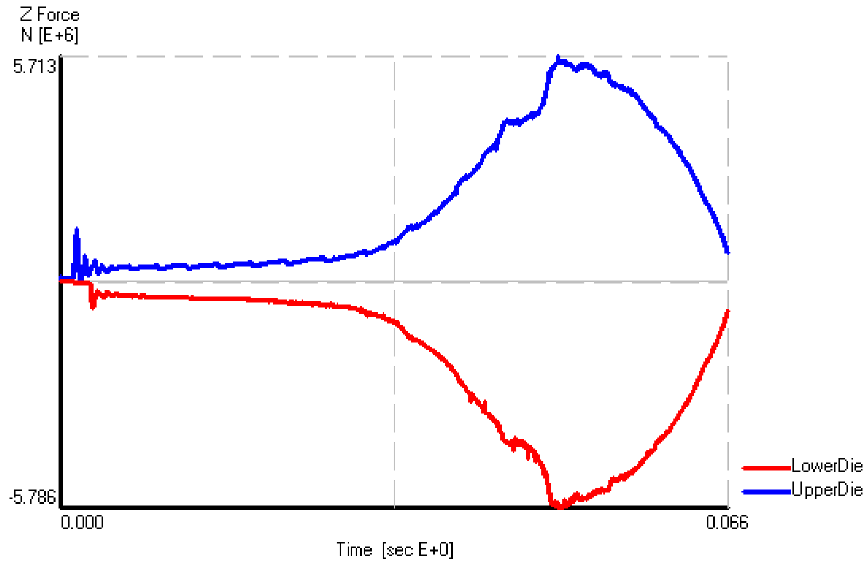


Figure 4.14 Die Load vs. Time Graph of 100Cr6 at 1100 ºC

4.6 Forging Simulation of M30 Eye Bolt

The forging process sequence of M30 Eye Bolt has been simulated according to the process sheet provided by the company. The weight of M30 is nearly four times that of M20 and a more controlled preforming stage is needed. In this thesis, a preform die geometry has been proposed by the author. The proposed geometry of the preform is given in Figure 4.15. According to the suggested sequence, the part is first upset 50% of its length, then preformed using an impression die, which has a cavity close to the finishing die geometry instead of flattening. The materials used in the simulations are a carbon steel (C45), a bearing steel (100Cr6), a stainless steel (X20Cr13), and a heat-treatable alloy steel (42CrMo4). The dies are heated up to 275 ºC and the workpiece up to 1100 ºC. 10 MN crank press parameters are used and the friction coefficient is taken to be 0.3 as in the previous case study.

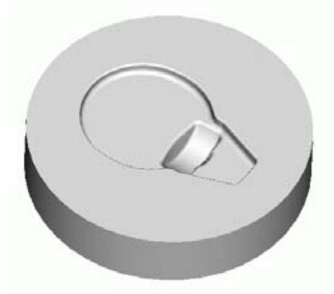


Figure 4.15 The Proposed Geometry of the Preform of M30 Eye Bolt

The flash thickness and billet size are also determined in this case study. The billet dimensions are determined by adding flash according to the recommendations of NADF, to the original part with the flash thickness of 4.5 mm. According to NADF, since the weight of the forging is 1.90 kg, the coefficient is taken from Table 3.1 as 0.0063 kg/cm and using the peripheral length of 447.71 cm the flash weight is calculated as 0.282 kg.

Simulations are initiated with a stock material having 30 mm diameter and height of 101 mm to satisfy the volume of the final forging including flash. The flash width is approximated to be 15 mm by using the NADF recommendation. In the preforming stage, the dies are closed until the distance between them is 20 mm to allow the material to deform in the upsetting direction in the final forging step. Process sequence is given in Figure 4.16.

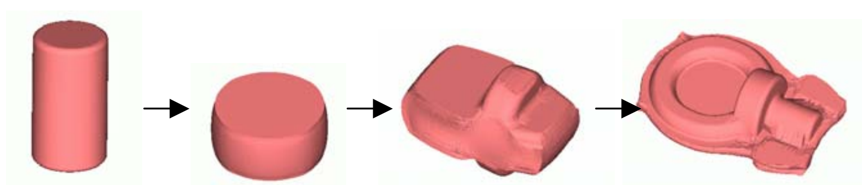


Figure 4.16 Process Simulation of Forging M30 Eye Bolt

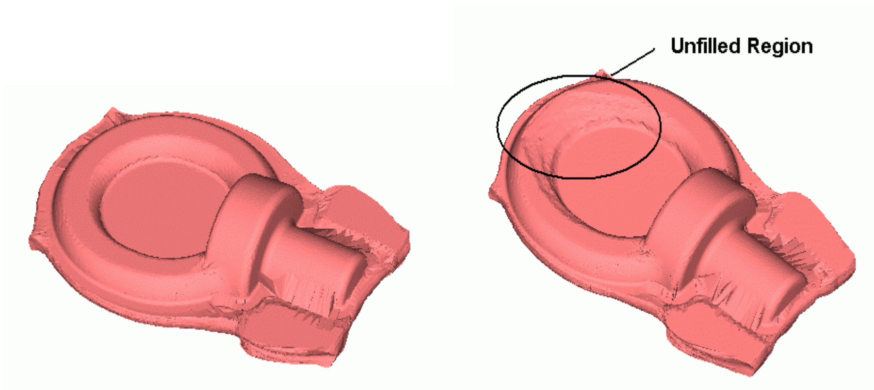
The maximum die loads in the simulations are represented in Table 4.5. It is observed that when the stock is heated to the initial temperature of 1100 ºC, the maximum die load of 100Cr6 is lower than the other steels.

Table 4.5 Maximum Die Loads for M30 Eye Bolt

	100Cr6 (DIN 1.3505)	C 45 (DIN 1.0503)	X20Cr13 (DIN 1.4021)	42CrMo4 (DIN 1.7225)
Die Loads	$6{,}972 \times 10^6$ N	$7{,}625 \times 10^6$ N	$8{,}782 \times 10^6$ N	$9{,}310 \times 10^6$ N

If the heat-treatable steel, 42CrMo4 is selected as the material of forging, it is seen that the required die load is close to the limits of the 10 MN press. If the efficiency of the press is taken into account, it may be recommended that a higher capacity press must be selected than the 10 MN press. The simulations should be repeated using the parameters of the newly selected press.

It is observed that the dies are filled only when 42CrMo4 is used, and not filled for the other steels. This is shown in Figure 4.17. In the simulations, in order to see the effects of material selection on the filling of the dies, the part whose material is C45 is placed on the same position as 42CrMo4. It is seen that dies are not filled in this case either. From this result, it is concluded that material selection may affect die filling. In the applications, 42CrMo4 is used as the workpiece material and this simulation verified that there is no problem in filling of dies if this material type is selected.



(a) (b)

Figure 4.17 Final Product in Forging M30 Showing (a) Filled and (b) Unfilled Regions

CHAPTER 5

CASE STUDY ON RUNNER BLOCKS

5.1 Introduction

Runner blocks, which are shown in Figure 5.1, are used in machinery and equipment in rail systems for linear motion purposes, and in material handling. They must be manufactured to a high degree of precision and corrosion resistance is very important. The product group which is analyzed in the study includes runner blocks, which are used in ball rail systems. A runner block assembled on a ball rail system is shown in Figure 5.2. A ball rail system consists of a guide rail with all surfaces ground and ball track zones hardened, and a steel runner block with bearing steel balls, integral all-round sealing of tracks, hardened and ground steel load bearing plates with ball tracks, and cage designed for optimum ball recirculation.

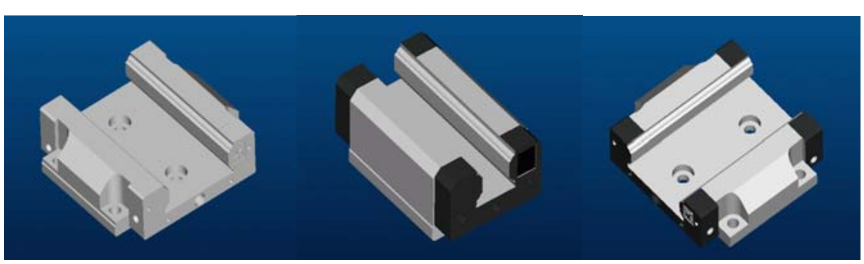


Figure 5.1 Models of Various Runner Blocks Used in Industry [29]

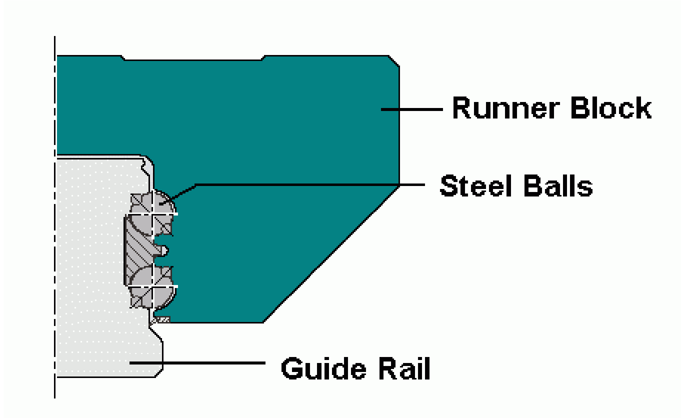


Figure 5.2 Ball Rail System [30]

In this chapter, the production of runner blocks has been presented and simulations are performed to compare the results with the simulations in Chapter 4 and the real-life application.

5.2 Company's Practice for Roller Bearings

In this process, three preforming stages are applied as a necessity which comes from the size and the weight of the product. For lubrication, a mixture of 1 liter graphite-base oil and 15 liters of water is used. Parting line is planar. It is very important that the part is handled carefully using a forging tong during the hot forming and after the trimming. Before trimming, the part is left for cooling for approximately 2 minutes and the temperature of the part decreases to about 900 ºC. 100Cr6 is used which is a ball and roller bearing steel as the material. The process sequence is shown in Figure 5.3 and the procedure applied by the forging company is given in Table 5.1.

1. Upsetting

2. Flattening

3. Preforming

4. Final Forging

5. Part Left for Cooling

6. Trimming

Products of the forging sequence

Figure 5.3 The Process Sequence of Forging a Runner Block

Table 5.1 The Process Sheet of the Process

Op #	Operation	Tool
1	Crop the square cross-section bar to a length of 185-186 mm with the side length of 90 mm	Cropping Tool
2	Heat the stock up to 1100^{o}C	970 KW Induction Heater
3	Check the temperature	Optical Pyrometer
4	First Preform: Upset the stock. After the upsetting operation, the dimensions should be 147-151 mm in height	40 MN Mech. Press
5	Second Preform: Place the stock to the die and lengthen the stock. After the operation the height should be 168-171 mm and the cross section should be 79 x 125 mm	40 MN Mech. Press
6	Third Preform: Place the stock to the die such that the height of the part becomes 66 - 67 mm	40 MN Mech. Press
7	Final Forging: Adjust the dies such that the flash thickness is 7-7.5 mm	40 MN Mech. Press
8	Place the finished part on the trimmer and trim the flash	40 MN Mech. Press

5.3 Simulation of Runner Blocks

Runner blocks have been analyzed using MSC.Superforge. In the simulation of runner blocks, two materials are compared in terms of a carbon steel, C45, and a bearing steel, 100Cr6. 10 MN press parameters are used with shear friction coefficient of 0.3. In Figure 5.4, computer models of the dies and the final product are given.

(a) (b) (c)

Figure 5.4 (a) The Final Product, (b) The Upper Die, (c) The Lower Die

Materials are selected from the database of the software. Ambient temperature is 20 ºC and rigid dies are at 250 ºC. Multi-stage forging is used and the initial temperature of the billet is 1160 ºC, which is averaged from the production temperature data. The part geometries obtained from the simulations are shown in Figure 5.5.

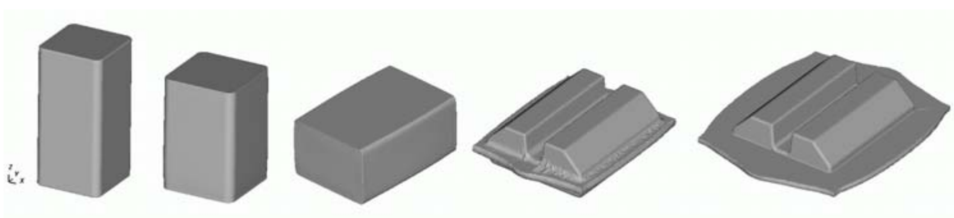


Figure 5.5 Simulation of the Forging Sequence

Die load curves in the final forging step for C45 and 100Cr6 are given in Figures 5.6 and 5.7. It is observed from the simulations that the bearing steel requires higher load than the carbon steel with the same geometry and temperatures.

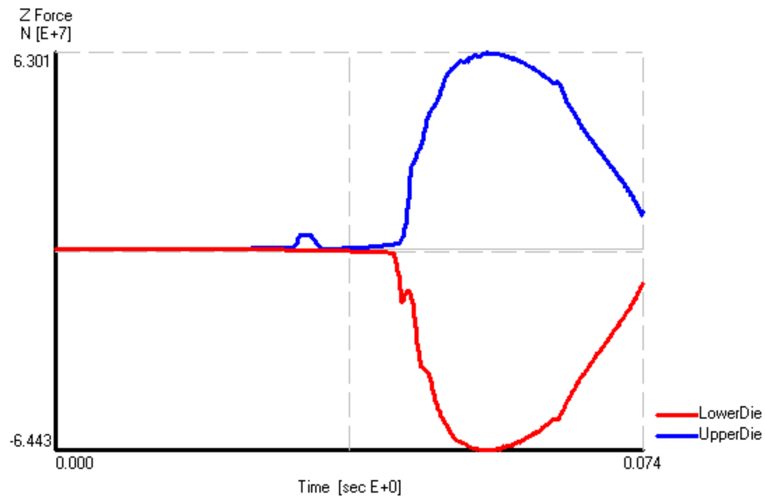


Figure 5.6 Die Loads in the Final Stage of Process for the Bearing Steel, 100Cr6

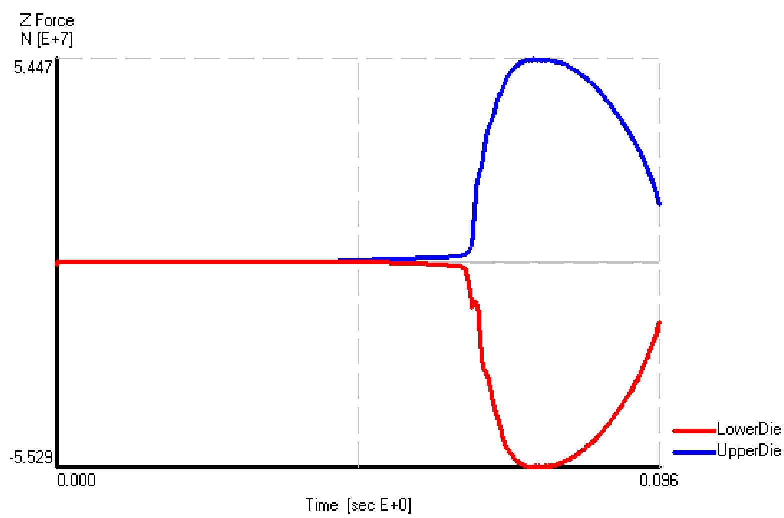


Figure 5.7 Die Loads in the Final Stage of Process for the Carbon Steel, C45

Effective stresses are higher for the carbon steel, but with a narrower distribution. From these results, it is expected that die wear occurs faster for the carbon steel than the bearing steel, but the area which is prone to wear is wider for the bearing steel. Effective stresses are represented in Figures 5.8 and 5.9.

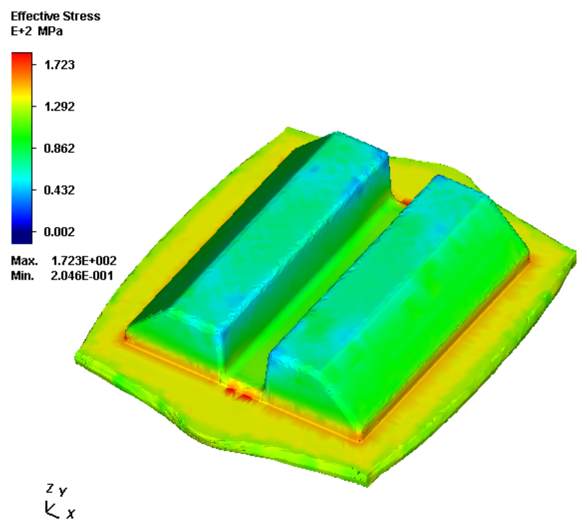


Figure 5.8 Effective Stress Distributions for Carbon Steel at 80 % of the Final Stroke

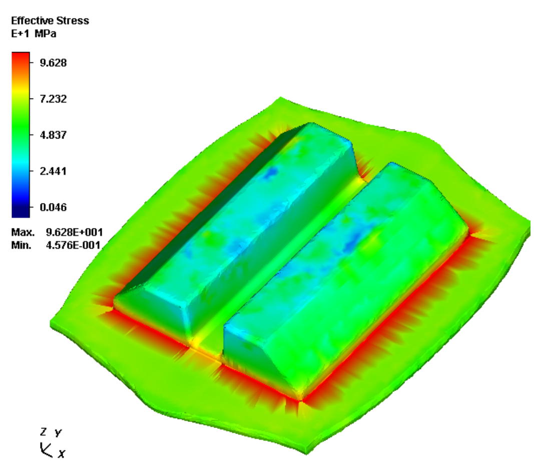


Figure 5.9 Effective Stress Distributions for Bearing Steel at 90 % of the Final Stroke

The stage of the final impression at which the effective stress is maximum, is different for the two steels. The occurrence of the maximum effective stress is at an earlier stage for the carbon steel.

When the material effects are compared, it is seen that in the simulation of M20 and M30 eye bolt, die loads are higher for the carbon steel than the bearing steel. This shows the effect of part geometry on the final loading.

In the simulations of both C45 and 100Cr6, dies are filled as in the real-life application. The maximum die loads and the maximum effective stresses are given in Table 5.2.

Table 5.2 The Maximum Die Loads and the Maximum Effective Stresses

Material / Result	C45	100Cr6
Maximum Die Load (N)	5.447×10^7	6.301×10^7
Maximum Effective Stress (MPa)	172.3	96.28

CHAPTER 6

CONCLUSION

6.1 Conclusion

In this study, the hot forging process of two groups; eye bolts and runner blocks which are manufactured from alloy steels have been examined. Simulations of M20 eye bolts are compared with the forging experiments. Results have been discussed by considering die-fill, effective stress distributions and temperature effects.

It has been observed that similar flash distributions are observed in the simulations for the selected materials. In the practice, the distributions follow similar contours; however for the carbon steel, the flashes distribution is more uniform than the bearing steel. This is seen in Figure 6.1.

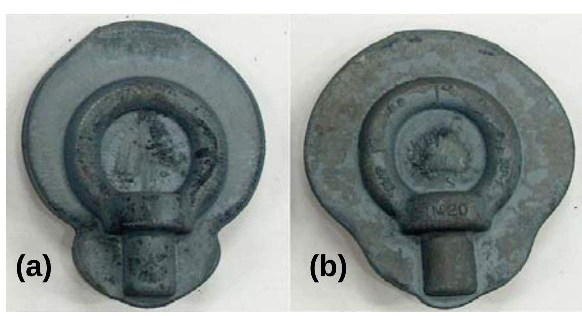


Figure 6.1 Flash Distribution of (a) 100Cr6, (b) C45

It is clear from Figure 6.1 that 100Cr6 has a higher resistance to deformation than the carbon steel; C45, meaning that the material flow is different for the two steels. Therefore during preform design, simulations for the difficult-to-form materials may be helpful in determining the preform shapes, number of preforms and the optimum flash thicknesses.

In simulations of M20 eye bolt, it has been observed that, the most appropriate forging temperature may be selected for different materials. Die load results can be used for the selection of forging press. The efficiency of the press should also be taken into consideration in selecting the most appropriate temperature. In mechanical presses, efficiency is not taken into consideration in the calculations; however the maximum load that the press exerts is in general lower than its capacity.

It can be concluded that, flow stresses of the material strongly effects the material flow and die fill, which in turn may effect billet dimensions in the forging operations.

In both the experiments and the simulations of M20 eye bolt, dies are filled. However, there occurred some mismatch between the flash distribution in simulations and during the test. The reason for this is mostly related with the friction conditions at the workpiece-die interface. The friction at the upper die and at the lower dies is taken equal in the simulations, but this is not the case in the experiments. The geometry complexity, pressure at various points on the die cavity, lubrication are the factors that change the friction coefficient in real-life environment.

Heat transfer coefficient is also an important parameter in forging simulations. Kutlu [25] has simulated with different heat transfer coefficients, he found out that changing the heat transfer coefficient parameter is not so effective in the simulation software. The flash formed at the end of the process acts as a seal that plugs the gap between the dies. The strength of this seal, which was a function of the flow stress of the steel in the flash, is the primary factor affecting the maximum forging load. The most important determinant of the steel's flow stress is its temperature, which in the flash region, was primarily controlled by the die heat transfer coefficient. The die heat transfer coefficient significantly affects the flash temperature, which significantly affects the forging load. Increasing the temperature of the dies may be a solution for decreasing the die loads.

During the experiments, it has been observed that the temperature of the heated billet is not constant over the entire length changing from 1080 ºC to 1280 ºC. Moreover, scale formation on steel during the heating, makes it difficult to measure the exact temperature of the billet. These incorrect readings and inhomogeneous temperature distributions are one of the reasons of the difference between the simulations and the experiments.

The cooling of the billet and dies due to delays of the operator and the positioning of the workpiece play a very important role on the final shape and properties, since the temperature decreases very rapidly as the heated billet is transferred from the induction heater to the forging die.

6.2 Recommendations for Future Work

In this study, the main control parameter is the high temperature material data, since the forging process in performed above the recrystallization temperature. These parameters are directly taken from the MSC.Superforge database. It should be valuable that these values are determined experimentally and entered into the software.

Also, the temperature values during the experiment are read using a portable optical pyrometer. The readings sometimes give incorrect values due to the scale on the workpiece. A static pyrometer may be used in the experiments so as to read a specific point on the part for each forging sequence.

In order to improve the mechanical properties of the final product, it is necessary to understand the relationship between the development of the microstructure and the thermomechanical variables. An analysis software can be developed in order to predict the microstructure evolution in hot forging applications using the results of the MSC.Superforge simulation package.

Die loads of the simulations may be compared with die loads in the experiments using special equipment.

In the simulation software, the initial temperature of the billet is taken constant throughout the entire volume. A computer program can be developed in order to approximate the temperature distribution in the billets at the beginning of the metal deformation in press.

The results of the MSC.Superforge which is a finite volume solver may be compared with finite element programs such as MSC.Superform, FORGE3, QFORM3D, DEFORM™-3D, MSC. Patran, etc.

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APPENDIX

INSPECTION OF M20 EYE BOLT

After the forging experiment of M20 eye bolt, a section is cut out from a C45 sample product including the web section, but without flash to investigate its interior structure. The section in on the symmetry plane of the part. To prepare the sample, first the part is cut using a band saw, and then the surface to be examined is improved on a manual milling machine. Further improvement on the surface is obtained on a grinding machine and after this operation; sand paper is applied on the surface. The surface is then etched for macro inspection.

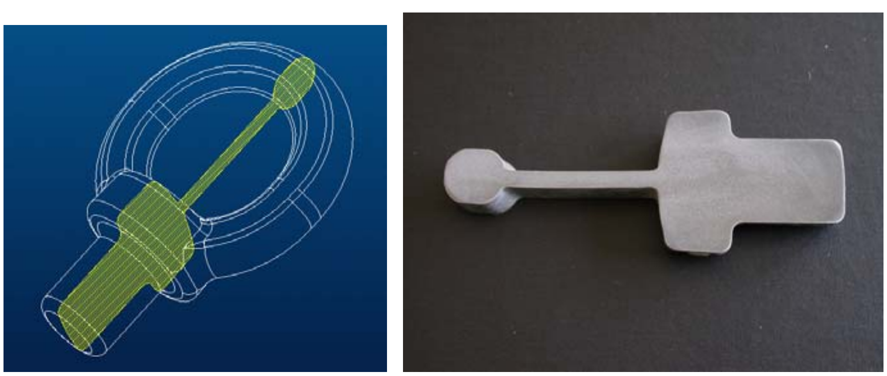

Figure A.1 A C45 Sample Taken out from the Symmetry Plane

As seen in Figure A.1, material distribution is homogeneous due to hot working. Segregation, flow, fold or laps have not been observed on the sample piece.