

DESIGN AND IMPLEMENTATION OF HOT PRECISION FORGING DIE
FOR A SPUR GEAR

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**DESIGN AND IMPLEMENTATION OF HOT PRECISION FORGING
DIE FOR A SPUR GEAR**

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ABSTRACT

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There is a strong need in forging industry to reduce waste of material, improve quality, and reduce cost of forgings. About 30% of the material is wasted during conventional closed-die forging. Therefore, in order to reduce the cost of forged products and to obtain near-net or net shape parts, new forging methods should be applied. Precision forging concept is a cost-effective way to produce net-shape or near-net shape components. In recent years, there has been an increased interest in the production of gears by the net-shape forging technique. This has specific advantages over the traditional manufacturing processes of cutting gears such as hobbing, turning, and grinding including savings on cost and raw material, increased productivity, and gears with higher dynamic properties than conventionally cut ones.

In this study, precision forging of a particular spur gear has been investigated. The precision forging die set has been conceptually designed and modeled in a computer aided design environment. The forging process of

particular spur gear has been simulated by using a commercially available finite volume program. After the successful simulation results, the prototype die set and the tube-shaped billets were manufactured. The real-life experiments have been realized by using 1000 tons mechanical forging press available in METU-BILTIR Research and Application Center Forging Laboratory. The results have been compared with the computer simulations. After the real-life experiments, it has been observed that the conceptual die design is appropriate and near-net shape spur gears are successfully obtained by the proposed precision forging die set.

Keywords: Precision Hot Forging, Flashless Forging, Near-Net Shape Forging, Spur Gear, Finite Volume Method.

ÖZ

BİR DÜZ DIŞLİNİN SICAK HASSAS DÖVME KALIBININ TASARIMI VE UYGULANMASI

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Dövme endüstrisinde malzeme kaybını azaltmak, ürün kalitesini arttırmak ve dövme maliyetlerini düşürmek için yüksek bir ihtiyaç vardır. Geleneksel kapalı kalıp dövme işlemlerinde yaklaşık %30 oranında bir malzeme kaybı vardır. Bu yüzden, dövülen ürünlerin maliyetlerini düşürmek ve son ürün veya son ürüne yaklaşık ürünler elde etmek için yeni dövme metotları uygulanmalıdır. Hassas dövme, son ürün veya son ürüne yaklaşık ürünler elde etmek için maliyet etkinliği olan bir yöntemdir. Son yıllarda, hassas dövme ile dişli üretme üzerine artan bir eğilim vardır. Bu yöntemin diğer gelenek dişli üretme tekniklerine nazaran (azdırma, tornalama, taşlama), malzeme ve hammadde giderlerinde tasarruf, yüksek verimlilik ve yüksek dinamik özelliklere sahip dişliler üretme gibi avantajları vardır.

Bu alıřmada, belirli bir dz diřlinin hassas dvmesi zerine alıřılmıřtır. Kavramsal bir hassas dvme kalıbı geliřtirilmiř ve bilgisayar destekli bir ortamda modellenmiřtir. Dz diřlinin dvme iřlem sreci ticari olarak piyasada bulunabilen bir sonlu hacim programında simule edilmiřtir. Bařarılı simulasyon sonularından sonra, prototip kalıp seti ve boru řeklindeki ktk malzemeler imal edilmiřtir. Deneyler ODT-BİLTİR Merkezi Dvme Laboratuvarında bulunan 1000 tonluk mekanik pres ile yapılmıřtır. Yapılan deneylerden sonra, kavramsal kalıp tasarımının uygun olduėu ve nerilen hassas kalıp setiyle yaklařık son rn olarak dz diřlilerin bařarılı ile elde edilebildiėi gzlemlenmiřtir.

Anahtar Szckler: Hassas Sıcak Dvme, apaksız Dvme, Yaklařık Son rn Dvme, Dz Diřli, Sonlu Hacim Yntemi

To My Family,

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CHAPTER 1

INTRODUCTION

Forging is generally defined as the process of plastically deforming metal of a simple starting form such as bar, billet or ingot into desired shapes under great pressure. The process usually includes sequential deformation steps to the final shape. In forging process, the deformation energy is provided by exerting compressive force upon the starting forms or preforms. The compressive force may be provided by means of manual or power hammers, mechanical, hydraulic or special forging presses. The process is normally but not always, performed hot by preheating the metal to a desired temperature before it is worked.

Compared to all manufacturing processes, forging technology has a special place because it helps to produce parts of superior mechanical properties with minimum waste of material. Forging process 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. Forging products are free from undesirable internal voids and have the maximum strength in the vital directions as well as a maximum strength to weight ratio. In contrast to forging; in machining processes, end grains are exposed, leaving the part more liable to fatigue. Also in casting processes, process cannot prevent formation of certain metallurgical defects such as internal voids. Grain flow and directional strength is not observed as a characteristic of the casting process [1].

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 commons are shown in Table 1.1.

Table 1.1 Common Applications for Forgings [1]

<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • Mechanical power transmission equipment • Oil field machinery • Plumbing fixtures, valves and fittings • Pumps and compressors • Railroad equipment • 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
---	--

Comparing the economic investments of the manufacturing techniques; forging process is an expensive process considering the cost of the machinery and the die assemblies required. Thus, forging process is only economically attractive when large number of parts must be produced and/or when the mechanical properties required in the finished product can be obtained only by forging process.

1.1. Classification of Forging Process

There are various classifications applied for the forging process. In general, forging processes can be classified as:

- Forging Temperature: Hot Forging, Cold Forging, Warm Forging

- Type of Machine Used: Hammer, Mechanical Press, Hydraulic Press, Roll Forging, etc.
- Type of Die Set: Closed die, Open die

Classification of Forging Process According to the Temperature:

In hot forging, the billet is heated above the recrystallization temperature thus avoiding strain hardening. A greater degree of deformation can be achieved in a single operation than in cold or warm forging method.

The temperature of metals being cold forged may range from room temperature to the temperatures below recrystallization temperature. Small range of parts and materials can be utilized at cold forging. No shrinkage occurs. High forces are required.

Warm forging is performed with the workpiece heated to a range that is generally above the work hardening temperature and below the temperature at which scale forms. Compared with cold forging, warm forging has mainly the potential advantages of; reduced tooling loads, reduced press loads and increased steel ductility [2].

Classification of Forging Process According to Type of Machine Used:

The hammer is the most inexpensive and versatile type of equipment for generating load and energy to carry out a forging process. Therefore, it is the most commonly used forging equipment, especially in forging of steel, in small and medium size production factories. The hammer is an energy restricted machine. During a working stroke, the deformation proceeds until the total kinetic energy is dissipated by plastic deformation of the forging stock and by elastic deformation of the ram and anvil when the die faces contact with each other. A hammer or ram, delivering intermittent blows to the section to be forged, applies this pressure. The hammer is dropped from its maximum height, usually raised by steam or air pressure. Hammer forging can produce a wide variety of shapes and sizes. The disadvantage of this process is that; finish machining is often required, as close dimensional tolerances cannot be obtained [3].

In press forging, the deformation is achieved with the slow squeezing action of the press that penetrates through the metal and produces a more uniform metal flow. The squeezing pressure developed by the forging press differs from the impact pressure of a hammer. The energy exerted by the forging press increases in intensity as the metal tends to resist a change in shape. The maximum pressure is exerted at the end of the stroke.

The screw press, along with hammers and mechanical presses, is a widely used type of equipment for die forging in Europe. The screw press uses a friction gear, electric or hydraulic drive to accelerate the flywheel and the screw assembly and it converts the angular kinetic energy into the linear energy of the ram.

The mechanical forging press has proved to be an efficient machine, and the most widely used equipment for closed die forging. Mechanical presses are stroke restricted presses. The drive of the most mechanical presses is based on a slider crank mechanism that translates rotary into linear motion. The eccentric shaft is connected through a clutch and brake system directly to the flywheel as illustrated in Fig.1.1. The flywheel, which is driven by an electric motor and V belts, stores energy that is used only during a small portion of the crank revolution, namely during deformation of the forging material. The blow of a press is more like a squeeze than like the impact of a hammer. However, the initial cost of a press is much higher than with hammer, so that large production runs are needed.

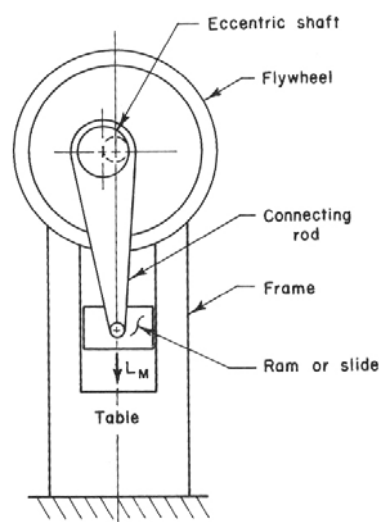


Fig.1.1. Schematic of a Mechanical Forging with Eccentric Drive [4]

The operation of hydraulic presses is relatively simple and is based on the motion of a hydraulic piston guided in a cylinder as illustrated in Fig.1.2.

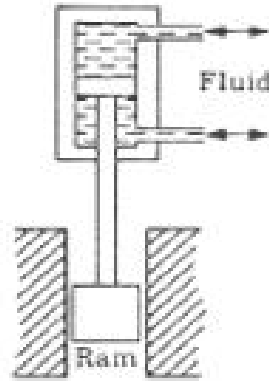


Fig.1.2 Schematic of a Hydraulic Press [4]

Hydraulic presses are essentially load restricted machines; i.e., their capability for carrying out forging operations is limited mainly by the maximum available load. These machines are used for both open die and closed die forging operations. In hydraulic presses the maximum press load is available at any point during the entire ram stroke. Since most of the load is available during the entire stroke, relatively large energies are available for deformation also within the limits of the machine; the ram speed can be varied continuously at will during an entire stroke cycle. Adequate control systems can regulate the ram speed with respect to forging pressure or product temperature. On the other hand within the capacity of a hydraulic press, the maximum load can be limited to protect the tooling and it is not possible to exceed the set load since a pressure release valve limits the fluid pressure acting upon the ram.

More information about these machines can be found in several publications [1, 3-6].

Classification of Forging Process According to Type of Die Set:

There are mainly two type of forging processes according to type of die set which are open die and closed die forging.

Open die forging is shaping metal by hammering or pressing it between flat or simple contour dies while manipulating the workpiece between blows. An open die forging process can be seen in Fig.1.3.

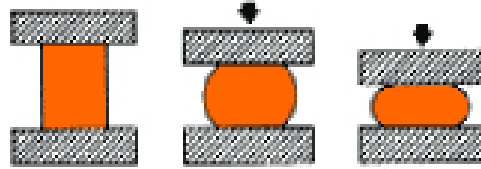


Fig.1.3 Open Die Forging Operation [1]

Closed die forging is the most common process of forging which accounts for the majority of forging production. In closed die forging, two dies are brought together and the workpiece undergoes plastic deformation until its enlarged sides touch the die side walls. Then, some material begins to flow outside the die impression, forming flash (Fig.1.4). The flash cools rapidly and presents increased resistance to deformation, effectively becoming a part of the tool. This builds pressure inside the bulk of the workpiece, aiding material flow into unfilled impressions [1].

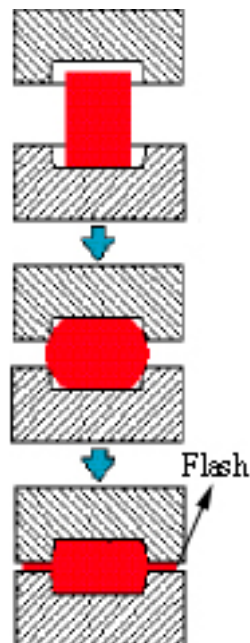


Fig.1.4 Closed Die Forging Operations [1]

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. Consequently one of the most important aspects of the closed die forging process is the design of preforms to achieve adequate metal distribution. With proper preform design, in final forging operation defect free metal flow and complete die fill can be achieved and metal losses into flash can be minimized [7-12].

1.2. Forging Process Design Considerations

Once the decision has been made to use forging for a particular component, there are several process variables that must be considered. Many times, these process variables will control various aspects of a forging design. By dictating the forging designs, many of the design criteria for the tooling are also established. The following is a list of some of the variables that will affect forging design and also the design of the die.

- The material selected for the forging
- Material properties desired in the forging
- Grain orientation
- Machining allowances
- Location of the parting line
- Part shape: ribs, webs and bosses
- Draft angles
- Determination of flash requirement
- Volume of flash
- Scale allowance
- Billet geometry
- Existence of internal cavities
- Preform geometries for forging process
- Forging load
- Dimensional tolerances for die block
- The quantity of the parts

In Fig.1.5; a presentation of drafts, ribs, machining allowances, edge radii and fillet radii are shown. Recommended values for these features are given in the related standard [13]. It should be taken into consideration that design of the dies requires past experience and skilled personnel.

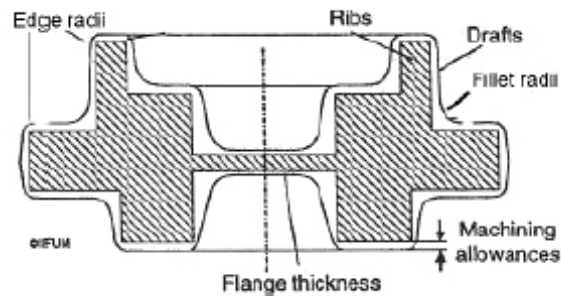


Fig.1.5 Forging Designs [12]

1.3. Forging Defects

Defects in forgings can be caused by several input variables. Classifications of some faults are presented as follows [8];

- Billet related; billet material chemical composition and microstructure, thermal and physical properties, billet cross-sections, length and lateral dimensions, billet temperature
- Die related; inaccuracies in the die geometry, die material and hardness, surface coating, die temperature, wrong preform dies, die temperature
- Mechanics of plastic deformation related; material flow, stresses, velocities, temperatures,
- Equipment used; production rate, force and energy capabilities, rigidity and accuracy
- Interface conditions; surface finish, lubrication, friction, heat transfer

Typical error source percentages have been acquired from AKSAN forging company, which is based in Ankara and presented in Table 1.2 [14].

AKSAN forging company has been working on hot forging more than 40 years and they have been hot forging steel products weighing 0.3 kgs to 32 kgs.

Table.1.2 Classification of scrap metal in forging according to fault types[14]

#	Fault Areas in Hot Forging	% to Total
1	Wrong design of the preform and forging dies	17.2
2	Trial forging processes	10.1
3	Lamination on the forging, emerging from preform design	9.4
4	Misalignment of die pairs	9.0
5	Wrong placement of the forging	6.9
6	Short billet size	6.8
7	Defect in the billet material	5.6
8	Unsuitable material properties (hardness, heat treatment, etc.)	5.4
9	Die fatigue	4.3
10	Inadequate metal flow in die cavity (incomplete impression)	3.5
11	Forging tilted during forging operation	2.9
12	Crack propagation on the billet during preforming operation	1.4
13	Others	17.5

If the table is evaluated, it can be seen clearly that wrong design of the preform dies is the most common fault in forging process. First and third most common faults in the list are directly caused by wrong preform design. The item number 10 is also related with the wrong design of the forging dies. This data clearly shows the importance of the preform design period both for economically and for loss of production time.

The second common fault is the trial forging processes which are made at the start of the forging process for making appropriate adjustments before starting forging operation. These faults are inevitable and must to be done to achieve a successful forging operation.

It can be seen from items 4, 5, 6, and 11, which are misalignment of die pairs, wrong placement of the forging, short billet size, and tilted forging during forging operations, which is 25.6% of the total error amount are caused by

operator faults. Consequently operator faults should not be left out of account and should be taken into consideration. This percentage also clarifies the importance of the operator's experience factor for the forging operation. To decrease operator faults some adjustments can be made in the forging die design.

The items 7, 8, 9 are related with the material properties of the dies or the billets. Other than these faults there can be some other problems like forging equipment errors, billet and die temperature, die lubrication, etc.

1.4 Scale Formation

Steel forgings are coated on the surface with a thin layer of iron oxide or scale, which caused by contact of the heated steel with air. Steel begins to oxidize at about 200°C; however, serious scaling, where substantial material may be lost and oxidized material spalls off the surface of the material, does not begin until the material reached about 850°C [15]. The amount of scale that is formed depends upon the forging temperature to which the steel is heated and the length of time of heating. The scale that is formed during the heating stage must be cleaned before placing the billet on the die; it helps to reduce die wear due to scale. Sometimes in the practice, the heated stock is being hammered or squeezed between the dies; hence, the formed scale begins to crack and separate from the forged material, and fall into the die. A scale allowance has to be applied to the calculations of the billet volume. Bruchanow and Rebelski [16] recommended the values given in Table.1.3 for the calculation of scale allowance. However, these allowances may change due to individual conditions of the used heating equipment and surface temperature of the billet.

Table 1.3 Scale Allowance Values [16]

Type of Furnace	Scale Allowance
Oil Box	4%
Gas Box	3%
Gas Continuous	2.5%
Electric	1.5%
Induction	1%

1.5 Introduction to Precision Forging

There is a strong need in forging industry to reduce waste of material, improve quality, and reduce cost of forgings. About 30% of the material is wasted during conventional closed-die forging. More competitive goods will be produced if the amount of flash is reduced and the dimensional accuracy of the product is improved. In order to reduce the cost of forged products and to obtain near-net or net shape parts, precision forging concept should be considered.

A form of closed die forging called as precision forging does not depend on flash formation to achieve complete filling of the die. Material is formed in a cavity that allows little or no escape of excess material, thus placing greater demands on die design. Precision forging is a closed die process and is largely associated with elimination of the features causing overtime work, scrap of excess material, etc., that arise from conventional forging practice. The objective of precision forging is to maximize the value added to raw material and by the means to produce finished products at lowest cost. Precision forging concept is discussed with details in Chapter 2.

1.6 Computer-Aided Design and Manufacturing (CAD/CAM) Applications in Forging

The conventional methods of designing forging dies are based on empirical guidelines, experience and intuition. However, developed computer-aided design (CAD), Computer-Aided-Manufacturing (CAM) and Computer-Aided-Engineering (CAE) methods may be used to;

- design the preforming dies,
- predict forging loads and stresses,
- manufacture the dies by NC (Numerical Control) machining

By using CAD/CAM software, the designer can create the 3-D model of the forgings, preform geometries, and the necessary dies. These provide the comfort of easily changing the parameters such as dimensions, taper angles, fillet radii, shrinking factor, etc. The designer can also point out the problems that may occur during the preforming stages by the help of the computer analysis

techniques; thus, reduces the cost and time [7-12, 17]. However, the experienced designer who should manage to design the process and dies properly is still essential in real-life applications.

Finite Element Method (FEM), which is one of the computer analysis techniques, is a widely used numerical technique for finding solutions in metal forming processes. Applications of finite element method include linear and nonlinear structural, thermal, dynamic, electromagnetic, and flow analysis. Some programs used as simulation packages which use this algorithm are ANSYS, MARK, DEFORM, FORM etc. [18-21]. By using these programs, metal flow, stress, strain and temperature distributions can be predicted.

Finite Volume Method (FVM) [22] is utilized in forging simulations. FVM is common practice for material flow simulations of events like; underwater explosion, helicopter ditching, large three-dimensional material deformation such as forging, extrusion, etc. Unlike a traditional FE mesh, which distorts while attempting to follow the deformation material, the mesh is a fixed frame of reference and material simply flows through the finite volume mesh. Forging typically involves large material flow as well.

MSC.Superforge [23] is based on finite volume rather than finite element technology. This finite volume technology is particularly suited for simulating the gross material deformations in forging operations, and at the same time completely eliminates the need for volume re-meshing techniques, commonly considered as the main bottleneck in 3-D forging simulations based on the finite element method [24].

1.7 Some Previous Studies in Forging

Some previous studies have been conducted on different types of forgings. As a Ph.D. study at University of Birmingham, Gökler [25] developed a computer program for the design of the operational sequences and the dies for horizontal forging machines. Alper [7] developed a computer program for axisymmetric press forgings, which designs the forging geometry and the die cavity for preforms and finishing operation. Kutlu [8] studied on the design and analysis of preforms in hot forging for non-axisymmetric press forgings. Karagözler [9]

studied on the analysis and preform design for long press forgings with non-planar parting surfaces. Gülbahar [10] studied on the preform design and analysis of hot forging process for a heavy vehicle steering joint. Civelekoğlu [11] studied on analysis of hot forging for three different alloy steels. Also Doege and Bohnsack [26] studied on different tool systems which allow manufacturing of straight and helical gears, connecting rods and alternator poles. In this study, based on practical experience with spring assemblies in order to provide the necessary closing force, an alternative closing device for forging dies is introduced.

In precision forging there are lots of studies that have been made. Dean [27] outlined net shape forging. He gave some examples on die design of precision forging. He also mentioned the advantages and told about the restrictions of the method. Vazquez and Altan [28] dealt with the preform design for flashless forging of a connecting rod and introduced a new tooling concept for forging of complex parts with a controlled amount of flash. Douglas and Kuhlmann [29] studied to produce highly accurate forgings which were only achievable by cold forging. Behrens, Doege, Reinsch, Telkamp, Daehndel, Specker [30] described the adopted methods and development process of a precision forging process exemplary considering a helical gearwheel and a crankshaft. Yoshimura and Tanaka [31] described the outline of a closed die forging equipment. Then they gave some net shape forming examples of steel and aluminum alloys. Finally the possibility of closed die forging was discussed. Shan, Xu, and Lu [32] mainly described the key problems in the precision forging of large and complex-shaped light alloy components. By means of a developed technique, several magnesium alloy and aluminum alloy forgings have been produced successfully.

There are also some studies which were developed related with precision forging gears. Dean [33] has completed many studies regarding precision forging gears. Dean described the background of the research on the forging of spur and helical gear forms with particular attention on the production of high quality gears for land transport application. Dean, Cai and Hu [34] dealt with the aspects of die design in the gear forging process. They discussed alternative tool designs which may be used on a press with only one moving slide and ejection system. They

examined the influences of different designs on the metal flow and load requirements through experiments and finite element simulation. The effects of friction on the loads and mode of metal flow are discussed. Hua, Wang and Liu [35] researched three design schemes with different die shapes in this study. Finite element method is used to simulate the cold forging process of the spur gear with two-dimensional axisymmetrical model, and the strain distributions and velocity distributions are investigated through the post processor. Three-dimensional simulation for the relatively better scheme is further performed considering the complicated geometric nature of gear, and the results show that the corner filling is improved and well-shaped gear is forged.

1.8 Scope of Thesis

As described in the previous sections, if the undesirable results of conventional forging can be eliminated, much more cost-effective products can be manufactured. Precision Forging concept is introduced to eliminate flash entirely or in-part. Between the studies accomplished in METU, this study would be the first precision forging study.

In this study, precision forging of a particular standard spur gear is examined. A precision forging die design is aimed to produce near-net shape spur gears with hot forging process by a single forging stage.

In Chapter 2, precision forging process is examined in detail. In Chapter 3, the proposed method and conceptual precision forging die design for a standard spur gear is presented. The sample part and dies will be modeled by using Pro-Engineer Wildfire III [36]. In Chapter 4, precision forging simulations of the particular spur gear is examined by using Finite Volume Method. In Chapter 5, design, manufacturing and assembly of the dies are presented. The real-life experiments are given in Chapter 6. Finally, general conclusions and suggestions for future works are given in Chapter 7.

CHAPTER 2

CHARACTERISTICS OF PRECISION FORGING

2.1. General Definition of Precision Forging

Precision forging is defined as a flashless net-shape or near net-shape forging operation using closed dies which generates high quality parts concerning surface quality and dimensional accuracy. The products of net-shape precision forgings are used directly without any machining operations. Generally cold or warm forging is applied to achieve net-shape precision forging. On the other hand, the products of near-net shape precision forging require simple machining operations after forging process. Compared to conventional forging, these machining operations require less effort and time. Also hot forging is generally applied in near-net shape forging.

In the past, precision forging processes have been industrially established for axis-symmetric parts, e.g. gear wheels and steering pinions. Further development of the technology to more complex parts, e.g. helical gears, connecting rods and crankshafts is expected to lead to a wider implementation into industry. Fig.2.1 shows variety of parts which were precision forged at the Institute of Metal Forming and Metal Forming Machine Tools of the University of Hannover and the IPH, Germany [30].

The advantages of precision forging can be listed as;

- Major material savings;
- Production efficiency is high with lower cost and good output, total production time is reduced;

- Largely eliminates the machining operation or reduces the material to be machined;
- Better strength properties due to unbroken fiber orientation after forging in case of elimination of machining;
- Cleaner workshop floor, no scrap metal, reduced pollution, environmental protection.



Fig.2.1. Some Precision Forged Parts [30]

2.2. Comparison between Precision Forging and Conventional Forging

The first important difference between precision forging and conventional is flash formation. In precision forging process, the preform is totally enclosed in the die cavity so that very little or no flash formation is allowed. Two different kinds of forged connecting rods which are precision forged and conventionally forged is shown in Fig.2.2.



Fig.2.2. Conventionally forged and precision forged connecting rod [15]

In conventional forging, flash formation directly affects the cost of the forging process. Considering the total cost of a forging, material costs are %50 of the total cost of the forging process [37] as illustrated in Fig.2.3. In forging process, it is convenient that the total material cost per forging includes;

- Net weight of the forging (forge weight),
- Waste material due to scale loss,
- Waste material due to flash,
- Waste material due to saw cut, etc.(cutting scrap) and bar end loss,

Among all the material losses, flash losses are the most important ones. Depending on the size of the forging, flash losses may be 5 to 30 percent of the whole part.

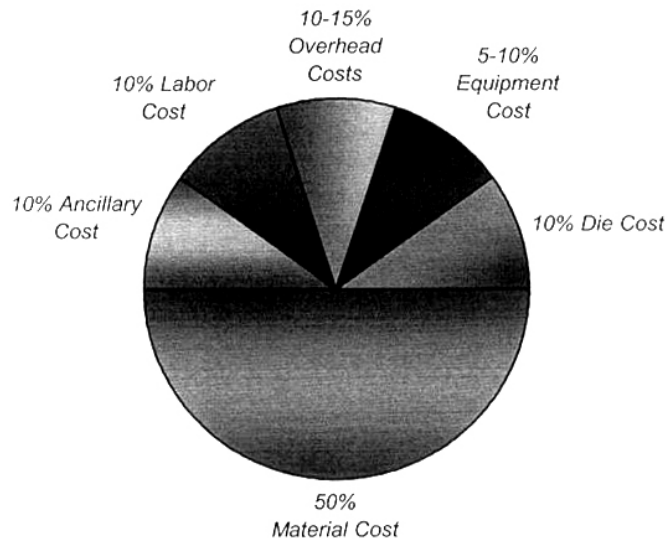


Fig.2.3 Breakdown of Total Costs for Steel Forgings [37]

Other than flash formation, the undesirable aspects of conventionally forged parts are mainly; draft, dimensional inaccuracy and poor surface finish. These can be eliminated entirely or partially by appropriate die design and tight control of process conditions, in other words precision forging.

In precision forging, careful planning of the size and shape of the billet is the most essential item in the precision forging process. Variation of the volume of the billet will directly affect the filling or underfilling of the cavity and

overloading on the tooling. Design of precision forging tools and carrying out the process are much more complex than conventional closed die forging with flash.

Accuracy of precision forging process can be affected by many different parameters. In the following sections, these parameters will be handled in three different categories which are;

- Precision forging process parameters
- Precision forging tool parameters
- Precision forging press parameters

2.3 Precision Forging Process Factors

The factors that should be taken into consideration by the designer and during forging process are;

- Billet volume
- Workpiece temperature
- Positioning of the billets inside the die
- Lubrication

a) Billet Volume:

Most important factor in precision forging is the accuracy of the billet volume. Variation of billet volume will cause variation in the filling of a die cavity or overloading on the dies.

In contrast to conventional forging, superfluous material cannot flow into the flash areas in precision forging, therefore if the billet volume is larger than the volume of finished product; overloading on the dies occur. On the other hand, if the billet volume is less than the volume of finished product; the die cavity will not be completely filled so the part will not be completed. On this occasion, underfill may occur in the part as illustrated in Fig.2.4. Consequently in precision forging, the billet should be manufactured such that volume or mass of the billet

should be extremely precise to avoid overloading on the dies or underfill on the part.

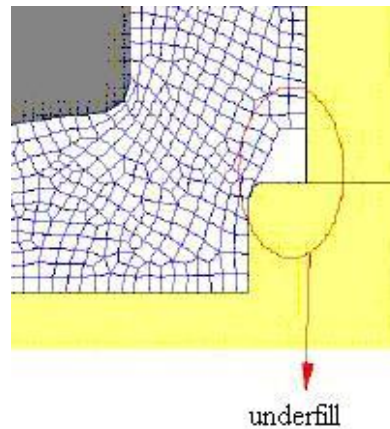


Fig.2.4 Underfill in the Forged Part

Calculation of the billet mass is made according to the final forged part mass and scale loss in case of hot precision forging. Thermal expansion should also be taken into consideration in case of hot precision forging process. Scale formation is presented in Chapter 1 in detail.

In precision forging, typically allowed mass variations should be between ± 0.5 and $\pm 1\%$ of the billet mass [26]. Each billet mass must be the same, within the tolerances and must be very tight controlled. To achieve this accuracy, every billet should be manufactured precisely and should be weighed by using a precision balance after the manufacturing of the billet.

The common practice of cropping of hot rolled bar is not suitable for manufacturing the billets for precision forging process. Volume variations are very high and tight volume control is not possible with this method. Instead of cropping, sawing cold rolled bar billets should be used to achieve much better dimensional control and accuracy. For some special cases, turning and grinding of billets are also considered.

b) Workpiece temperature:

Because of the thermal shrinking of the forged part, the forging temperature correlates directly with the forged part geometry and accuracy. Furthermore the forging temperature influences the flow stress of the material, the

deformability and, by thermal expansion, the volume of the billet during forging process, since the hot dimension of precision forging dies are designed according to the assumed workpiece temperature.

c) Positioning of the billets inside the die:

To guarantee a constant form filling of the whole die an exactly defined position of the billet inside the die is necessary. For the axisymmetric parts, the eccentrically located billet also affects the forging load. Fig.2.5 illustrates schematically the deformation of an eccentrically positioned cylindrical billet in a completely closed die cavity. The greater is the eccentricity, the greater forging loads to completely fill in the cavity [27]. To avoid these circumstances, extra precautions must be taken while positioning the billets inside the die. The process of positioning billets can be automated or the dies can be designed such that the operator faults are minimized.

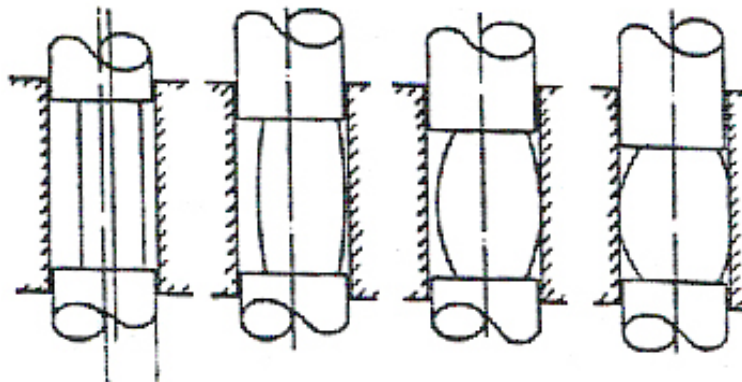


Fig.2.5. Deformation of an Eccentrically Positioned Cylindrical Billet [27]

d) Lubrication:

In general, lubrication during precision forging is important because it reduces the friction at the interface between workpiece and die. Reduced friction will decrease load and die wear, and aid die cavity filling. The lubricant will also cool the die surface, reducing the die wear by plastic deformation and ensuring a fairly consistent die temperature throughout the forging run.

Lubrication is also important in precision forging process, because very small (even zero), draft angles are used and lubrication will help the ejection of

the forging from the die permitting the use of smaller draft angles and in some cases allowing zero draft forging. To maximize the beneficial effects, an effective lubrication system should be relatively insensitive to temperature and pressure. Most important, it should be applied uniformly and consistently throughout a forging run. Hand lubricating, either by swabbing or spraying, should be avoided wherever possible [26, 27].

2.4 Precision Forging Tool Factors

With increasing demands on shape complexity and demands on the accuracy of the forged parts, the dies become more and more important factors for cost and quality of the workpiece.

There are some different variations of die sets that exist in precision forging process. In Fig.2.6, the tool concept proposed by IFUM-Institute for Metal Forming and Metal Forming Machine Tools, University of Hannover, Germany can be seen [30]. In this design, the punch enters into the closed die through integrated guiding assemblies. At the start of the process, the workpiece is inserted in the die set. In the next step, the tool closes initially without deforming the part, subsequently, the upper and lower die punches move into the die to form the hot material to its final geometry. After the complete filling of the form, the punches return, the dies open and the finished product can be taken out.

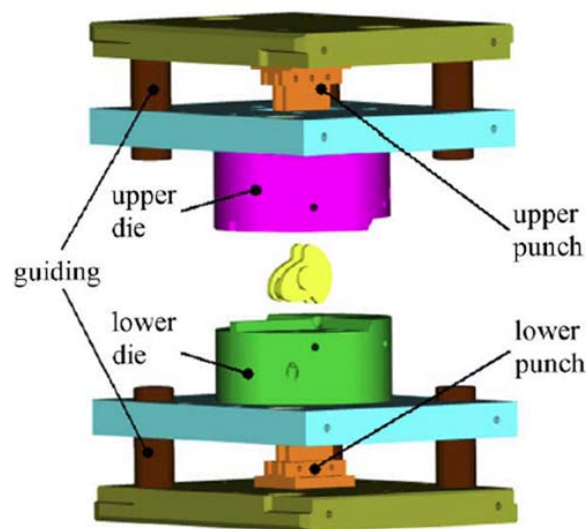


Fig.2.6 Tool Concept for Precision Forging [30]

In some other applications of precision forging processes; the upper die moves in to the die cavity to deform the workpiece as can be seen from Fig.2.7. In order to enter the die cavity, the upper die must have the same geometry of the periphery of the cavity. In Fig.2.7 and 2.8, the left of the picture shows the die set and the workpiece before the forging process and the right of the picture shows after the forging process.

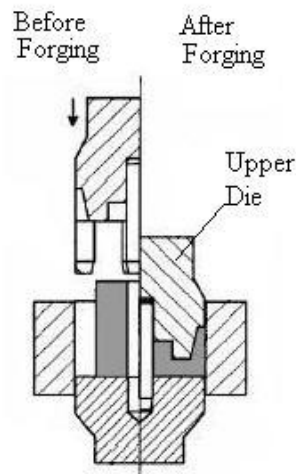


Fig.2.7 Penetrating Upper Die Precision Forging Die System [30]

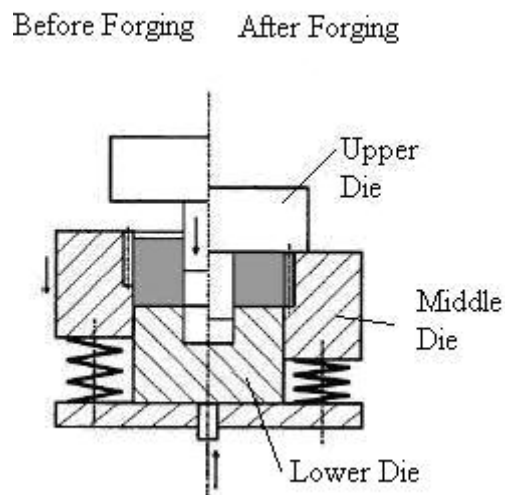


Fig.2.8. Sliding Middle Die Precision Forging Die System [30]

In Fig.2.8, the upper die, instead of entering into the die cavity, pushes the middle die downwards. Compared to conventional forging dies, precision closed die forging requires special attention to fulfill the following aspects.

a) Exact guidance of tool elements:

The dies should be accurately mounted onto the die holder before forging operation and should be inspected carefully. An exact guidance of the upper die and lower die is necessary to provide alignment, because of the small gaps between the dies when they are closed. Moreover, the accurate position of the die elements is important for the geometry of the workpiece. Slight faults at the guidance of the dies may cause defective products or severe damages in the dies and even may harm the press.

b) Constant die temperature:

Dies should be manufactured with an expansion tolerance. Thermal expansion of the precision forging dies decreases gap dimensions and can block precision forging tools. Regarding small tolerances of the dies and small gaps between relatively-moving die components, a constant die temperature is very important for a reliable die to function.

c) Die material:

Die hardness and toughness have great influence on die life. A die made of well-chosen material at proper hardness and toughness can withstand the severe strains imposed by both high pressure and heavy shock loads, moreover can resist wear and cracking. By applying complex heat treatment, optimum hardness and toughness values can be obtained.

Precision forging dies have smaller radii and have smaller tolerances compared to conventional forging dies. Smaller radii and narrower tolerances can generate cracks at high loads. Consequently extreme caution should be taken while choosing the die material for precision forging to overcome the risk of fracture in the precision forging dies.

2.5 Precision Forging Press Factors

The presses have to fulfill some special requirements for precision forging such as tool mounting space and ejector existence and its properties, to achieve a successful forging operation.

a) Tool mounting space:

With regard to the process and tool requirements for precision forging the mounting space for the tools between the anvil and the ram must be large enough for a tool system with closing elements and spring assemblies. These assemblies increase the height of the forging dies more than the standard height value. More detailed information will be given in Chapter 5. Furthermore, cooling and lubricating devices should be integrated into the press.

b) Ejectors:

Dies for precision forging usually have no draughts, so the forgings have to be completely ejected out of the die. The press which will be used for precision forging should have special equipment to eject the part completely after the forging operation is finished [34]. The technical properties of the ejectors are given in Appendix D.

CHAPTER 3

PROPOSED METHOD AND CONCEPT DESIGN FOR NEAR-NET SHAPE SPUR GEAR FORGING

Gears are important machine elements which are used for transmitting rotary motion (Fig.3.1). At the present time, gears are mainly manufactured by hobbing as can be seen from Fig.3.2, or by a combination of conventional hot forging and metal cutting.



Fig.3.1 Gears

Compared with the conventional methods, the precision forging process of gears brings many advantages, such as great reduction of material waste and machining time, therefore, considerable improvement of the productivity in the forging process and increase in strength properties of the gear teeth due to the microstructure of the forged gear. The precision forging has greater potential for

large quantity batch production, such as required by automotive companies. In recent years, there has been an increasing interest in the production of gears by net-shape and near-net shape forging technique. For applications where extreme high quality of tooth form is not necessary, such as automotive differentials, forged gear forms can be employed without further machining [35].

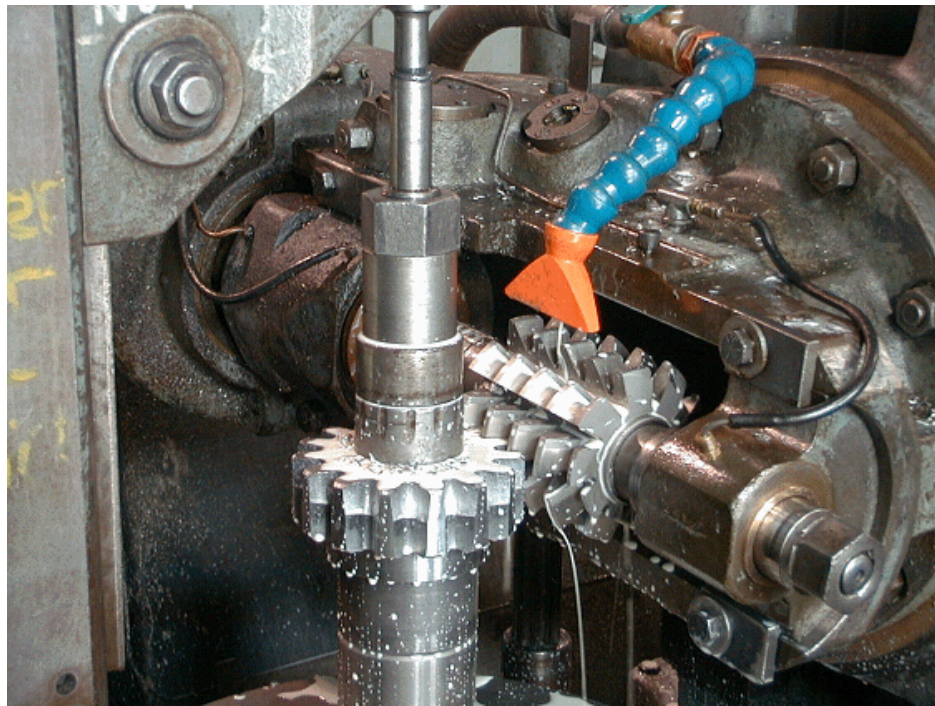


Fig.3.2. Conventionally manufacturing of gear by hobbing

3.1 Case Study for Precision Forging

As the case study, precision forging of a spur gear is analyzed. The spur gear with 16 teeth, module of 4 mm and pressure angle of 14.5° has been considered. The gear material is 16MnCr5 which corresponds to DIN 7131, and its properties are given in Appendix A. In Fig.3.3, the technical drawing of the spur gear which is selected for the case study is shown and in Fig.3.4, the 3-D model of the part can be seen.

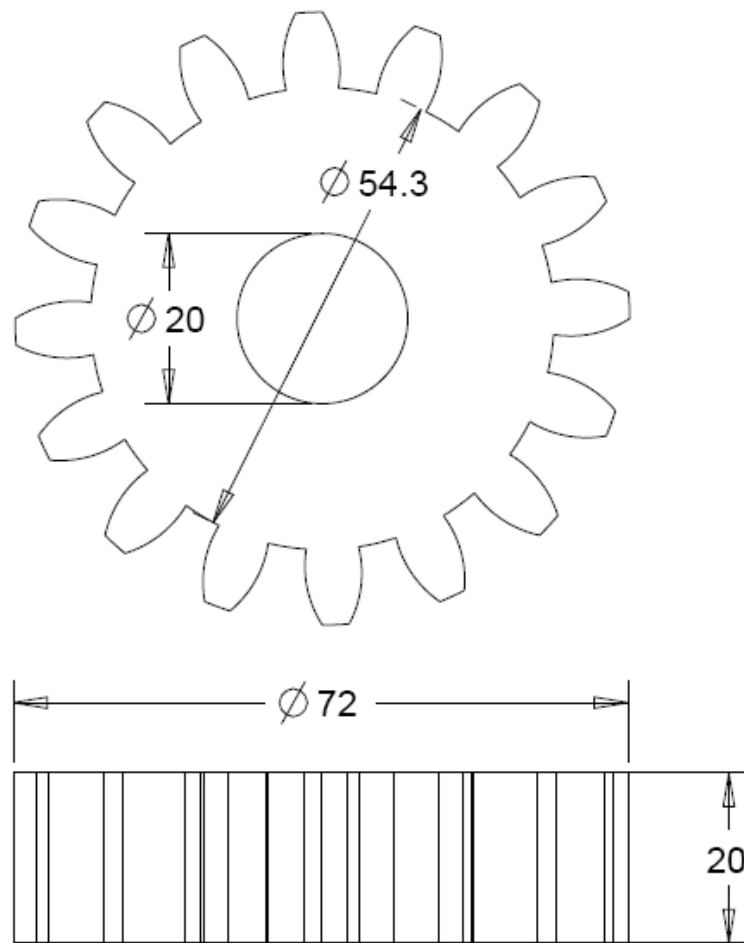


Fig.3.3. Manufactured Spur Gear with 16 teeth

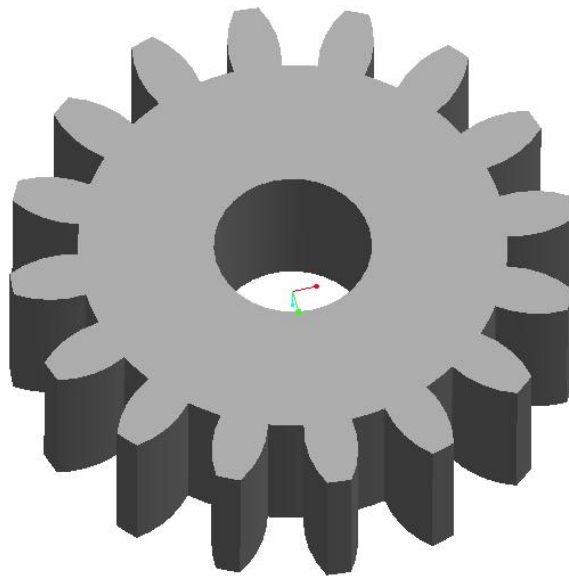


Fig.3.4. 3-D Model of the Manufactured Spur Gear with 16 teeth

Hot forging process of a particular spur gear is simulated for different configurations of die sets by using a commercially available finite volume program until an acceptable design is obtained with a successful filling of die cavity and no flash formation. Finite Volume Analysis of the particular spur gear is presented in Chapter 4. After the computer analysis was completed, the die set geometries were determined and the dies were manufactured in METU-BILTIR Center CAD/CAM Research and Application Laboratory, and experimental studies were conducted on 1000 tones mechanical press which is available in METU-BILTIR Center Forging Research and Application Laboratory. The dimensions, tolerance values and manufacturing details of the dies are presented in Chapter 5. In the following sections; billet preparation, proposed die design and die details are presented.

3.2 Billet Preparation

As mentioned in Chapter 2, billet preparation is very important in precision forging. For hollow parts like gears, billets are manufactured or purchased as tube, as illustrated in Fig.3.5, to achieve a net or near-net shape product, therefore eliminate the waste of material along the axis.

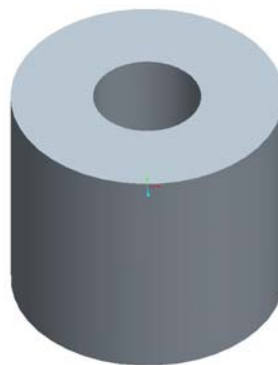


Fig.3.5. 3-D Model of Billet

The billet dimensions should be calculated according to volume of the gear before manufacturing the billets. The volume of the gear is obtained by using Pro/Engineer and the billet volume is calculated accordingly to this data. After the

manufacture of the billets, they are weighed on the precision balance to check if they are within the specified tolerance. The billets which are out of the desired tolerance are scrapped.

Although the required billets in the form of tubes are available in the market, the supplier of raw materials generally are not interested to sell small quantities. Since an experimental study with limited number of billets will be conducted, it is much more cost effective to manufacture the tubes from the solid bars instead of purchasing them.

The billets are manufactured in three operations. Firstly, the standard solid stock material with a length of 6m is cut by sawing process, and afterwards by drilling operation the holes on the billets are obtained, and finally by turning operation the billets are manufactured to their final dimensions. The dimensions and tolerance values in billets are presented in Chapter 5.

3.3 Proposed Precision Forging Die Design

Different die set alternatives which are mentioned in Chapter 2, are examined, and an adequate die set for the particular gear manufacturing is designed. The proposed die set of precision forging mainly consists of 8 parts as seen in Fig.3.6, which are;

1. Upper Die
2. Lower Die
3. Middle Die
4. Mandrel
5. Springs
6. Spring Adjustment Bolts
7. Ejectors
8. Restraining Bolts

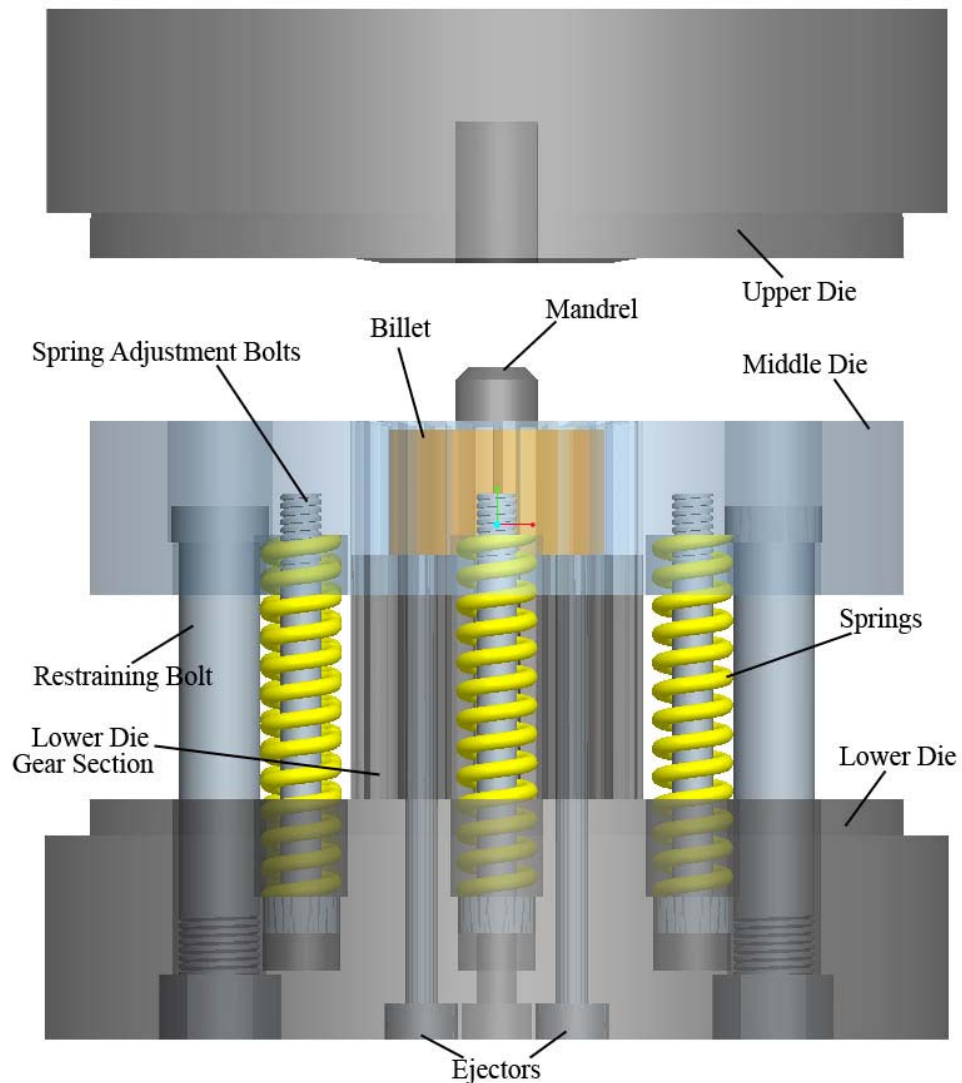


Fig.3.6. Assembly of Die Set

The main objective in the design is to have a completely closed die forging operation which does not allow any excess material to escape outside of the die and so that no flash formation occurs. The dimensions of the dies are given in Chapter 5. The proposed dies which are modeled in Pro/Engineer Wildfire III [36] also can be seen separately from Fig.3.7, Fig.3.8 and Fig.3.9. Moreover the description of the assembly during the forging process is presented in the next paragraphs.

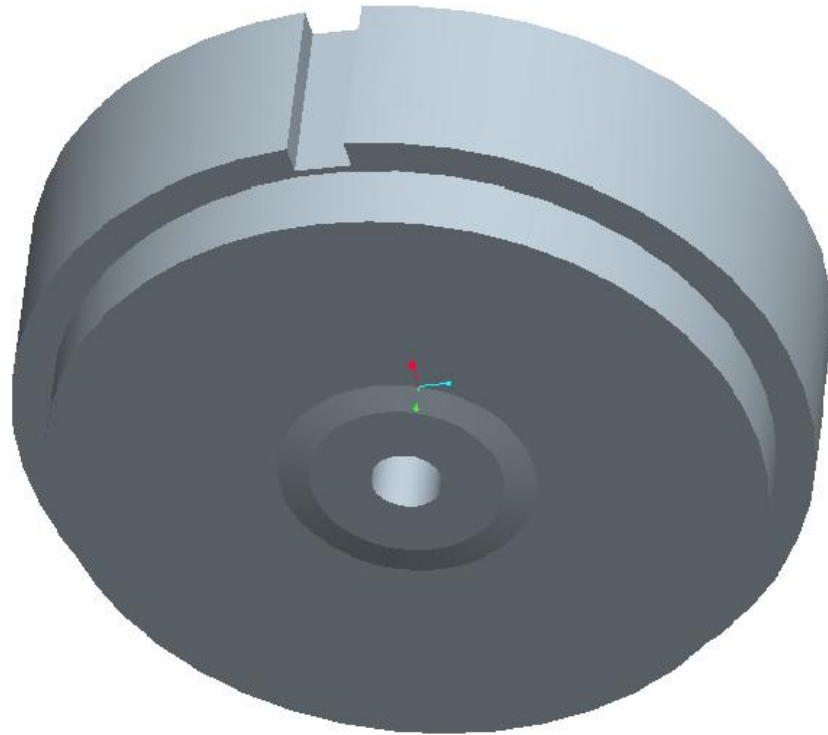


Fig.3.7. 3-D Solid Model of Upper Die

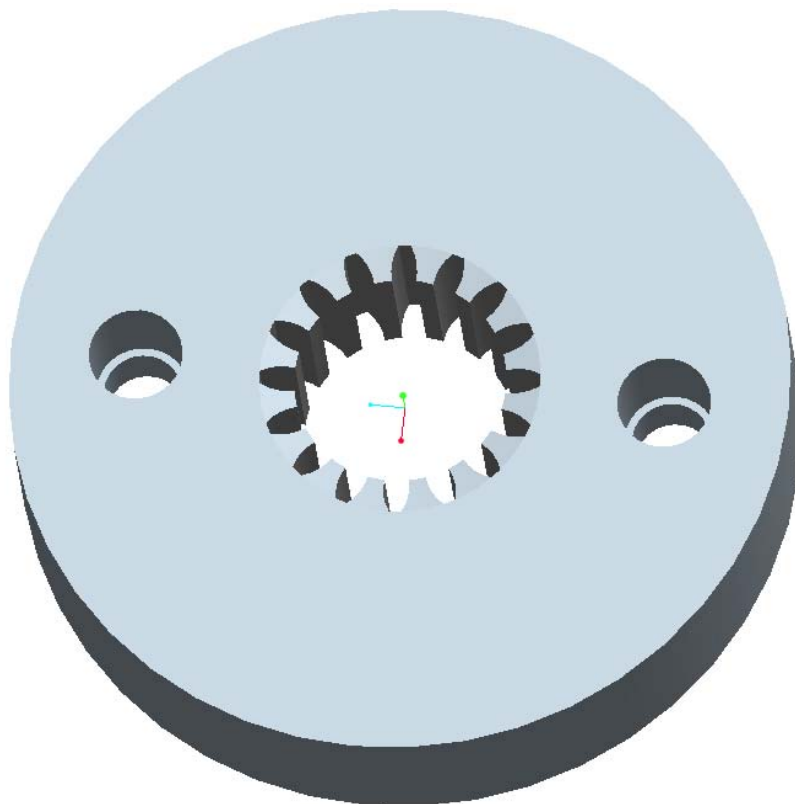


Fig.3.8. 3-D Solid Model of Middle Die

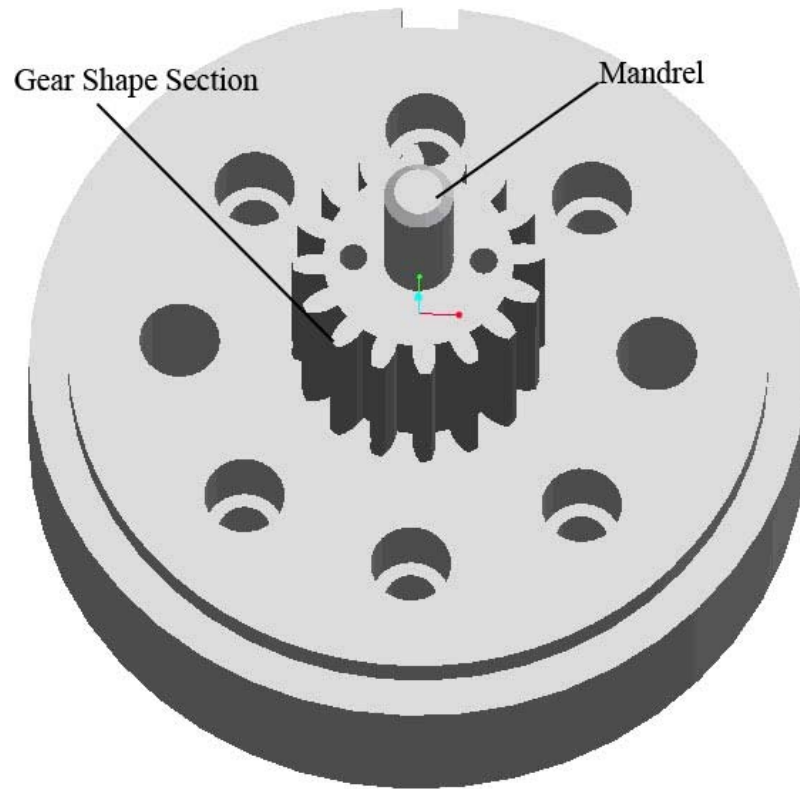


Fig.3.9. 3-D Solid Model of Lower Die

At the start of the forging process, operator places the heated hollow billet into the middle die and onto the lower die by the guidance of the mandrel (Fig. 3.10). Subsequently, the upper die which is mounted on the ram moves down. As the upper die moves down, it hits the middle die and starts to push it downwards; consequently they move together. When the upper die touches the billet, deformation stage starts and as the ram advance to the bottom dead center, the hollow billet deforms and takes its final shape (Fig.3.11). When the ram starts traveling from the bottom dead center to the upper dead center; the upper die ascends to its initial position. At this stage, the load on the middle die is released and by the help of the helical springs, the middle die returns to its original position (Fig.3.12). Restraining bolts are integrated into the assembly to prevent the middle die from moving upwards more than the desired value. Finally, the finished product is taken out with the help of the ejectors. There are two ejector pins present to eject the finished product from the die (Fig.3.13).

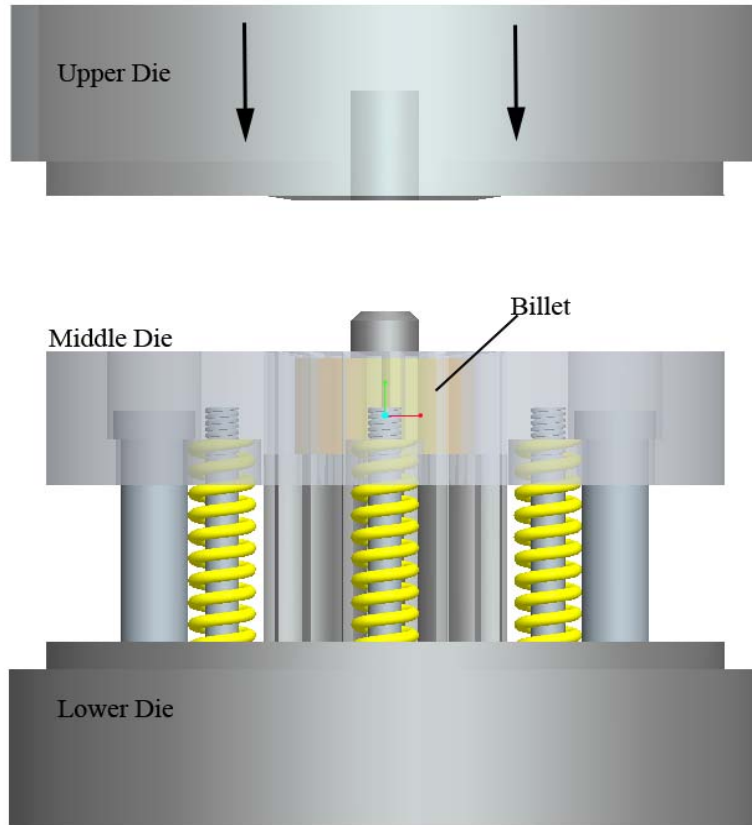


Fig.3.10 First stage in the precision forging process

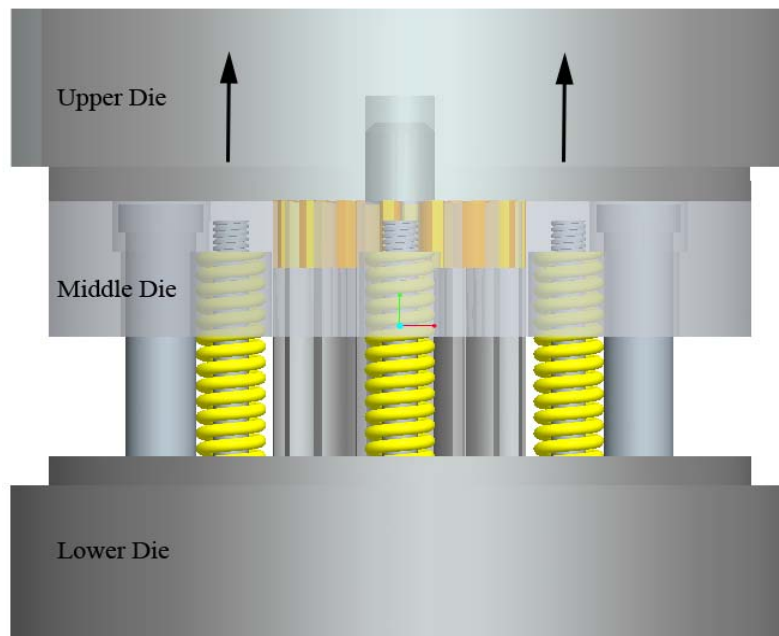


Fig.3.11 Second stage in the precision forging process

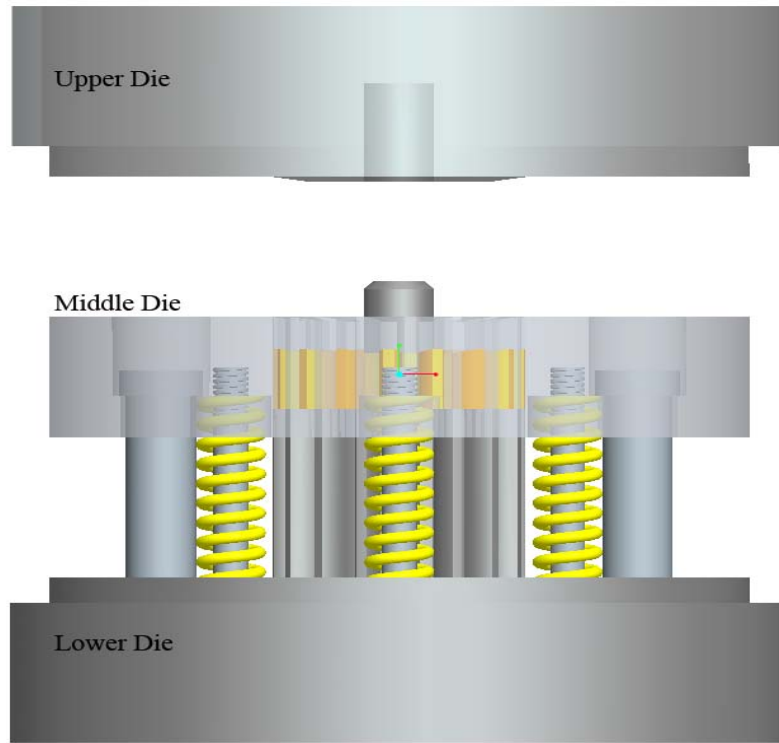


Fig.3.12 Third stage in the precision forging process

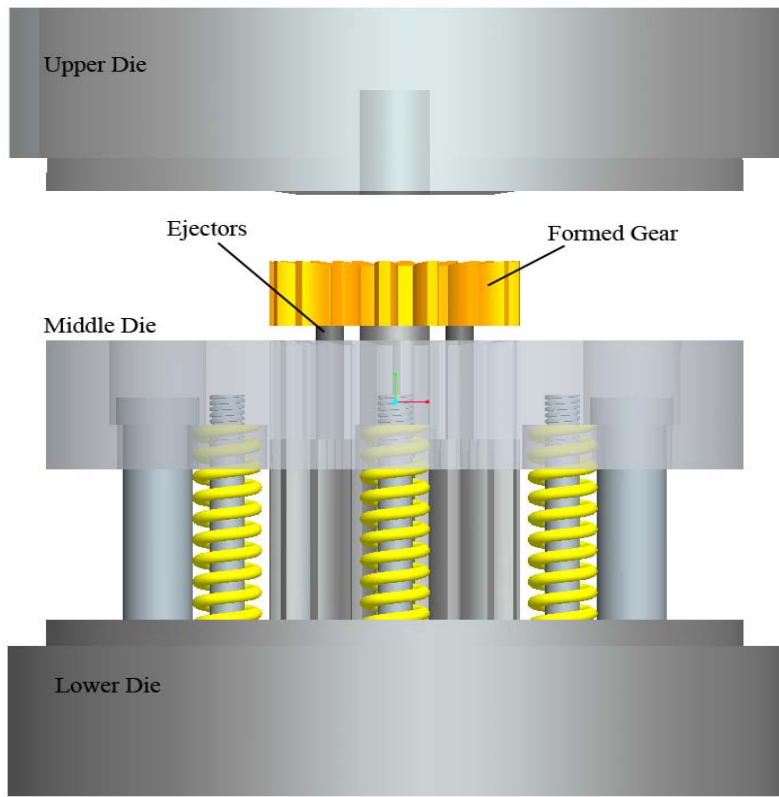


Fig.3.13. Fourth stage in the precision forging process

In the proposed design, six helical springs are used between the upper die and the middle die. The upper die does not enter into the die cavity, but pushes the middle die downwards, so that no tooth forms are needed on the upper die; a simple cylindrical shape is enough. The mandrel is integrated to the lower die as seen in Fig. 3.9, and brings difference from the previous designed methods which have been presented in Chapter 2.

3.4 Description of the Die Set

The description of the die set which is used to make a feasible design will be given in the following subsections.

3.4.1. Upper Die and Middle Die Assembly

The billet volume, accordingly billet mass, must be within very tight tolerance limits for each billet. Slight changes in the mass will cause imperfections on the forged part and consequently after forging process, the number of the scrapped parts will be very high. Producing billets with these tight tolerances affects the total cost of the forging seriously. If a little compensation space can be provided inside the dies to increase the tolerance requirements, the percentage of producing successful parts will increase and as a result of this, the forging cost will decrease. Considering this, chamfered sections are designed on the upper and middle dies as illustrated in Fig.3.14. The separate views of the compensation chamfers are shown in Fig.3.15. The process will be a closed die operation, but instead of net shape forging operation, it will be near-net shape forging operation. The production efficiency will increase in a considerable amount with the new design. Subsequently the forged part will transform to the part as illustrated in Fig.3.16. The chamfered section of the gear as seen in Fig.3.17 is an excess material. The formed chamfer will be removed after the forging operation with a very low cost, given that the full tooth volume is formed.

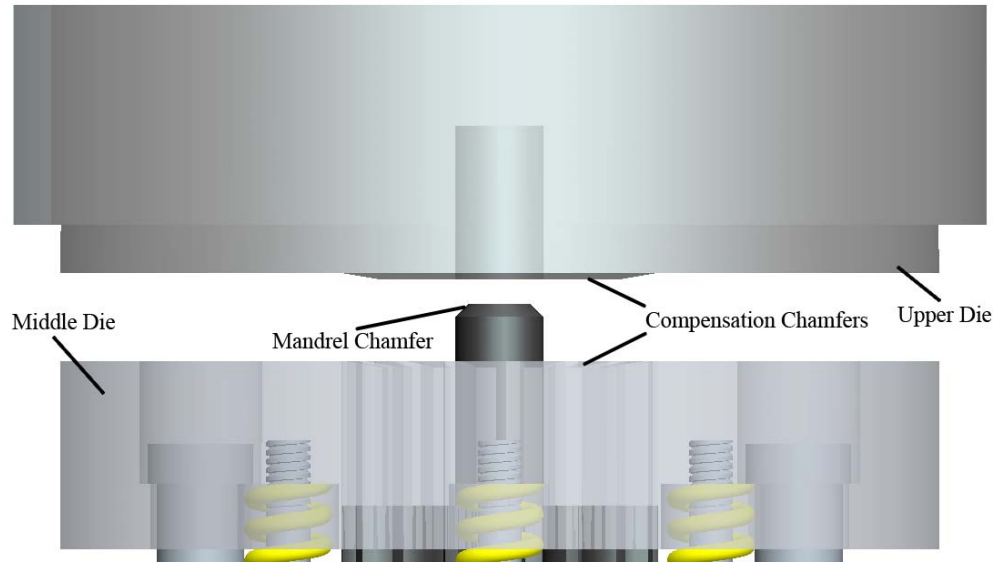


Fig.3.14. Upper and Middle Die Assembly

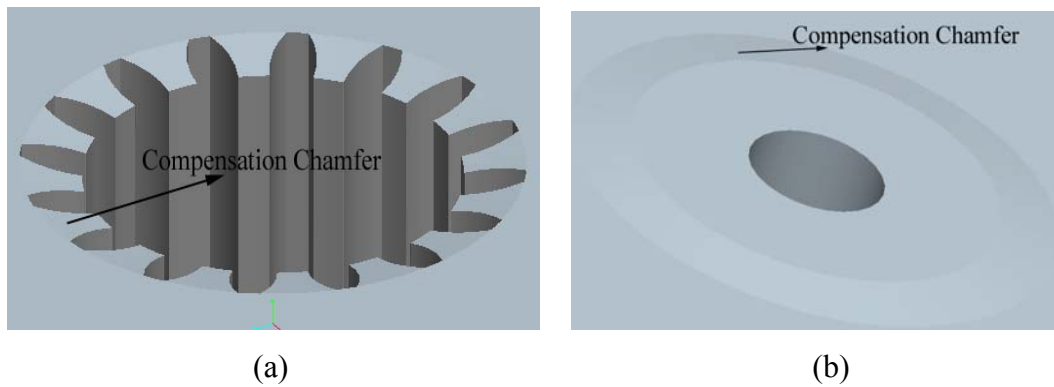


Fig.3.15. (a) Compensation Chamfer on the Middle Die and (b) Compensation Chamfer on the Upper Die

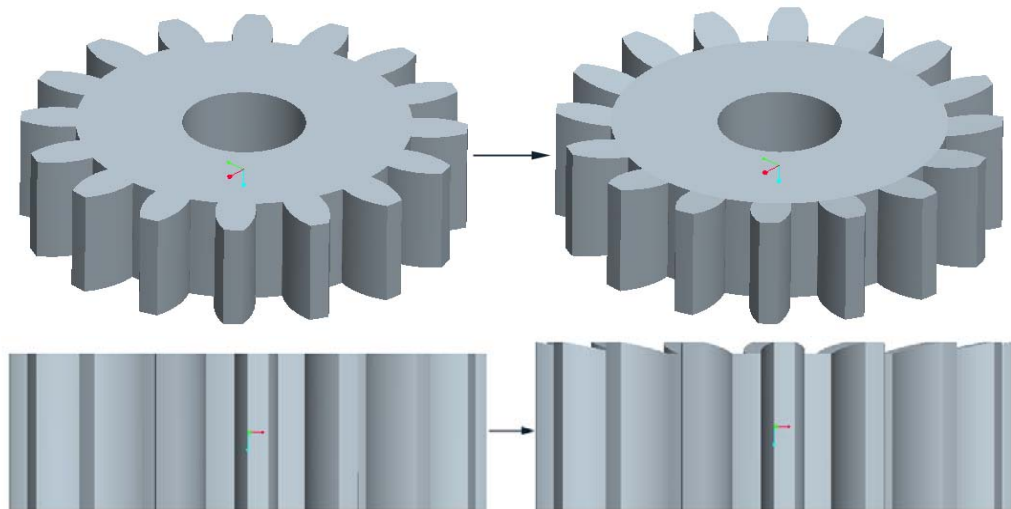


Fig.3.16. Forged Gear Model with Flat Dies and Chamfered Dies

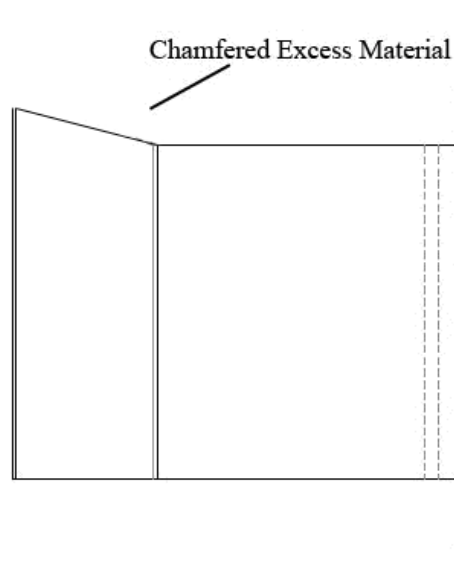


Fig.3.17 Chamfered Section of the Gear

Another important design consideration in the upper die and the lower die assembly is the guidance of the mandrel which will insert into the upper die during forging process. Just before the upper die hits the middle die, the mandrel enters to the cavity of the upper die. Positioning and the guidance of the dies are highly important. Slight adjustment errors of the dies before forging can cause the mandrel to hit the upper die. As illustrated in Fig.3.18, the mandrel is designed with a chamfer other than a complete cylinder. This partially helps the guidance of the mandrel to align the upper and middle die. The dimensions of the designed chamfer are given in Chapter 5.

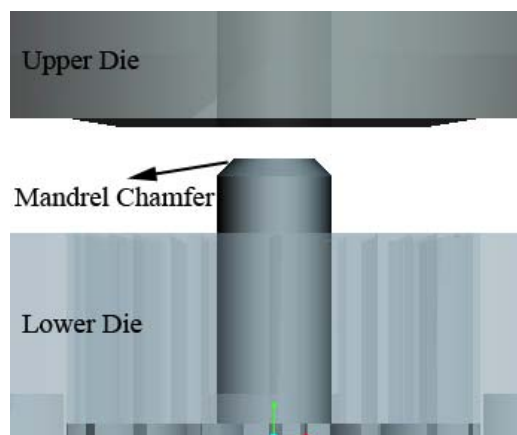


Fig.3.18. Mandrel Chamfer

3.4.2. Spring Assembly

As mentioned above, the lower die is stationary and the middle die is moving through the cavity of the lower die. The middle die and the lower die are assembled to each other by locating helical springs between them. In each stroke, the springs compress and then return to their original position.

According to the design, the role of the springs is lifting the middle die back to its initial position after the forging process. The springs also partially help to prevent sticking of the formed gear between the mandrel and the middle die at the end of the forging process. The spring material should be resistant to high temperatures because of the high temperatures during the pre-heating and the forging processes.

The diameters of the springs will affect the selection criteria because of the mounting spaces of the springs on the dies. Moreover the operating distances of the springs is also another criteria while choosing the appropriate spring because the selected operating travel should meet the stroke of the middle die in each forging operation. According to the required features, the springs are selected from ISO 10243 Die Springs, illustrated in Fig.3.19 [38]. For the specified diameter and operating distance indicated below at Table.3.1, the spring which has the maximum stiffness value is selected from the catalog.

Table.3.1 Selected Spring Features

Spring Constant	69,5 N/mm
Free Length	89 mm
Operating Travel	13 mm
Preload	2 mm
Total Deflection	15 mm
Hole Diameter	20 mm
Rod Diameter	10 mm

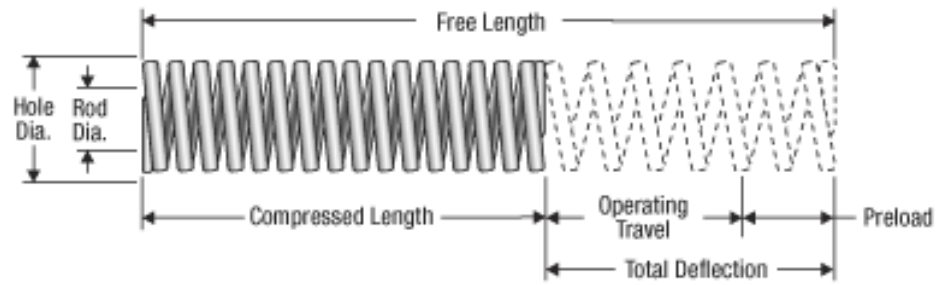


Fig.3.19. Die Springs [39]

In Fig.3.18, a die spring with its features can be seen. The free length is the length of a die spring before it is subjected to any operating force or load. The springs should be preloaded into the assembled tool to prevent the possibility of shock loading. The preload height is generally %5 of the free length. Operating travel should not exceed %25 of the free length. It is advised for long cycle life that, %17 of the free length should be used for operating travel of the spring [39]. Deflection beyond the safe limits may cause early spring failures. As it can be seen from Table.3.1, the selected spring's free length is 89 mm and its operating distance is 15 mm, consequently the operating distance is %17 of the free length.

The die springs are manufactured with ends ground and squared so that they stand on their own base and compress evenly under load. For the considered design, the springs are inserted inside the pockets at the middle die and the lower die (Fig. 3.20). These pockets help the spring guidance. Faulty spring guidance may cause buckling and possible spring failure. Each spring pocket needs to have a flat bottom, so the springs will work on a flat surface and provide uniform stress on each coil as it is compressed. Also in the occasions where more than one spring is used, each bottom surface of the spring should be on the same level of height to balance the dies.

In addition to these, there are spring adjustment bolts that exist inside the springs (Fig.3.20). These bolts protect the springs against fracture, moreover they permit the spring's lateral movement. These bolts are screwed to the middle die. When the middle die move downwards, the bolts move downwards too. A bolt gap is left in the lower die for the bolt head to move in and out during the forging stroke.

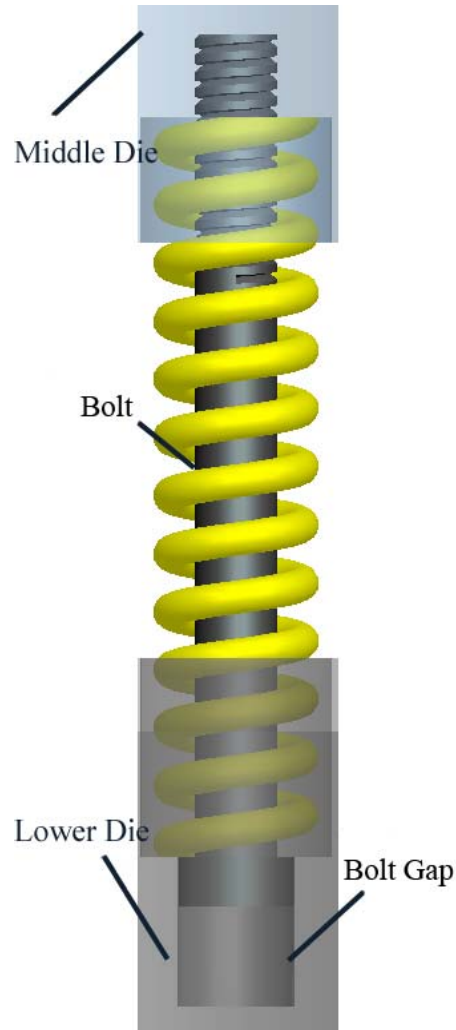


Fig.3.20. Designed Spring Assembly

3.4.3. Middle Die Restraining Assembly

After the deformation stage, upper die ascends to its initial position and consequently the force on the middle die is released. At this stage, the forces on the springs push the middle die upwards. To prevent the dislocation of the middle die from the assembly, restraining bolts are integrated into the die-set as can be seen from Fig.3.21. The restraining bolts are fixed by nuts in the lower die assembly and the bolt head is free in the middle die assembly. When the middle die and the upper die are moving as a unit downwards, the restraining bolt head rises in the bolt pocket. At that instant the force on the middle die is released, the compressing forces of the springs push the middle die upwards. By the help of the restraining bolts the movement of the middle die is limited. In addition to this,

at the ejection stage, while ejecting the formed gear out of the die-set, the possibility of the middle die rising up with the formed gear is overcome by the restraining bolts.

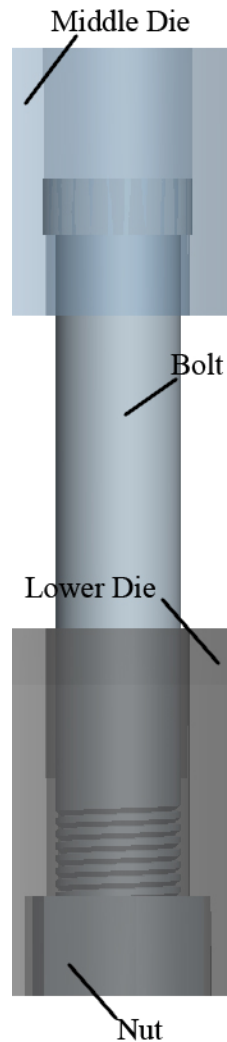


Fig.3.21 Middle Die Restraining Assembly

3.4.4. Lower Die Assembly

The lower die consists of three modules as illustrated in Fig.3.22 which are;

- Mandrel
- Gear shaped section
- Base

These three modules will be manufactured separately and will be assembled. With the help of the modular design, the modules can be changed in the case of die wear or fracture without re-making the whole lower die. Also design modifications can be made like; increasing the mandrel diameter or height, increasing the number of ejectors, etc, by changing the modified module(s).

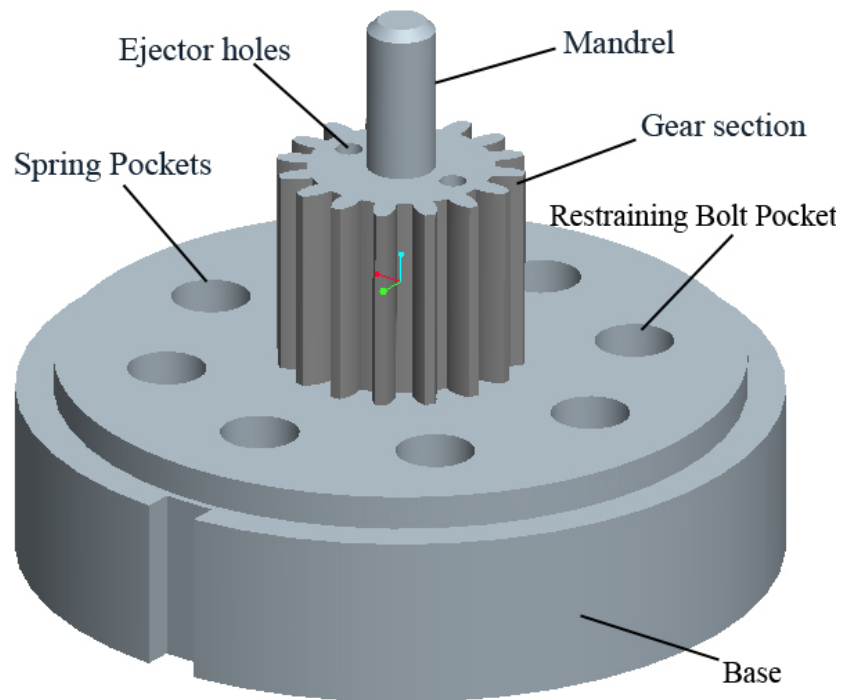


Fig.3.22. A view of Lower Die Assembly

The mandrel is fastened to the gear section through the base section with a bolt as can be seen from Fig.3.23. The gear section will also use the same bolt to be assembled to the lower die. The bolt is fastened to the mandrel tightly. When the bolt is fastened, it both fixes the mandrel and the gear section to the base. Also the bolt partially restricts the possible rotation of the gear section's rotation. Actual restriction of the gear section's rotation is made by ejector pins. Two ejector pins present in the design. Other than ejecting the finished product from the dies, the ejector pins permit the rotation of the gear section on the lower die. Ejector pins are placed through the base section and then gear section.

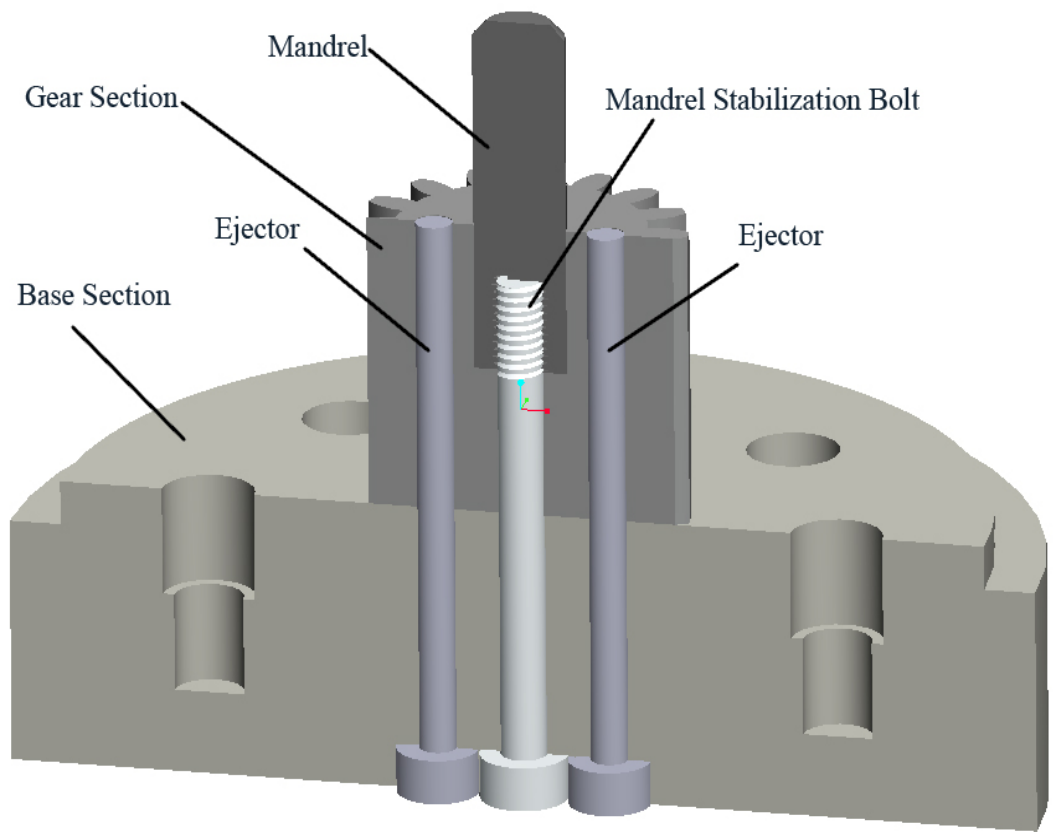


Fig.3.23. Section view of the lower die



Fig.3.24. A view of Mandrel

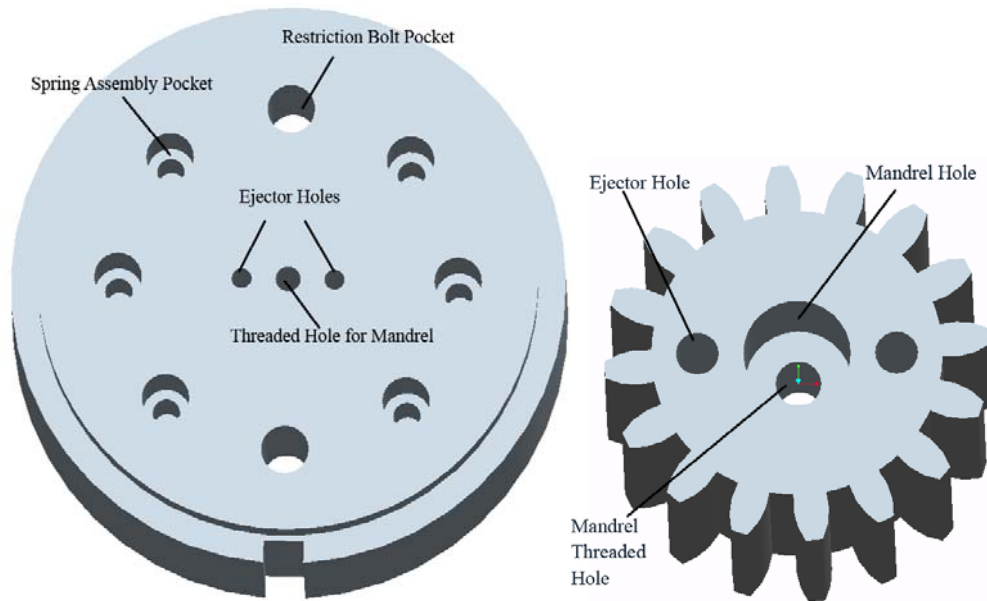


Fig.3.25. Base section and the gear section of the lower die

In Fig 3.24, the mandrel can be seen. At the bottom surface of the mandrel, a threaded hole is made for the assembly. In Fig.3.25, the base section and the gear section of the lower die can be seen. The ejector pins are inserted through the base section and then through the gear section of the lower die. The bolt is inserted through the middle holes in both sections for fixing the mandrel; consequently, both sections should be manufactured precisely to avoid the misalignments of the sections in the die assembly.

The mandrel is useful for aligning the billet in the precision forging dies. As can be seen from Fig.3.26, during the forging process the operator places the billet with the guidance of the mandrel, on to the lower die. Mandrel, by guiding the billet, minimizes the eccentricity caused by the operator and as a result of this, the errors caused by the operator are brought to the acceptable limit which is the gap distance between the central hole of the billet and the mandrel of the lower die as illustrated in Fig.3.27.

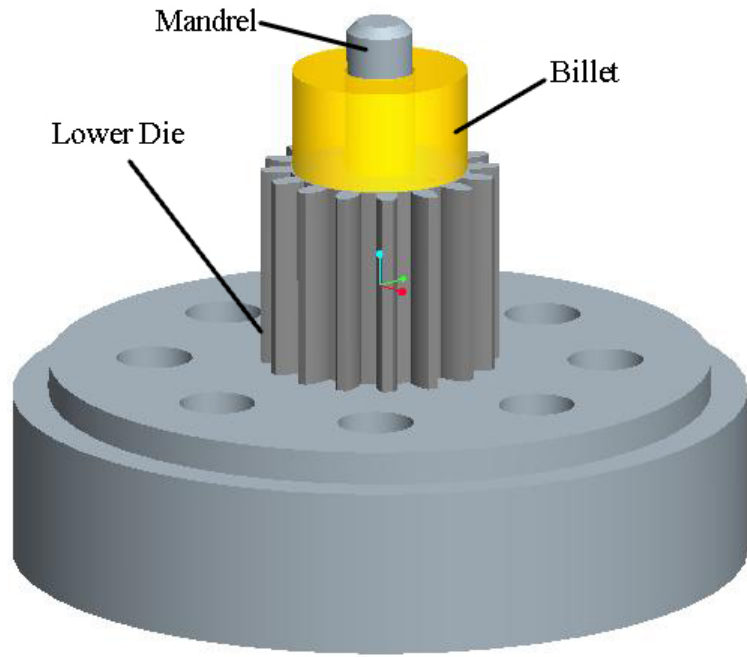


Fig.3.26. 3-D Model of Billet-Lower Die

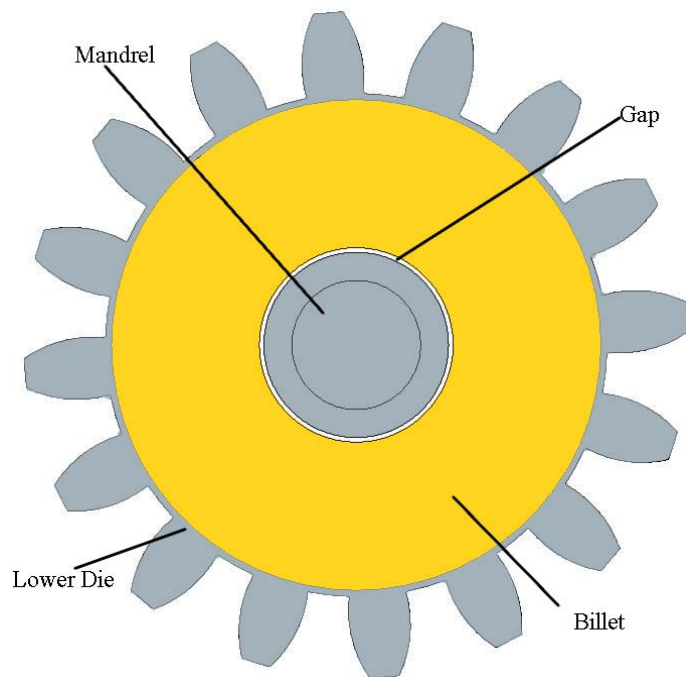


Fig.3.27. Billet and Lower Die Top View

CHAPTER 4

DIE FILLING SIMULATIONS OF A PRECISION FORGED SPUR GEAR

The design of the dies and the selection of the process parameters in forging processes are still performed to a large extent by trial-and-error methods in industry. In many cases, this trial-and-error procedure is neither optimal nor cost effective in terms of achieving the desired properties in the finished product. With the development of numerical analysis techniques, the finite element method was introduced in the early 1980's as a possible alternative. The finite element method has been extensively employed by several research groups [40]. However, in some applications, the finite element method may not meet the highest standards for industrial acceptance [41], e.g.:

- The prediction of metal flow, stress, strain and temperature distributions requires accurate and robust algorithms. Since the process of forging is typically characterized by gross 3-D material deformation and continuously changing boundary conditions, its complexity requires much simulator expertise and sometimes "tricks and tweaks" to produce a full solution.
- It may be required that the user must complete studies in relatively short calculation times. However, finite element methods are relatively time consuming to use. Even rather than simple 3-D applications can take several days on a workstation.
- Finite element meshes usually get over-distorted; auto-remeshing is then necessary to complete the simulation. But the auto-remeshing technology

for three-dimensional problems is not so robust and also very time consuming [42].

- Even for two-dimensional elastic-plastic problems, the remeshing may lead to erroneous result [43]. Each remeshing step will involve quite a lot of loss in volume, which is not acceptable for forging simulations.

With the above challenges in mind, new software started performing forging simulations with finite volume method, a 3-D analysis code for analyzing highly nonlinear, short-duration events involving the interaction of fluids and materials. It appeared that the finite volume method is well suited for 3-D forging process [44]. Finite Volume Method has been used for many years in analyzing the flow of materials in a liquid state. However, in recent years, some codes for computer simulation of solid state metal forming operations, such as MSC.SuperForge, have been established on the basis of this method. In the Finite Volume Method, the grid points are fixed in space and the elements are simply partitions of the space defined by connected grid points. The material of a billet under analysis moves through the finite-volume mesh; the mass, momentum, and energy of the material are transported from element to element. The finite volume solver, therefore, calculates the motion of material through elements of constant volume; therefore no remeshing is required [45].

4.1 Modelling of Billet for Finite Volume Method

To calculate the dimensions of the hollow billets, the particular spur gear geometry which is aimed to be obtained at the end of the Finite Volume Analysis is used. The geometry is modelled and volume of the part is calculated by using Pro/Engineer Wildfire III. According to the volume of this geometry, the hollow billet dimensions which are used in the analysis are obtained. It should also be noted that, the hollow billet diameters should match with the standard tube dimensions that can be provided from the suppliers for mass production.

In this study, as explained above, MSC.SuperForge is used for the simulation and analysis. There are some common process parameters that are identical in all the simulations in order to obtain accurate results such as;

simulation type, the properties of the material used, the ram speed, the initial temperature, and the friction coefficients. After identifying these parameters, appropriate billet dimensions, which does not cause any faults such as buckling and early flash formation, are tried to be obtained.

In the following section, the process parameters for MSC.SuperForge and the simulation results for the particular spur gear geometry are presented.

4.2 MSC.SuperForge Simulation Process Parameters

In the first step of the simulation in MSC.SuperForge, the process type is selected from specific process types such as; open die forging, closed die forging, upsetting, gear forming, extrusion etc. “3-D Hot Gear Forming process” is selected for this study.

After the process selection, the models for upper die, lower die and billet geometry are imported to MSC.SuperForge in STL (stereolithography) format. In this format, the surface models consist of triangular shaped facets only. It should be noted that MSC.SuperForge requires a closed-volume surface model for both workpiece and dies. MSC.SuperForge treats the die models as rigid bodies; thus, the external geometries of the die sets are not modelled exactly as the real ones. As any deformation until the upper die hits the middle does not happen, the upper die and the middle die are modelled together for the Finite Volume Analysis, as can be seen from Fig.4.1.

In the finite volume simulations, the spring force is neglected, since it is small compared to the deformation force of the billet. Moreover the springs are used for lifting the middle die to its initial position as mentioned in Chapter 3. This stage is not simulated in this study; neither the ejection process of the finished product from the die is simulated in this study

In MSC.SuperForge, forging operation direction is aligned on the Z axis, therefore, after importing the models for the dies and the workpiece, the position of them with respect to each other and the forging direction may not be correct. These models are firstly aligned along the Z axis with using “Moving Option Toolbar”. Once the objects are aligned along the Z axis, the user can position the dies against the workpiece in initial contact by using “Positioning” option. During

the positioning, dies move until they are in contact with another object. The alignment of the dies and the workpiece and initial position of them are shown in Fig.4.1.

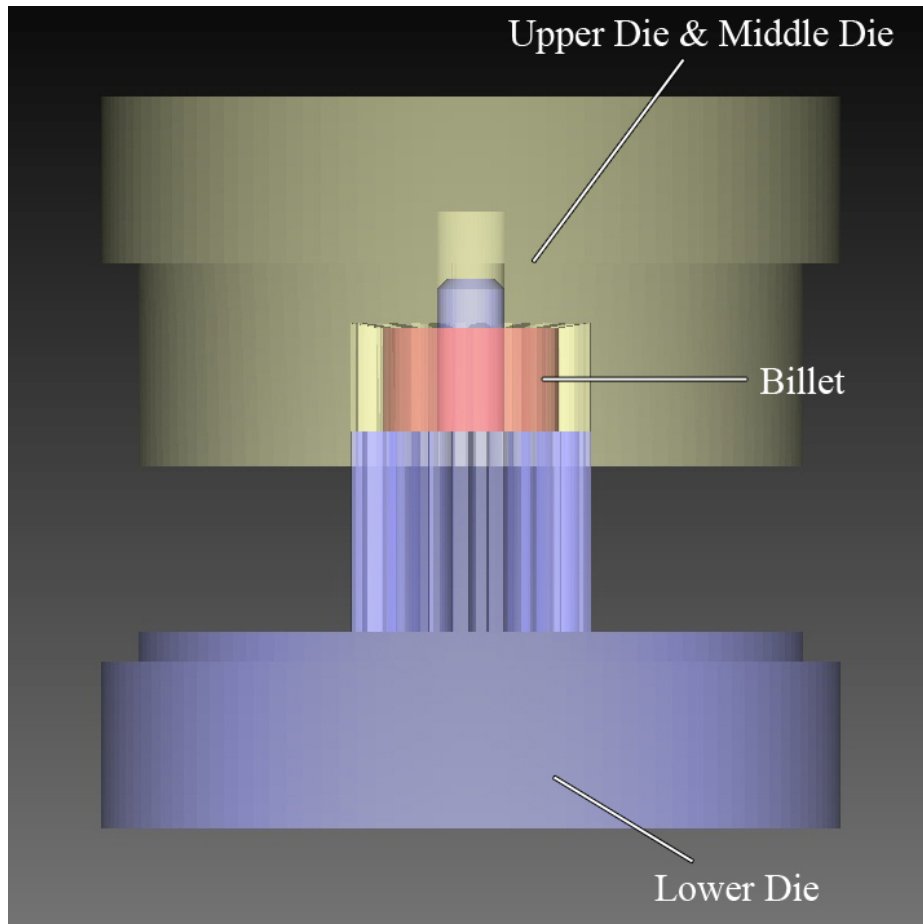


Fig.4.1 MSC.SuperForge Assembly

In another step, the material for the workpiece is defined. Since the dies are considered to be rigid bodies in this study, a material model needs to be defined only for the workpiece. There are the forging specific material models available for either cold or hot forging operations in the material library of the software. MSC.Superforge provides elastic-plastic models for workpiece material. In this study the workpiece material is 16MnCr5 which corresponds to DIN 1.7131. Fig.4.2 shows the workpiece stress-strain curves at constant temperatures of 1000°C and 1100°C for three different strain rates [46]. For the other temperatures, the program interpolates or extrapolates the values.

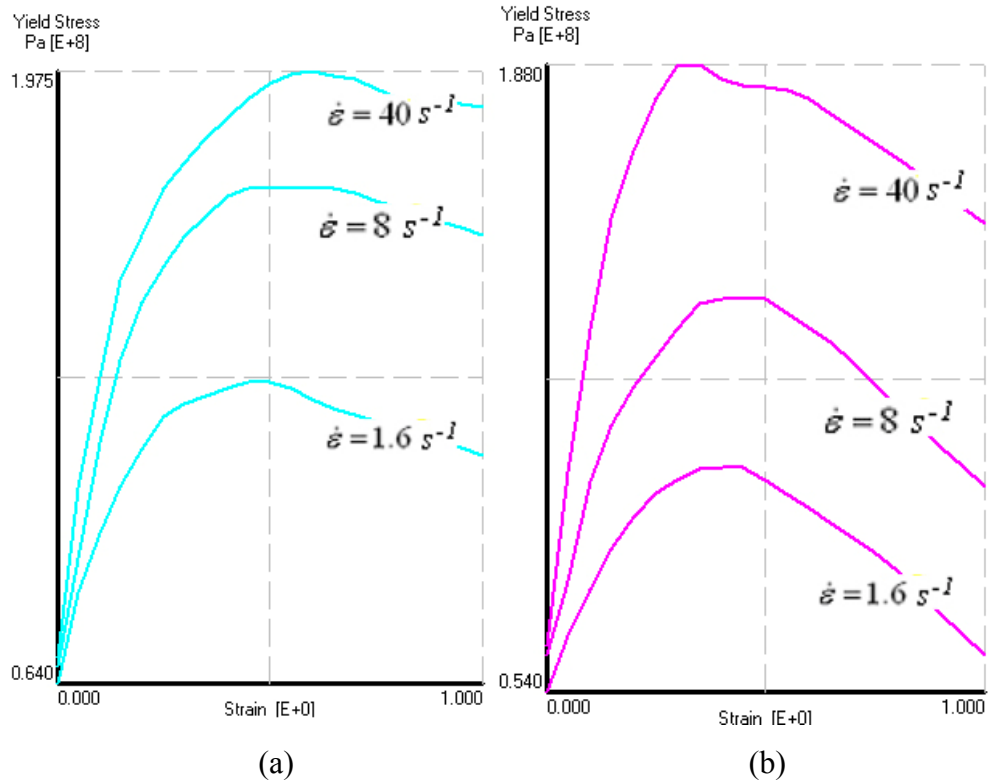


Fig.4.2 Workpiece material (16MnCr5) stress-strain curves at (a) 1000°C and (b) 1100°C at different strain rates [8]

The initial temperatures of workpiece and dies have great effect on the simulation of hot forging process as they influence the plastic behavior of materials. In industry, the dies are generally preheated before using in hot forging process. The initial temperatures of the billet in this study are taken as 1000°C, 1050°C, 1100°C and 1150°C. Initial temperature of die is assumed to be 250°C.

Other parameters that are used for the simulation related with temperature are;

- Ambient temperature: 25°C
- Heat transfer coefficient to ambient: 50 W/m².K
- Heat transfer coefficient to workpiece: 6000 W/m².K
- Emissivity for heat radiation to ambient: 0.25

Ambient temperature is taken as 25°C since induction heater is being used close to the press. The other values are taken as the default values taken by MSC.Superforge [52].

In the next stage, the forging equipment used in the process is selected. The software has six different types of forging machines that any of which can be applied for forging simulation; these are Mechanical Crank Press, Multi-Blow Hammer, Screw Press, Hydraulic Press, Mechanical Press with Scotch Yoke Drive and an alternate press defined by a table of time vs. speed. The Mechanical Crank Press type, which is available in METU-BILTIR Center Forging Research and Application Laboratory, is used in this study, the required data is entered and these definitions are assigned to the upper die-middle die assembly in the software. The entered data are given in Table 4.1 and the schematic view of the mechanical press can be seen in Fig.4.3.

Table.4.1. Properties of forging equipment

Type of Press	Mechanical Crank Press
Capacity of Press	1000 tonf
Crank Radius (R)	110 mm
Rod Length (L)	750 mm
Crank Speed (w)	100 rpm

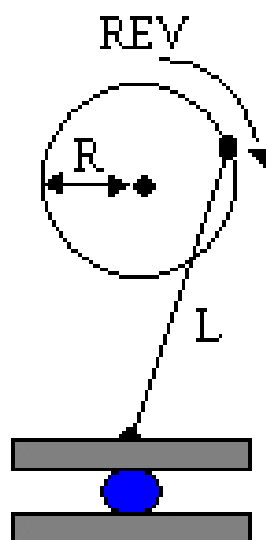


Fig.4.3 Input Parameters for 1000 tonf Mechanical Press

By applying the parameters given in Table 4.1, the velocity of the crank press can be obtained during its operation. Fig.4.4 shows the velocity of the press as a function of time. At the beginning and at the end of press operation the velocity is zero. The maximum velocity of the press is 1.164 m/sec after 0.15 sec of press operation.

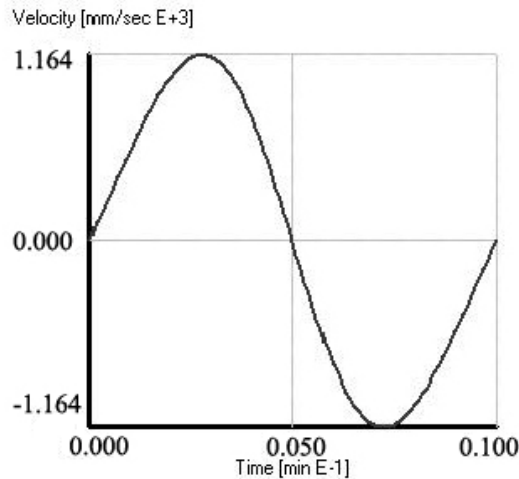


Fig.4.4 The velocity of the mechanical crank press as a function time

In the next step a friction model is applied to both of the dies. The friction always plays a particularly important role in metalworking processes. The properties of interface friction are very complex; for such friction is not only constant during the forming processes but it is also a function of the working parameters such as strain, strain rate and temperature [47]. However, in MSC.Superforge just one friction type can be applied to each die and this will be constant for all surfaces of the dies. For forging operations involving relatively high contact pressures, it is suggested by the MSC.SuperForge manual and previous studies to use plastic shear friction with a value of 0.2 [7-13]. Therefore, this suggestion is applied for simulations.

In the final step before starting the simulation for die filling analysis and determining the exact billet diameter, stroke of the upper die after contacting the workpiece, size of the finite volume workpiece element, output step size (as percentage of the process time or in defined stroke step sizes), are selected. Also, a solver optimizer is implemented in the simulation control unit; thus, the user can

change finite volume element size at any time and also coarsen the workpiece to decrease the number of elements. The parameters used in this step are given in Table 4.2.

Table.4.2.MSC. Superforge Simulation Parameters in Finite Volume Analysis

Workpiece element size	2 mm
Die element size	2 mm
Finite Volume Ratio	0.2
Number of Output Steps	20
Stroke of the Upper Die	Selected according to the billet height

After all of these steps are performed, the simulation for die filling analysis can be successfully started. At this step, the software performs a model check in order to control whether all of the simulation parameters are defined correctly or not. After completing the model check, the simulation starts and during simulation, the user can monitor the simulation progress from the simulation bar.

4.3 Finite Volume Die Filling Simulation Results

A lot of Finite Volume Simulations have been made to obtain the appropriate billet geometry for %100 die-filling of precision forging die set of the particular spur gear. The results of these Finite Volume Simulations are; die contact (die fill) analysis, effective stress analysis and the die loads are presented in the following paragraphs.

The die-workpiece contact analysis for the obtained hollow billet dimensions can be seen in the Fig. 4.5. In the figure, red color indicates the exact contact between the die cavity and the workpiece. Blue color indicates that there is no contact between the die and the workpiece. In Fig.4.6, the cross-section of the assembly during the simulation is shown. It should be noted that for all the temperatures, billets fill the die cavity completely. Because of the existence of friction in the interface between the die and the workpiece, the movement of the

die assists the metal flow downwards and the bottom corner of workpiece is formed much earlier than the top corner. At the end of the process, the bottom is fully filled while a chamfer is formed at the top.

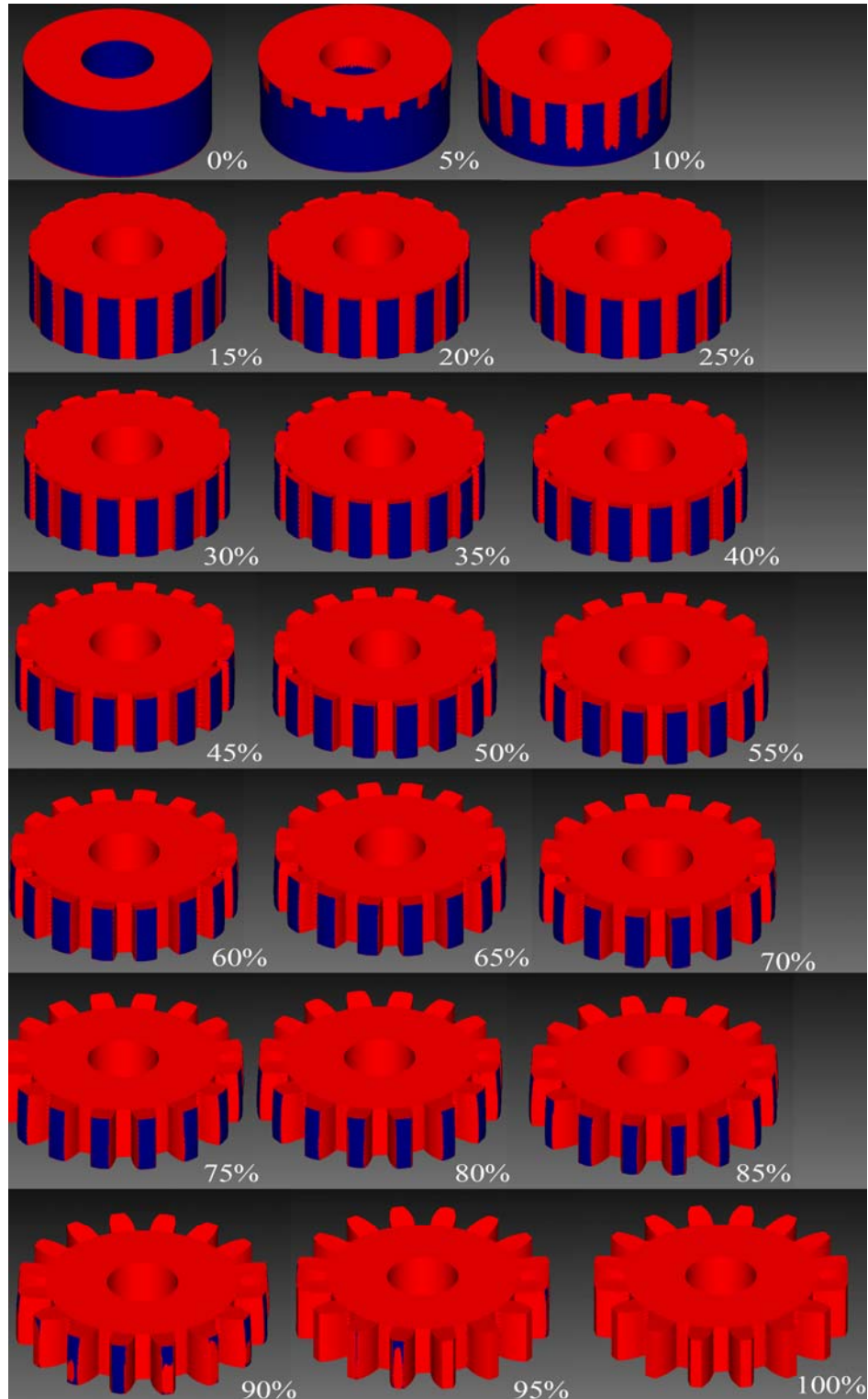


Fig.4.5 Die Contact (Die Filling) Simulation of the Spur Gear Forging at 1050°C

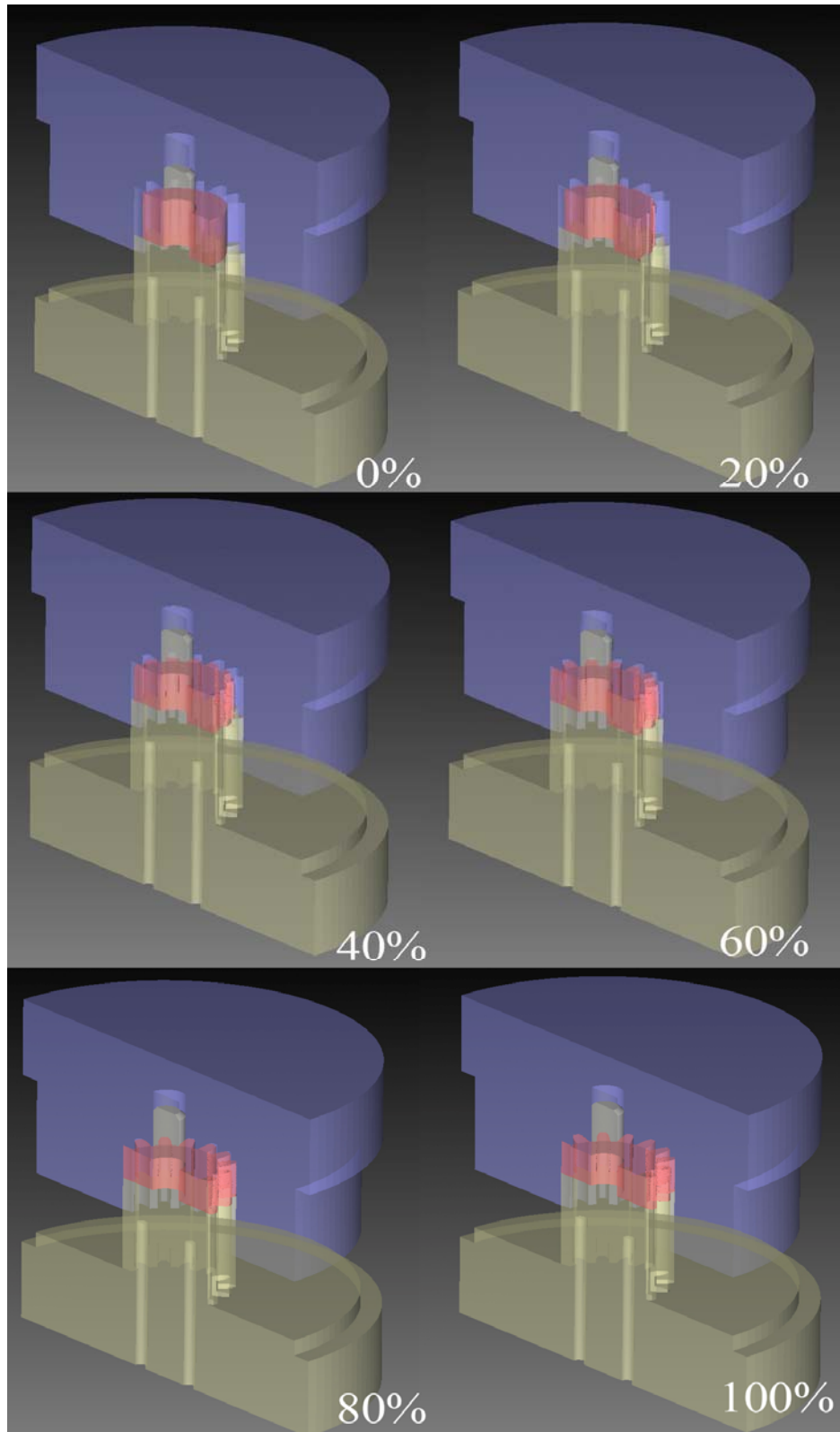


Fig.4.6 Cross-Section of the Assembly during Simulation

As it can be seen from Fig.4.7, at the end of the analysis whole part is in contact with the die, meaning that the 100% fill of the cavity is obtained. In the analysis, as it can be seen from Fig.4.7, in the marked area, the material looks like to be forced into the dies where it is not physically possible. It should be noted that, different sizes of faulty areas exist in different teeth sections. However these slight faults at the bottom of the teeth are occurred because of a fault in the algorithm of MSC.SuperForge (Fig.4.7) [48]. Therefore, the die is completely filled.

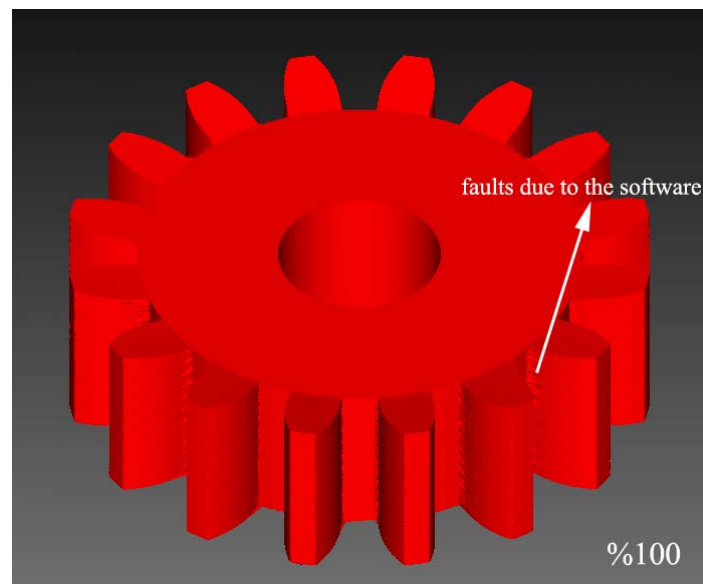


Fig.4.7 Faults due to the Software in the Obtained Spur Gear at the End of the Simulation

The stress distributions and the die force diagrams of the particular spur gear at different temperatures can be seen in Fig.4.8-4.15. Even though at the beginning of the process the stress distribution is uniform, as can be seen from the figures below, when the faults due to an error in the algorithm of the software (Fig.4.7) start to occur, the stress distribution starts to show differences in the geometry. In the force diagrams, the net forces on the dies are given as a function of time. As seen in Figures 4.9, 4.11, 4.13 and 4.15, an initial fluctuation in the force on the dies occurs during the initial contact between die and workpiece. After that, the force increases to a certain level and is kept within a range while the material flows into the gear teeth section of the die cavity. Close to the end of the process, when the material reaches to the wall of the die cavity, the forces on

the dies increase to the maximum value to form the complete teeth form. In Table 4.3, effective stress and die force values vs. billet temperature can be seen. If the table is examined, it is clearly seen that; as the billet temperature increases the forces on the dies and the effective stress values decrease as expected.

Table.4.3 Effective Stress and Die Forces Values vs. Billet Temperature

	1000°C	1050°C	1100°C	1150°C
Max. Effective Stress (MPa)	218.5	212.9	199.2	198.1
Max. Die Force (ton)	136	127.5	119	114

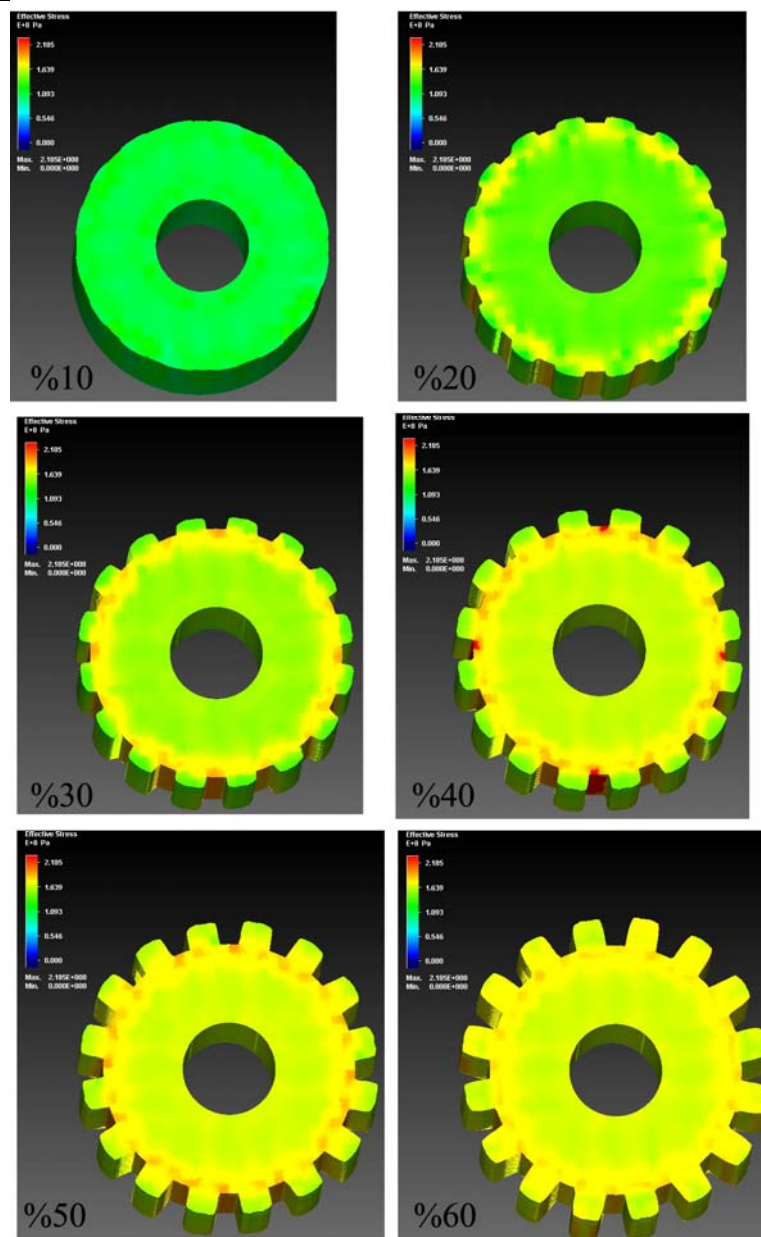


Fig.4.8 Effective Stress Distribution in the forged gear at 1000°C (cont'd)

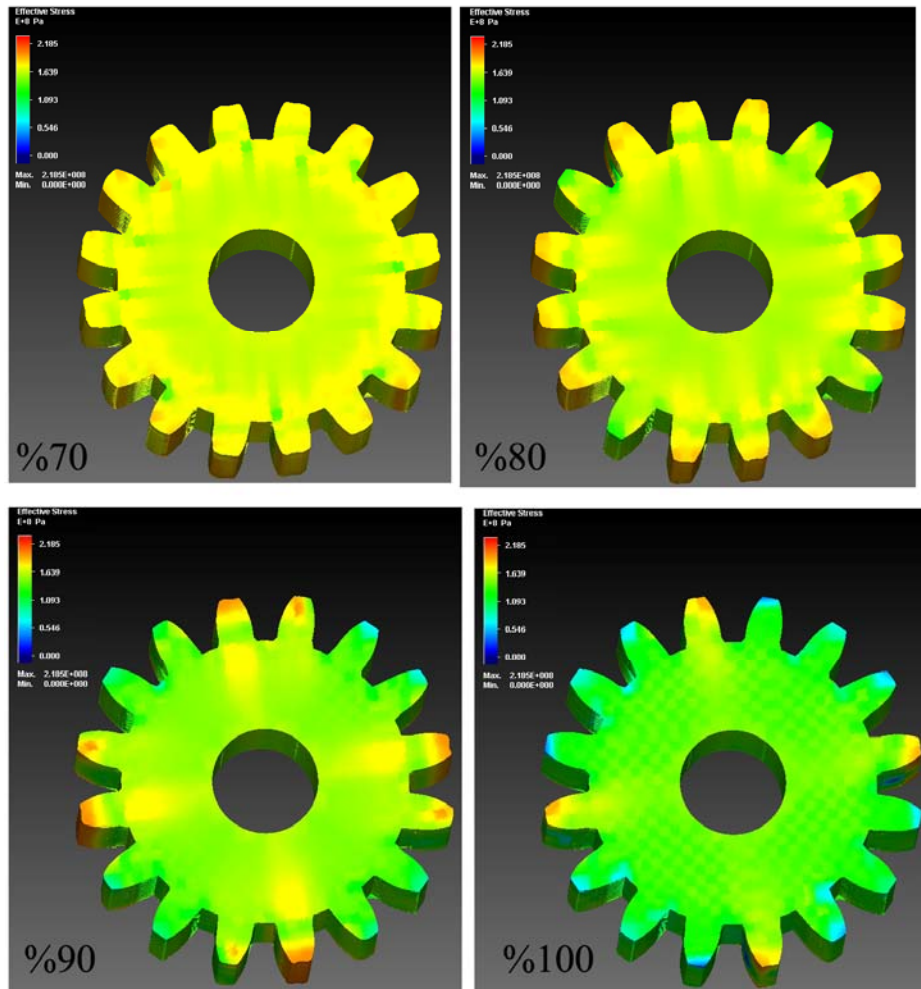


Fig.4.8 Effective Stress Distribution in the forged gear at 1000°C (cont'd)

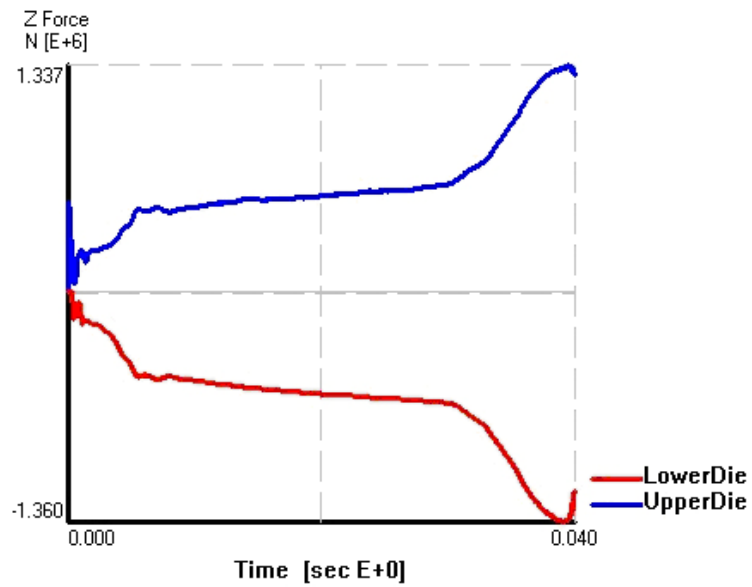


Fig.4.9 Die Force Diagram at 1000°C

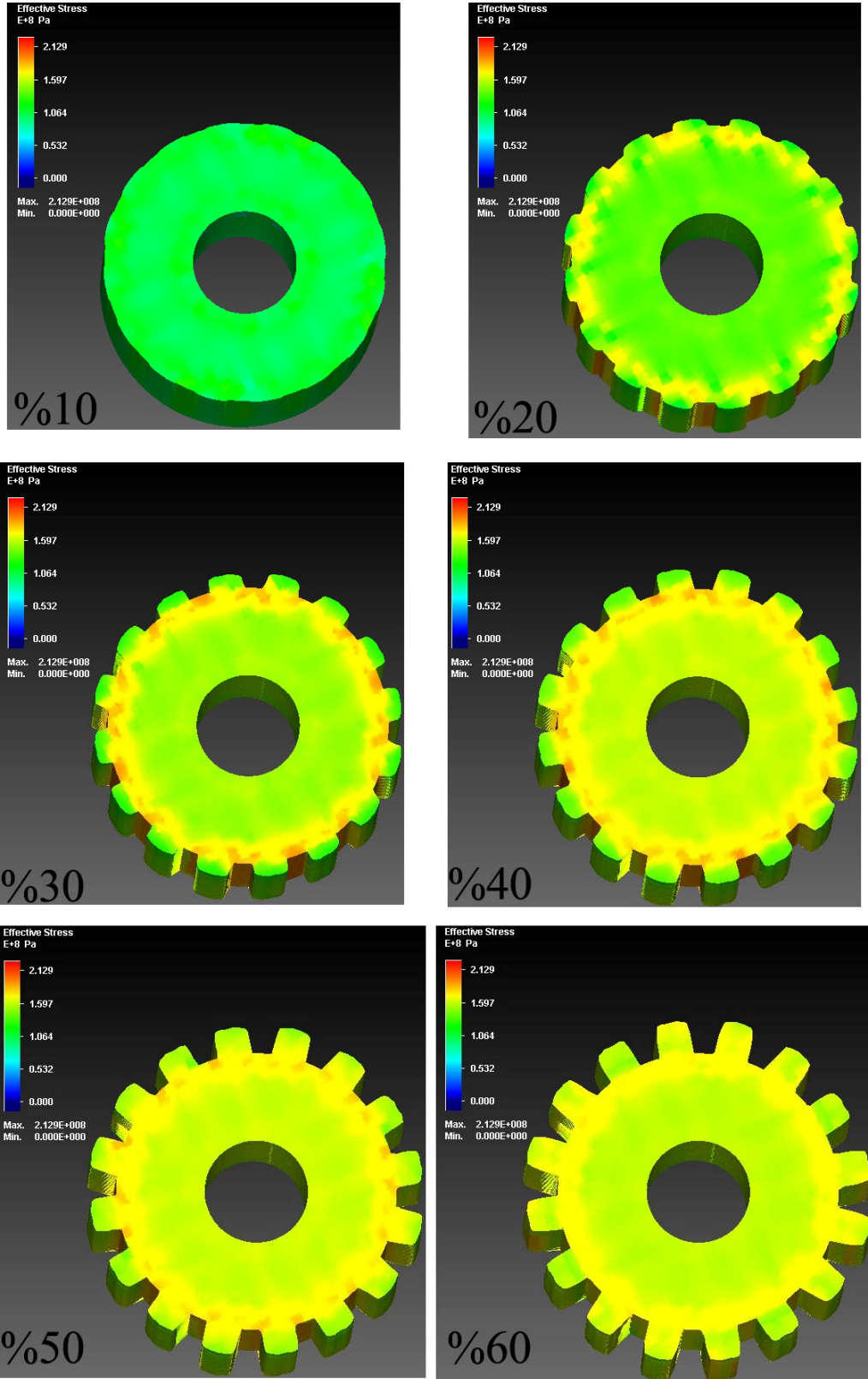


Fig.4.10 Effective Stress Distribution in the forged gear at 1050°C (cont'd)

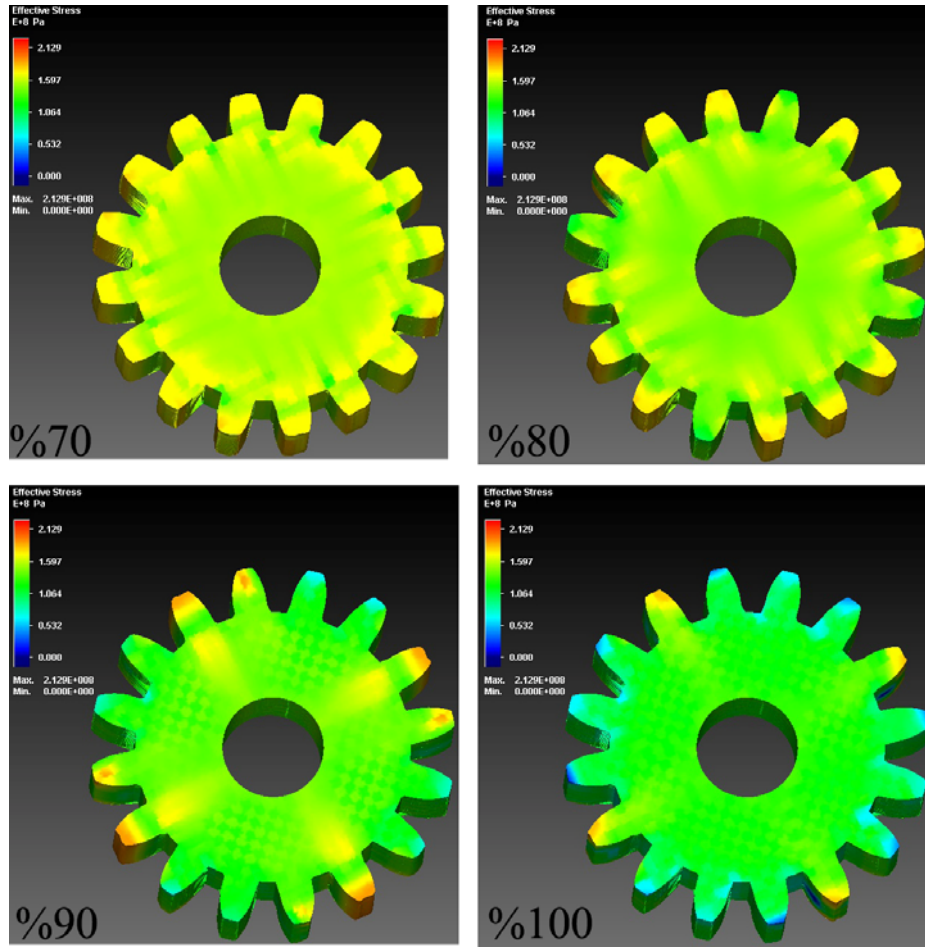


Fig.4.10 Effective Stress Distribution in the forged gear at 1050°C (cont'd)

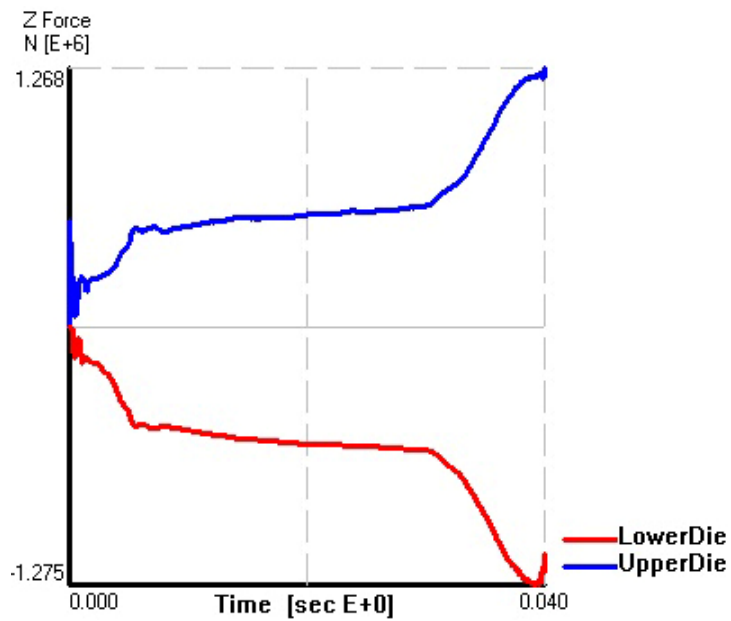


Fig.4.11 Die Force Diagram at 1050°C

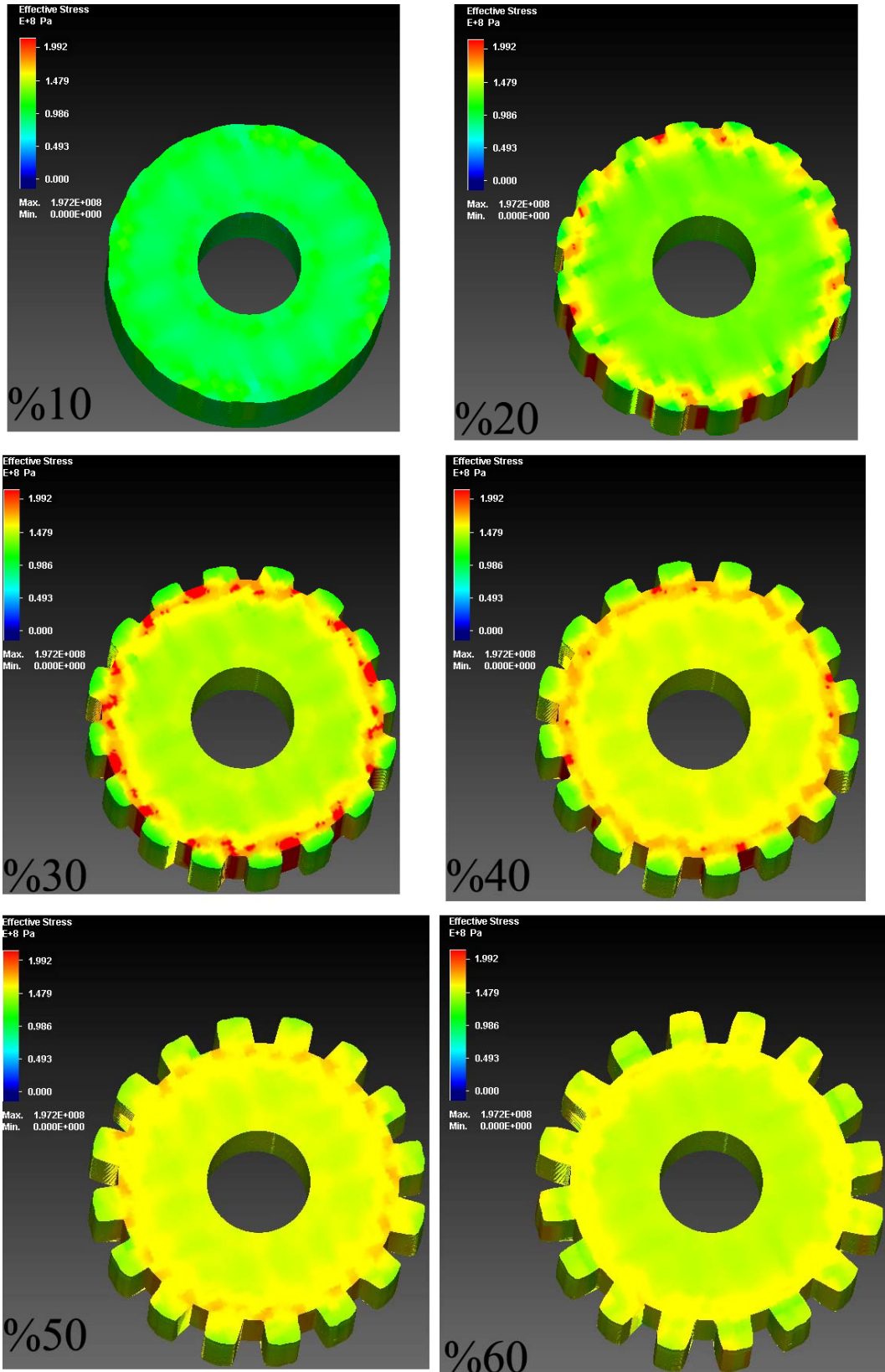


Fig.4.12 Effective Stress Distribution in the forged gear at 1100°C (cont'd)

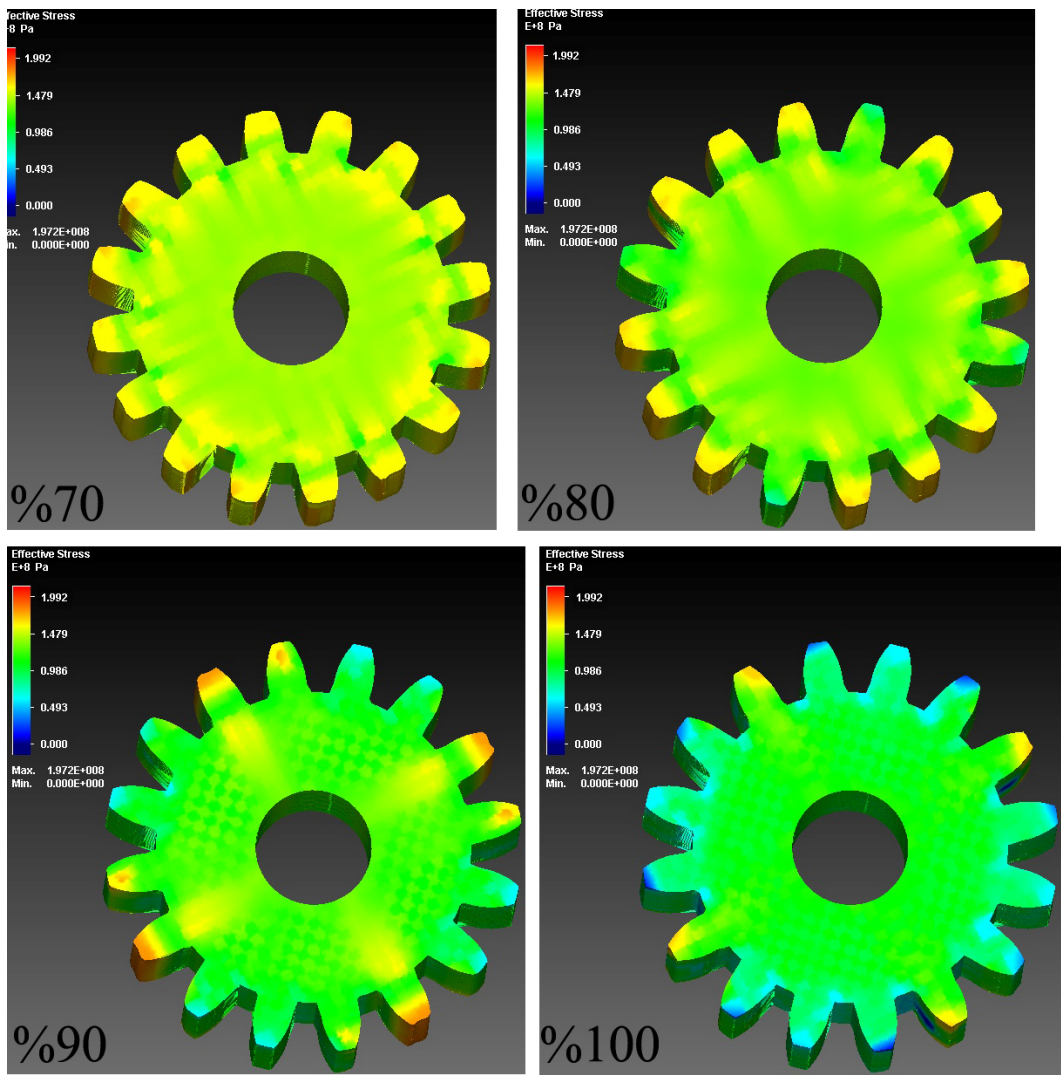


Fig.4.12 Effective Stress Distribution in the forged gear at 1100°C (cont'd)

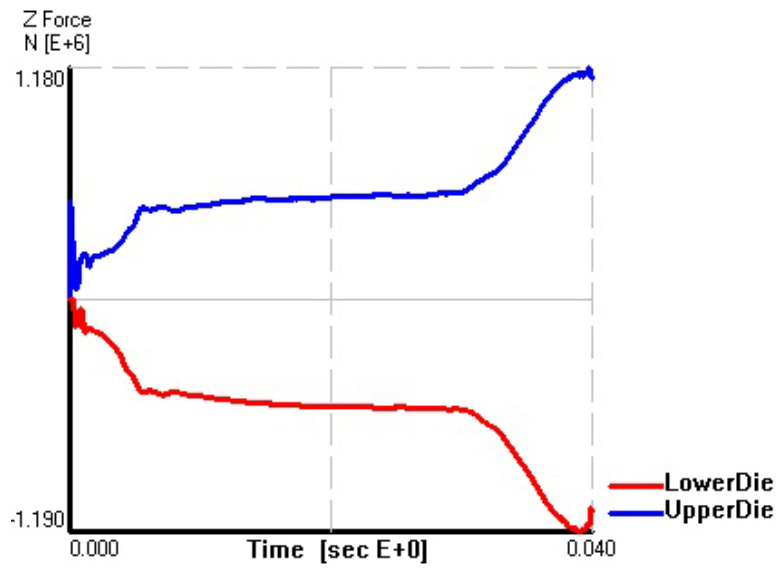


Fig.4.13 Die Force Diagram at 1100°C

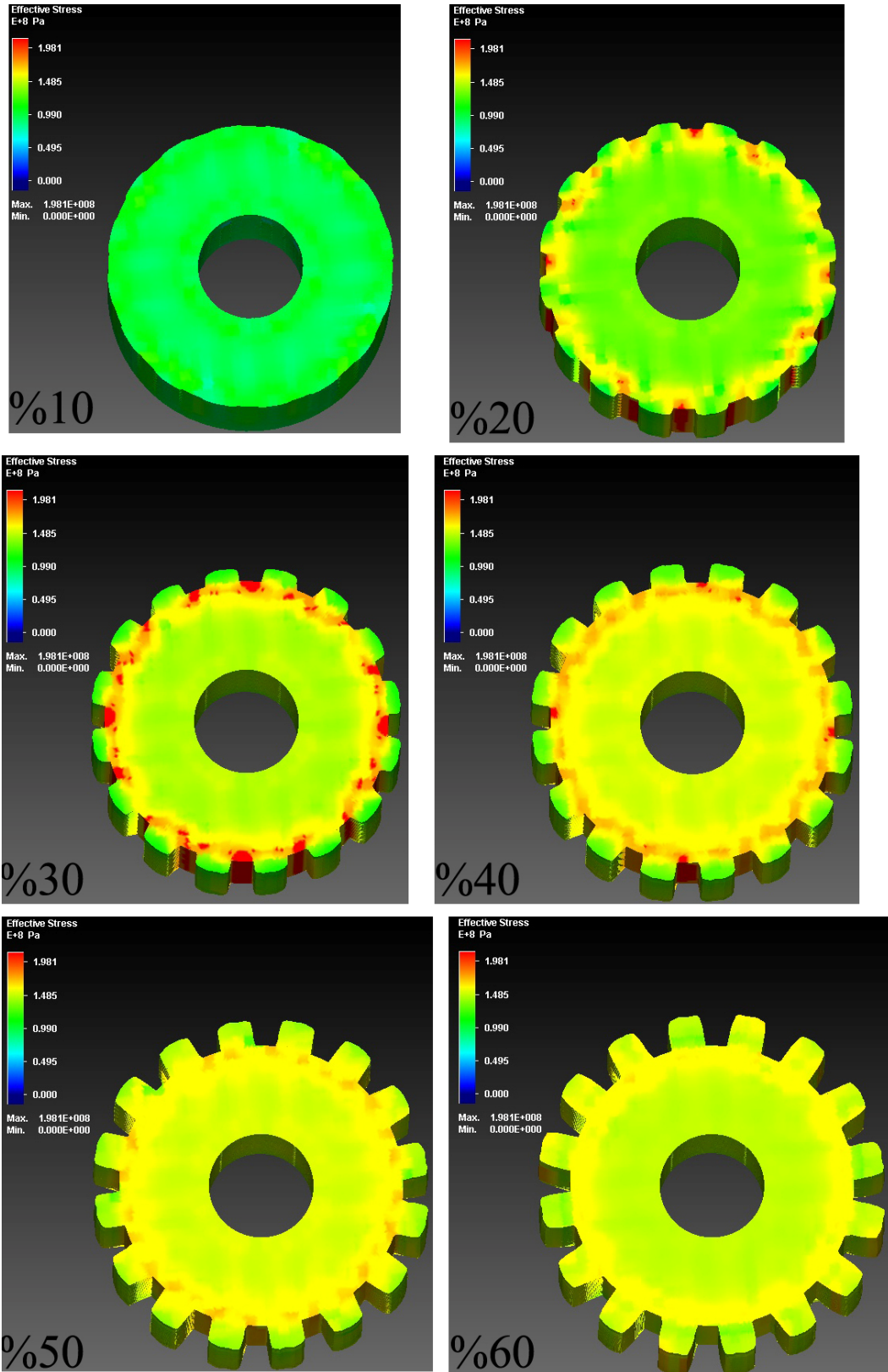


Fig.4.14 Effective Stress Distribution in the forged gear at 1150°C (cont'd)

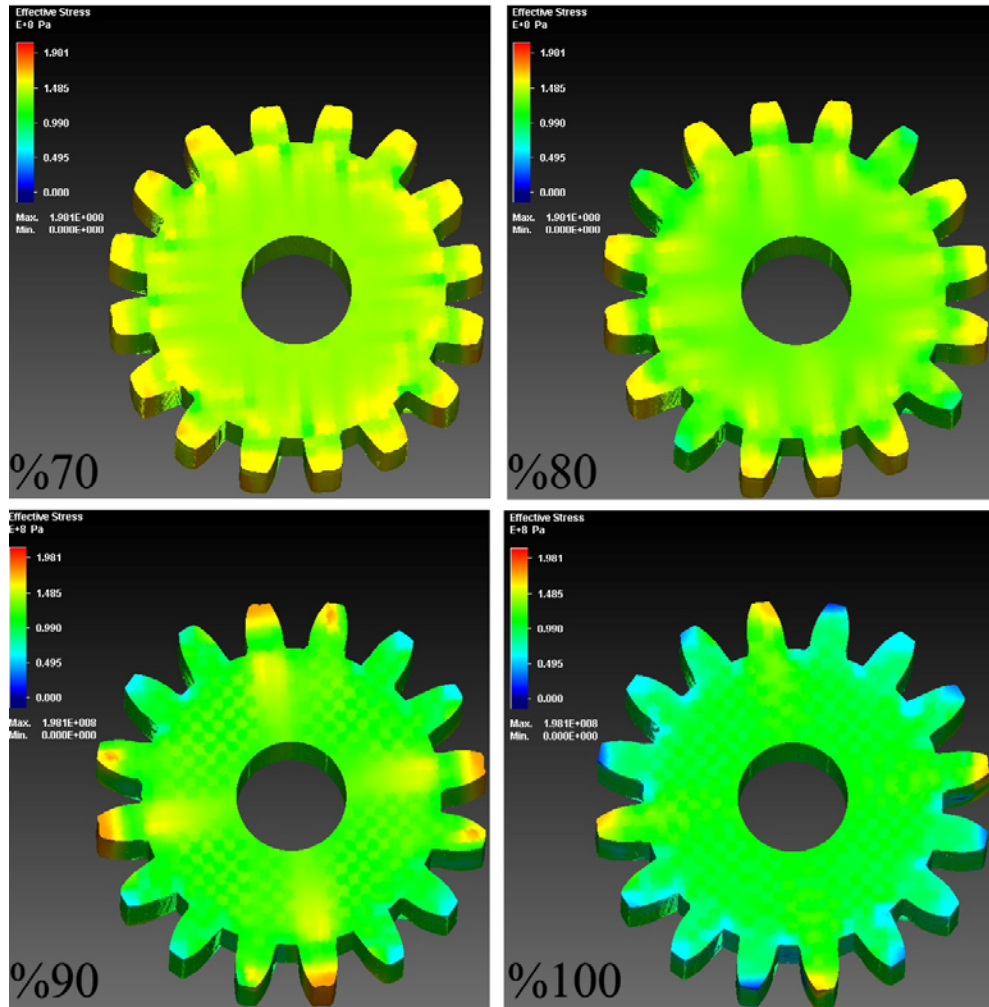


Fig.4.14 Effective Stress Distribution in the forged gear at 1150°C (cont'd)

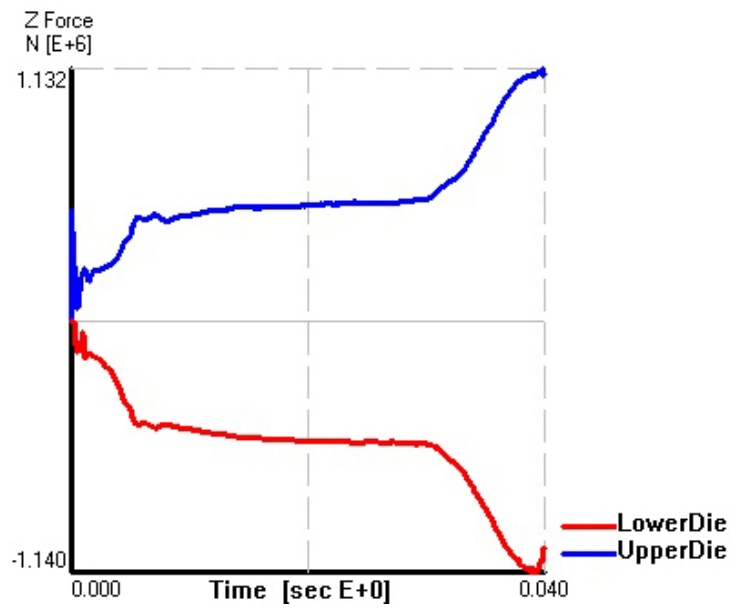


Fig.4.15 Die Force Diagram at 1150°C

CHAPTER 5

MANUFACTURING OF THE DIES AND BILLETS FOR PRECISION FORGING OF A SPUR GEAR

5.1 Dimensional Features of the Press, Die Holder and the Dies

The manufacturing and assembly of the die set for the precision forging of a particular spur gear is accomplished in METU-BILTIR Center CAD/CAM Research and Application Laboratory. In this section, the dimensional features of SMERAL 1000-ton mechanical press (Fig.5.1), dimensions of the die holder, dimensions of the dies, manufacturing and the assembly of the dies are presented.

The SMERAL 1000-ton mechanical press, which is available in METU-BILTIR Center Forging Research and Application Laboratory, has a ram stroke of 220 mm. The press has a shut height of 620 mm, which is the distance between the ram and the anvil when the ram is at its bottom dead center as can be seen from Fig.5.2. When the die holder is attached, and the ram is at its bottom dead center, there is a total distance of 200 mm left between the die locating surfaces of upper and lower die holder. Consequently, this 200 mm distance equals to the total allowable height for the forging dies. This distance should be taken into account to prevent the collision of the dies during the forging stroke. For this reason, it is extremely important to take extra caution against the calculation and manufacturing of the forging dies.



Fig.5.1 A view of Smeral 1000-ton Mechanical Press in METU-BILTIR Center Forging Research and Application Laboratory

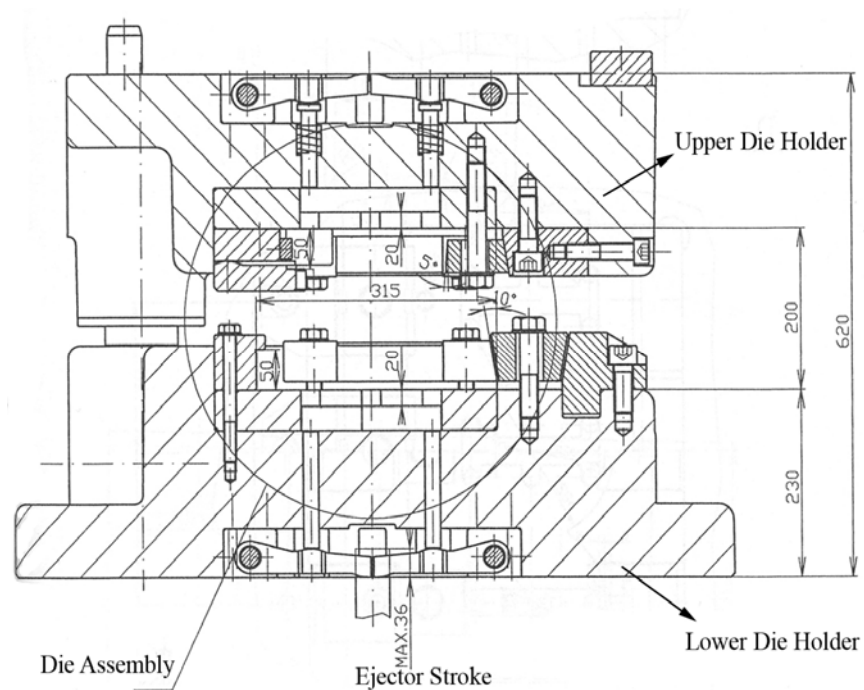


Fig.5.2.Shut Height and Die Holder of the Smeral 1000-ton Mechanical Press [49]

As it can be seen from Fig.5.3, the lower die holder has three sections for three different die sets. The same die holder locating geometry also exists for the upper die holder. It should be noted that, the middle section has the largest diameter (Fig.5.4). According to the forging design, either one die set, or all three die sets can be attached on the die holder.

In each set of die holder, key seats are provided. The key prevents the rotation of the dies in the die holder. The dimensions of the key seats are the same for all the die sections as can be seen from Fig.5.4, which are;

Width: 16mm (with the tolerance of H8) [50]

Depth: 9mm

As mentioned above, the height of the die set should be 200mm at the stage of fully closed die. This can also be seen from Fig. 5.5. For example, if the height of the upper die is 90mm, the height of the lower die must be 110mm, which adds up to a height of 200mm.

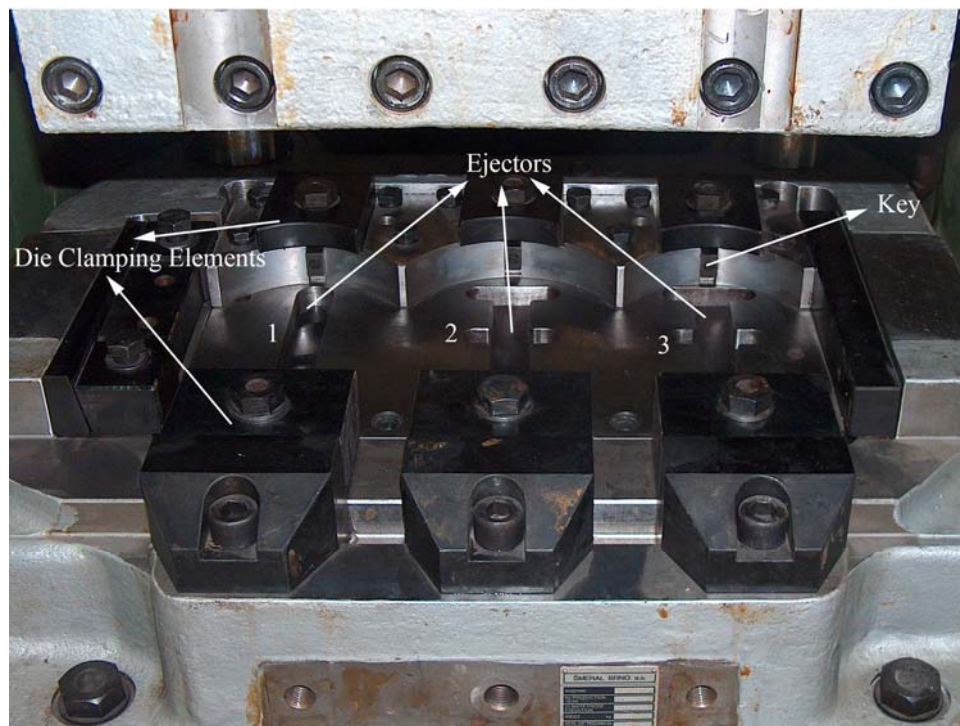


Fig.5.3. A view of Lower Die Holder

The dimensions of the dies according to the die holder can be seen in Fig.5.4 and Fig.5.5. There is a 50 mm stair distance for clamping the dies to the

die holder. The die clamping elements, which are seen in Fig.5.3, are used to fasten the dies to the die holder. These elements are mounted on the die holder by bolts. The distance from the lower surfaces of the dies to the clamping elements is 50 mm.

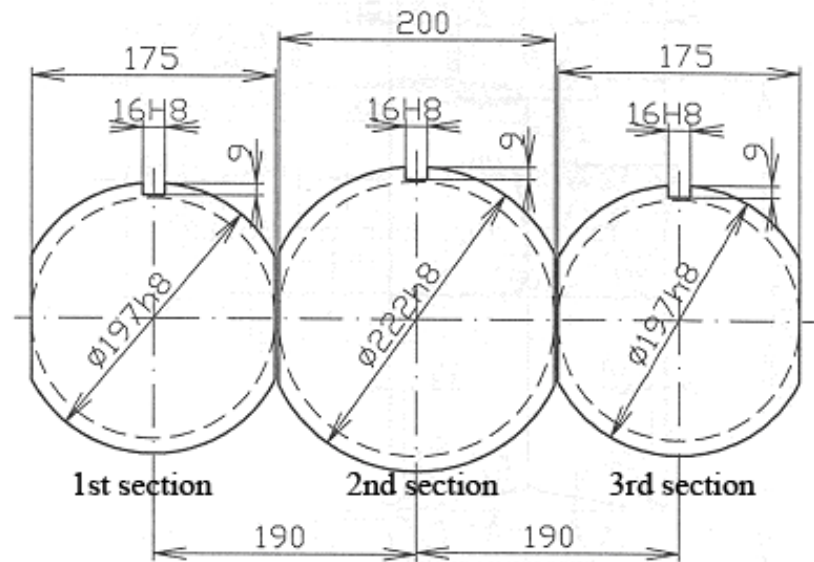


Fig.5.4. Top view of the Circular Dies [49]

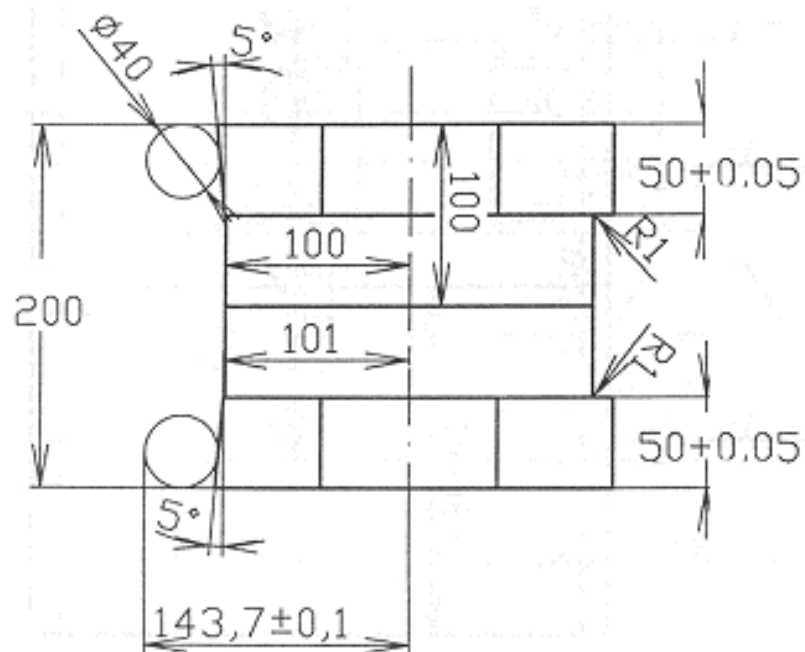


Fig.5.5. Front View of the Middle Circular Die [49]

5.2. Manufacturing of the Dies

The geometry of the die set is given in Chapter 3. DIEVAR is selected as raw material for the dies in precision forging process, because of its high toughness and high hardness values at high temperatures [51]. The detailed properties of DIEVAR [51] are given in Appendix B.

Most of the manufacturing works of the dies were accomplished in METU-BILTIR Center CAD/CAM Research and Application Laboratory, though some parts were manufactured in Aksan Forging Company in Ankara. The die parts with large diameter are turned in Aksan Forging Company. After the turning process, final size of the dies are given in MAZAK Variaxis 630-5X high-speed vertical milling machine, which is available in METU-BILTIR Center CAD/CAM Research and Application Laboratory. When the turning and milling operations are finished, the dies are sent for heat treatment. The heat treatment processes are given in Appendix C. After the heat treatment, the gear sections and the key seats of the dies are manufactured by Wire Electro Discharge Machine (W-EDM). These sections are manufactured after the heat treatment to avoid dimensional inaccuracies that may caused by heat treatment. In the figures 5.6-5.9, the technical drawings and the manufactured dies can be seen. Before manufacturing the dies, scale formation and heat expansion factors are given to the die cavity dimensions [14].

Gear sections of the lower and the middle dies are manufactured in Wire-EDM, which is available in METU-BILTIR Center CAD/CAM Laboratory. The manufacturing G-Codes are obtained from Pro/Engineer Wildfire III NC mode [36], and transferred to the Wire-EDM. The technical drawing of the gear section of the lower die and pictures of its manufacturing stages before and after cutting process can be seen in Fig.5.10 and Fig.5.11.

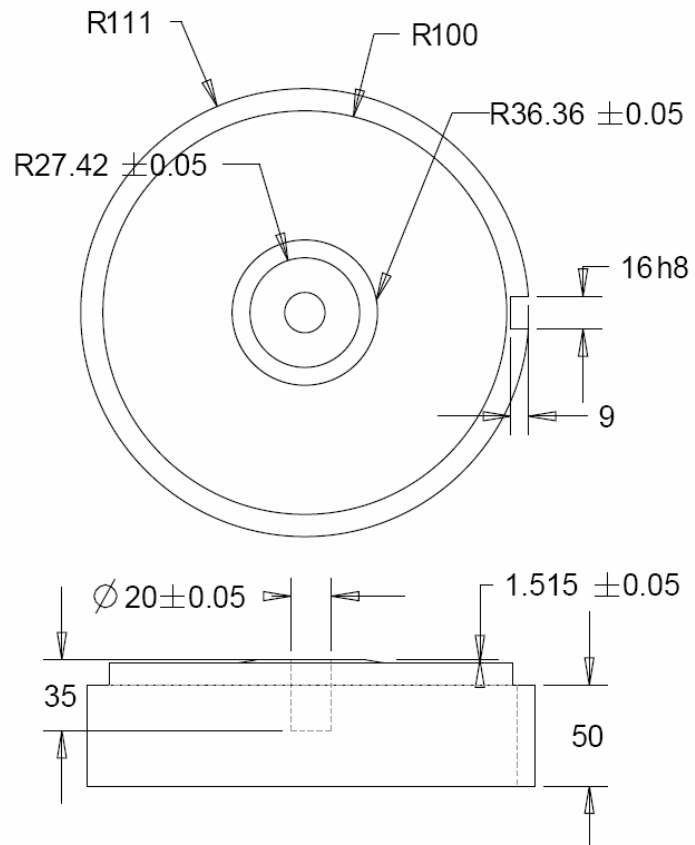


Fig.5.6. Technical Drawing of the Upper Die



Fig.5.7. A view of Manufactured Upper Die

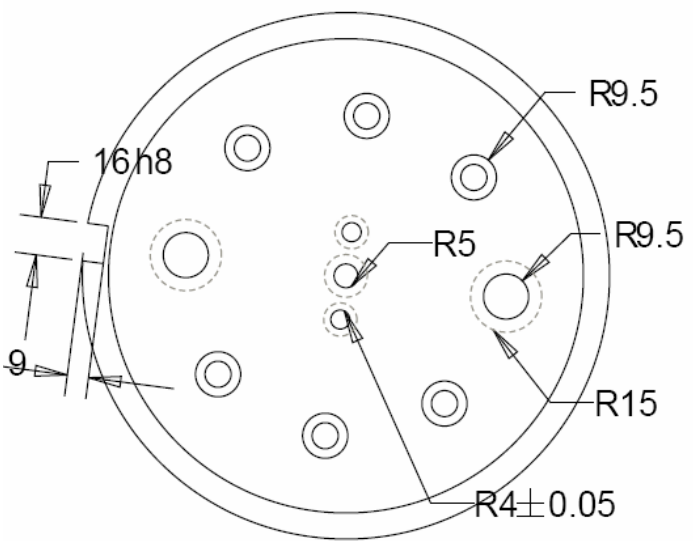
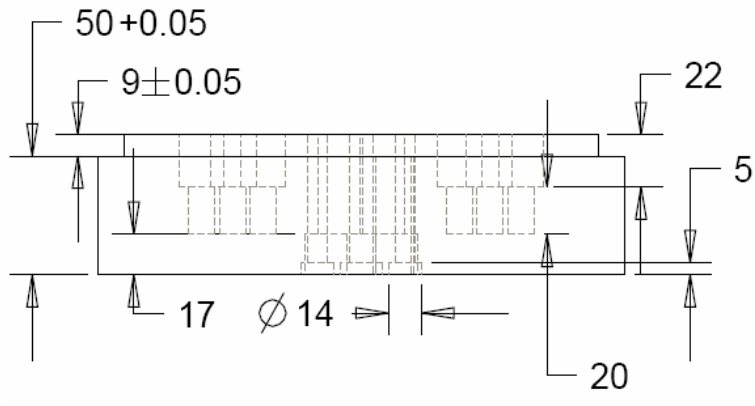


Fig.5.8 Technical Drawing of the Base Section of Lower Die



Fig.5.9 A view of Manufactured Base Section of the Lower Die

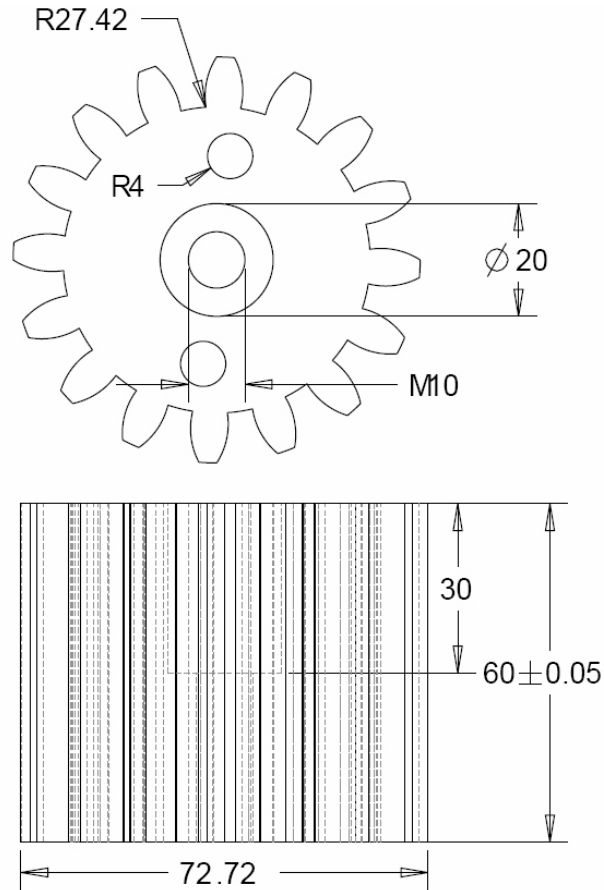


Fig.5.10 Technical Drawing of the Gear Section of the Lower Die

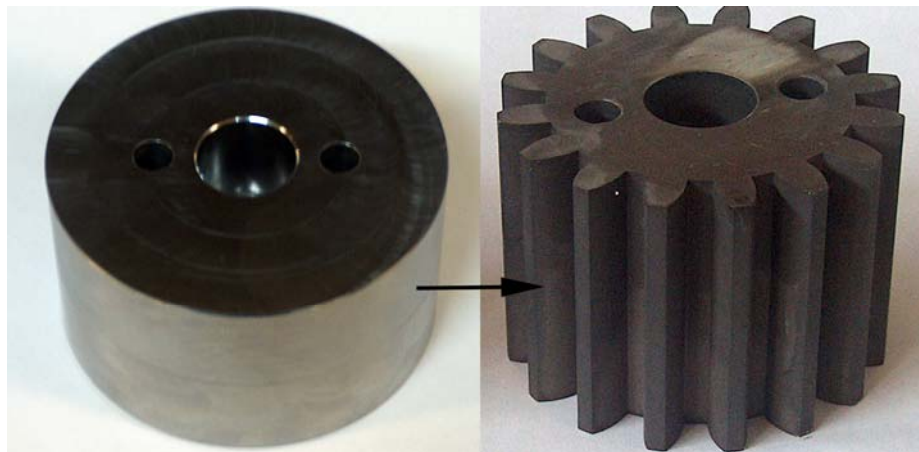


Fig.5.11 A view of Gear Section of the Lower Die

After the production of the gear section of the lower die, gear section of the middle die is manufactured in Wire-EDM. The technical drawing and the picture of the middle die can be seen in Fig.5.12 and 5.13 respectively.

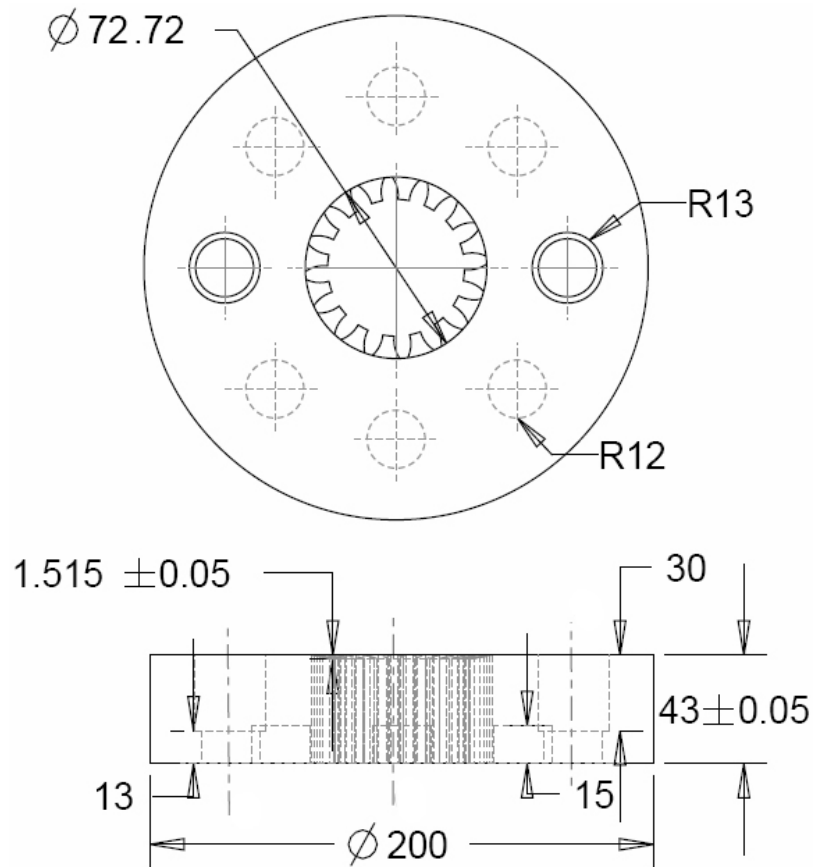


Fig.5.12 Technical Drawing of Middle Die



Fig.5.13 A view of Manufactured Middle Die

In the proposed design of precision forging, total height of the dies is greater than the 200 mm value, which is the limit in order not to have a collision in the forging process. In the proposed design, as mentioned in Chapter 3, the

upper die hits and pushes the middle die downwards. The traveled distance that the upper die and the middle die move together is 13mm. It is known that the stroke of the ram is 220mm, meaning that the upper die will advance 220mm downwards in each forging stroke. As it can be seen from Fig.5.14 that, the distance between the upper die and the middle die is 207mm when the ram is at its upper dead center. So the ram advances 207 mm at the start of the forging stroke and the upper die hits the middle die before the ram completes its stroke of 220 mm. In the last 13mm of the ram's stroke, the upper die and the middle die will advance together and form the part.

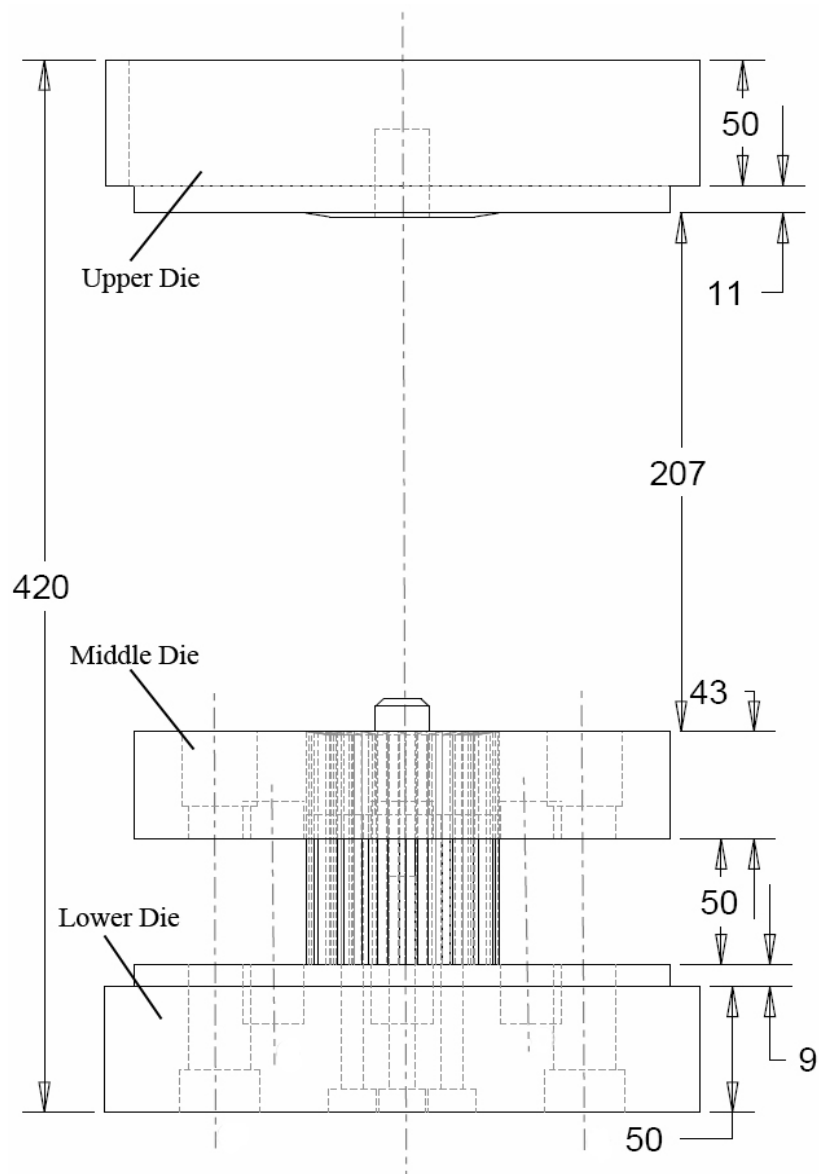


Fig.5.14 Total Position of the Dies in the Assembly

5.3. Assembly of the Dies

After completing the manufacturing, the dies were assembled and then installed to the press. The parts of the lower die assembly can be seen in Fig.5.15. These parts were assembled before the forging process.



Fig.5.15. A view of Lower Die Assembly

Technical drawings of the ejectors and the mandrel can be seen from Fig.5.16 and Fig.5.17 respectively. During the assembly process, first of all, the ejectors are mounted inside the lower die base section. Then, the lower die gear section is placed onto the base, by the guidance of the ejectors. And finally, the mandrel is fastened to the gear section with a M10 steel bolt. The ejectors can move freely up and down, due to the diameter clearance. On the other hand, the gear section and the mandrel are fixed to the base section. The lower die assembly stages can be seen in the pictures in Fig.5.18-5.20.

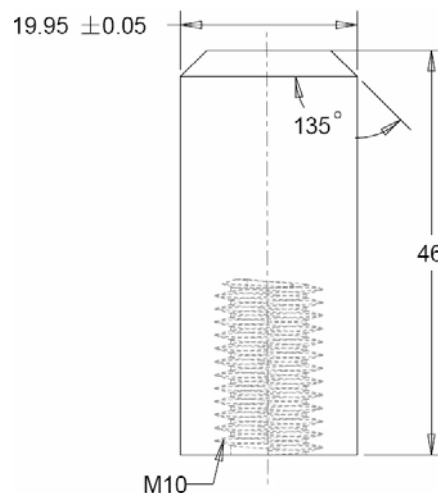


Fig.5.16 Technical Drawing of the Mandrel

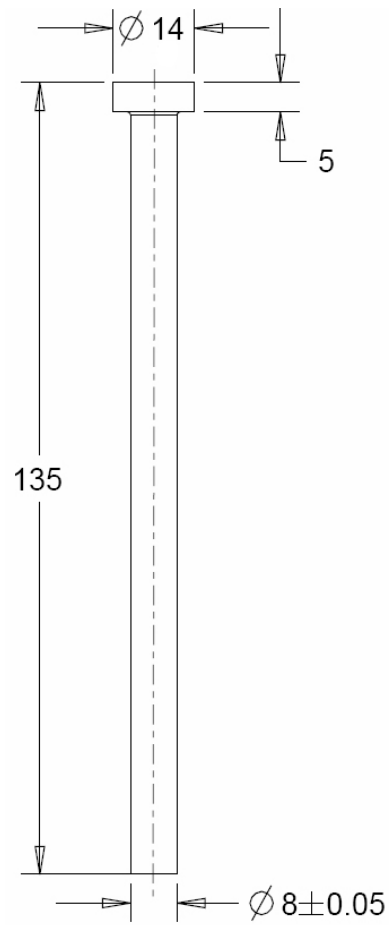


Fig.5.17. Technical Drawing of the Ejector Pin



Fig. 5.18 A view of Base Section of Lower Die and Ejectors



Fig.5.19 A view of Base Section of Lower Die, Ejectors and Gear Section



Fig.5.20 A view of Manufactured Lower Die Assembly

After finishing the lower die assembly, the springs are located onto the middle die with the spring adjustments bolts. Afterwards, the middle die restraining bolts are placed onto the middle die. Then the middle die is turned upside down and placed onto the lower die. The gear section of the lower die is assembled inside the middle die. Finally, the middle die is fastened to the lower die with the restraining bolt assembly, preventing the dislocation of the middle die from the assembly. The middle die assembly stages can be seen in Fig.5.21-Fig.5.24. In Fig.5.21, six of the holes will be used for the spring assembly and two of the holes will be used for the restraining bolts. The spring, spring adjustment bolt, restraining bolt and nut can be seen in Fig.5.22. The middle die with the springs and the restraining bolts attached can be seen from Fig.5.23. The fastened middle die and the lower die assembly can be seen in Fig.5.24. The whole assembly picture of the dies can be seen from Fig.5.25.

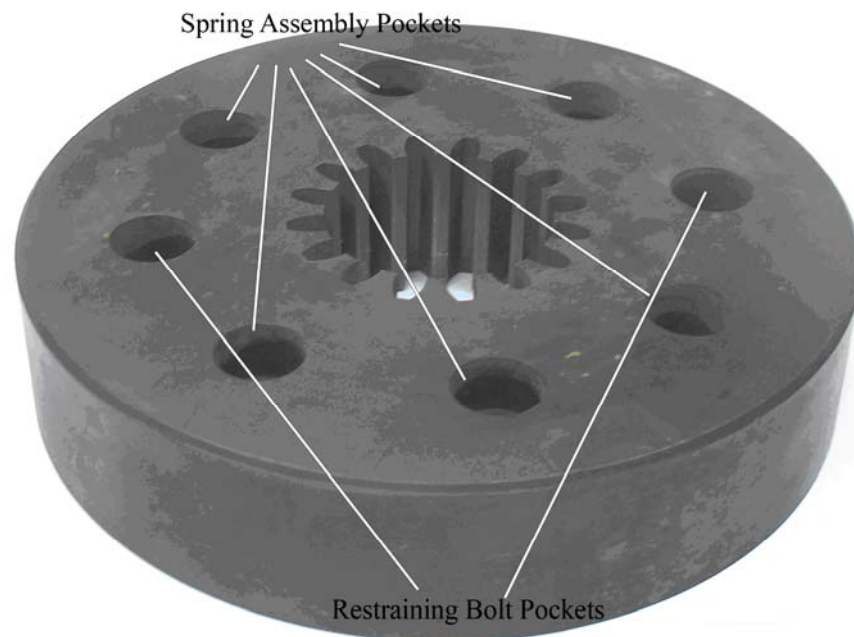


Fig.5.21 A view of Manufactured Middle Die



Fig.5.22 Spring, Spring Adjustment Bolt, Restraining Bolt, Nut



Fig.5.23 A view of Middle Die with Helical Springs and Restriction Bolts Attached



Fig.5.24 A view of Middle Die and Lower Die



Fig.5.25 A view of Complete Assembly of the Precision Forging Die Set

5.4 Billet Manufacturing

The volume of the billet is calculated from Pro/Engineer Wildfire III [36]. To calculate the volume of the billet, first of all the particular gear part volume and the gear part with the compensation are calculated, as can be seen from Table 5.1. The density of the gear material is 7850 kg/m^3

Table.5.1 Billet Volume and Mass Calculation

	Volume (* 10^4 mm^3)	Mass (g)
Particular Gear Part	5,66	444,1
Particular Gear Part with Compensation Space	5,72	448,8

According to the Table.5.1, the manufactured billet dimensions and its technical drawing can be seen from Fig.5.26. It should be noted that, the diameters of the billet are obtained according to the Finite Volume Results as mentioned in Chapter 3. Also in the determination of the diameter values of the billet, the standard values for mass production are taken into account.

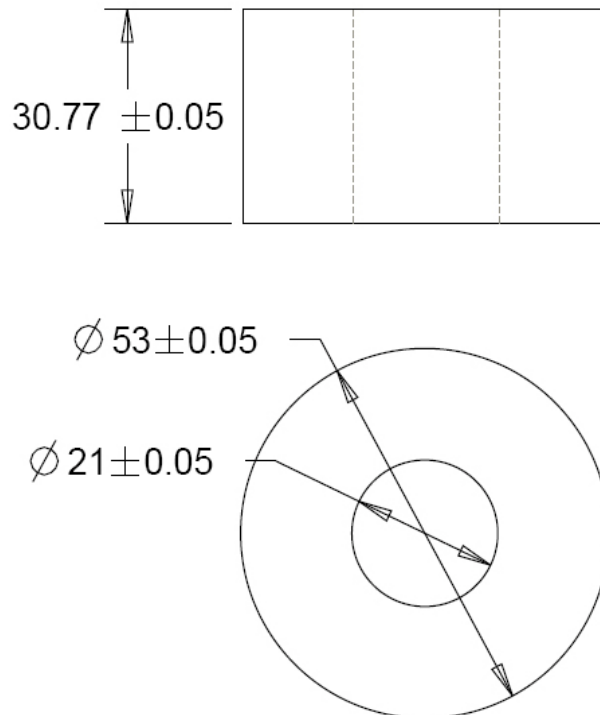


Fig.5.26. Billet Dimensions

After the billets are manufactured, they are weighed on precision balance to check if they are inside the given tolerances, which is between 446.0 grams and 458.8 grams. In Fig.5.27, there can be seen a manufactured billet and its weighing process on precision balance.



Fig.5.27 Billet on Precision Balance

CHAPTER 6

REAL-LIFE EXPERIMENTS

6.1. Preparation for the Experiments

Before experiments, several preparations are required. Most important of these are, manufacture and measuring the dimensions and the mass of the billets. Although 50 billets had been prepared, only six of them were used during the experiments due to the reasons presented in Section 6.3. For these particular six billets, values of the manufactured billet dimensions and billet mass can be seen, in Table 6.1 and Table 6.2. The billets are measured by using the Coordinate Measuring Machine (CMM) with the tolerance of ± 0.001 mm and the billets are weighed on the precision balance with the tolerance of ± 0.01 gram. All the dimensions and the mass of the billets in the table are measured three times and their averages are taken and given in Table.6.1. The measurements for the mass of the billets are repeated likewise and the same values have been read on the digital screen of the balance.

In the setup of the dies, the assembled lower die is pushed into the key seat to prevent the rotational movement of the die and then fastened from both sides to the lower die holder by clamping elements as can be seen in Fig.6.1. The upper die is fastened to the upper die holder likewise. When both of the dies are fastened, few test runs without billet are made to check the alignment of the dies. After it is ensured that the alignment of the upper and lower dies is appropriate, pre-heating of the dies is initiated. Pre-heating of the dies is performed to extend die life by decreasing the temperature differences between the die wall and billet and by this way decreasing thermal fatigue. Pre-heating of the dies is realized by a LPG heater flame gun. To measure the temperature of the dies, an optical

pyrometer is used. Every 5 minutes, during the heating stage, the temperature of the dies is measured.

Table.6.1 Billet Dimensions

No	Billet External Diameter (mm) (1)	Billet External Diameter (mm) (2)	Billet External Diameter (mm) (3)	Average External Diameter (mm) (3)
1	53,036	53,04	53,042	53,039
2	52,971	53,096	52,978	53,015
3	53,051	53,062	53,059	53,057
4	53,035	53,049	53,047	53,044
5	53,068	53,062	53,061	53,064
6	53,029	53,022	53,021	53,024
No	Billet Internal Diameter (mm) (1)	Billet Internal Diameter (mm) (2)	Billet Internal Diameter (mm) (3)	Average Internal Diameter (mm) (3)
1	21,103	21,117	21,115	21,112
2	21,088	21,089	21,084	21,087
3	21,119	21,112	21,118	21,116
4	21,086	21,086	21,081	21,084
5	21,079	21,08	21,089	21,083
6	21,079	21,067	21,082	21,076
No	Billet Length (mm) (1)	Billet Length (mm) (2)	Billet Length (mm) (3)	Average Billet Length (mm) (3)
1	29,058	29,052	29,073	29,061
2	30,475	30,468	30,477	30,473
3	30,845	30,841	30,835	30,840
4	30,789	30,785	30,791	30,788
5	30,829	30,844	30,848	30,840
6	30,835	30,825	30,836	30,832

Table.6.2. Billet Mass

	Mass of the Billets (g)
Sample 1	421,84
Sample 2	441,86
Sample 3	448,37
Sample 4	447,95
Sample 5	448,07
Sample 6	447,56

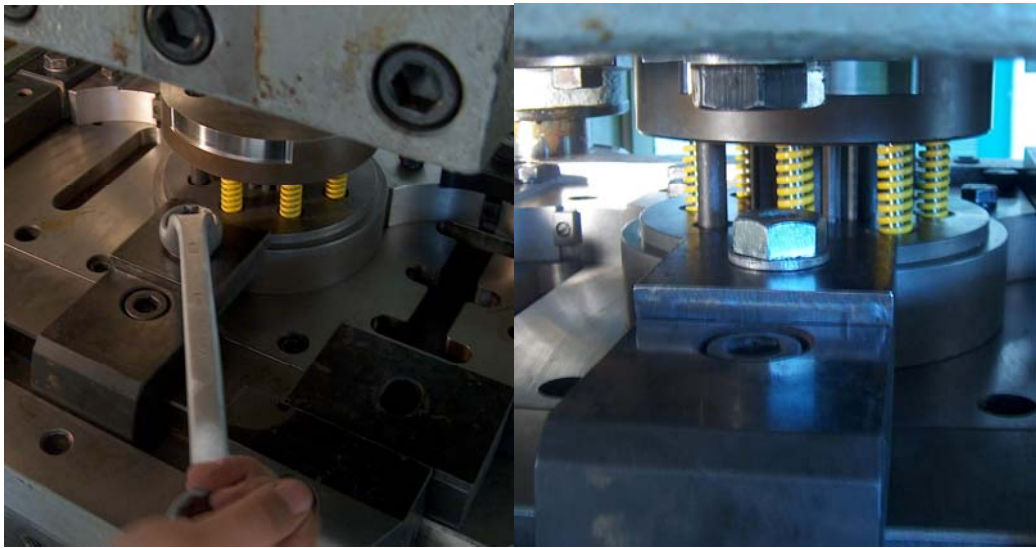


Fig.6.1. A view of Clamping of the Dies

The dies are pre-heated for nearly two hours about 250°C from different sides of the die-set to provide a homogenous heat transfer, as can be seen in Fig. 6.2.

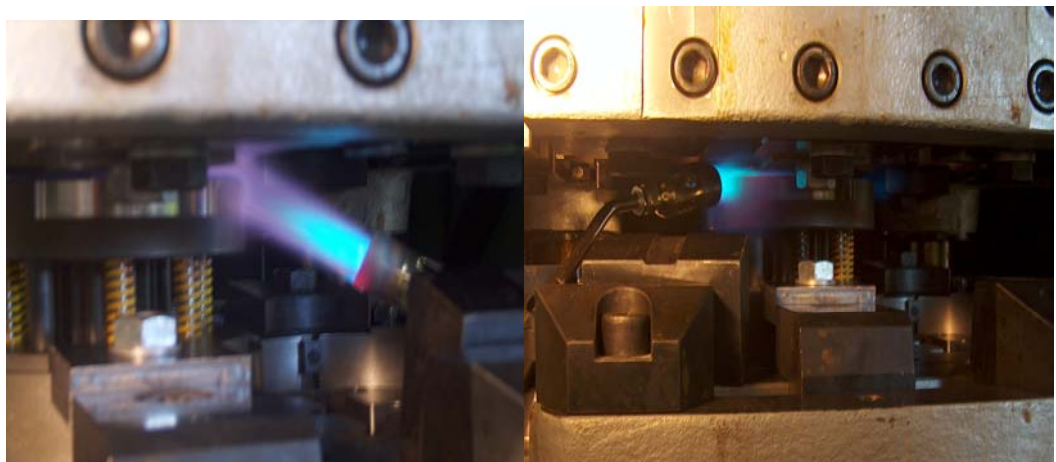


Fig.6.2. Pre-Heating of the Dies

During the pre-heating of dies and the forging process, the springs are exposed to high temperatures. Due to this as mentioned in Chapter 3, the spring material should withstand to high temperatures. These kinds of springs are not available in Turkey. On the other hand, it takes long time to import the springs from abroad and the suppliers are unwilling to provide necessary springs at a very low quantity. Therefore, the springs are selected from standard die springs which are used in sheet metal press dies and available in Turkey and prototype precision forging die is aimed in this particular study.

6.2. Real-Life Experiments

The test equipment used in the real-life experimentation can be seen in Fig.6.3. The tube-shaped billets are heated in a 125 KVA induction heater. The temperature of the billets are measured by a fixed pyrometer at the induction heater exit and by another pyrometer just before forging process (Fig.6.4).

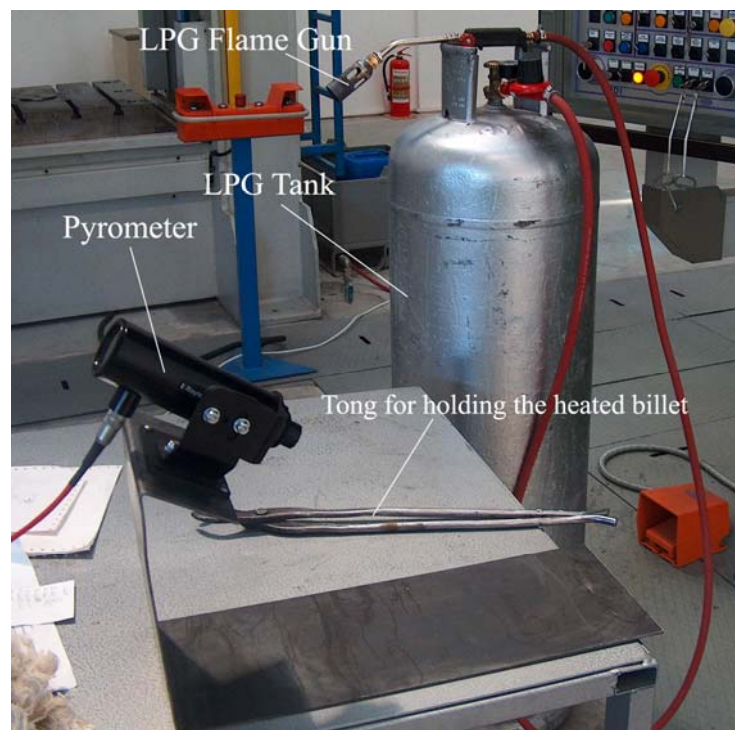


Fig.6.3 Test Equipment used in the Real-Life Experimentation

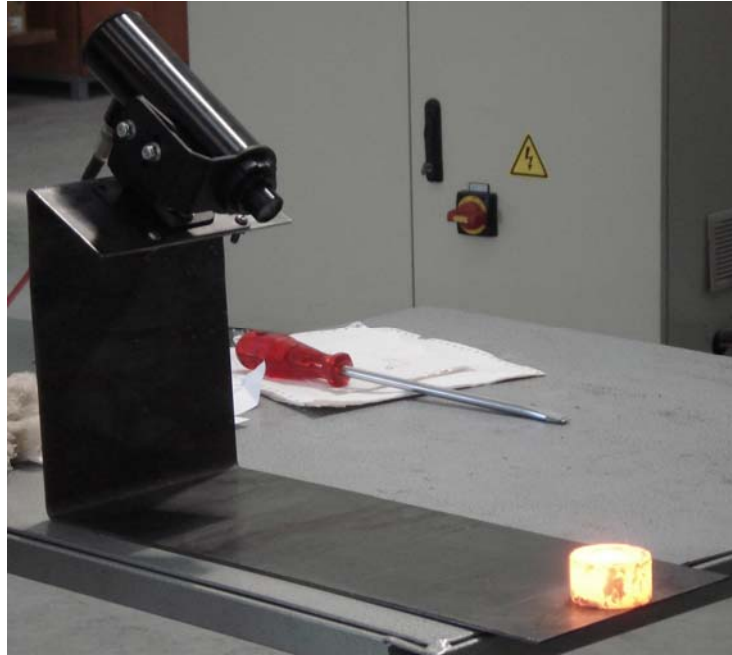


Fig.6.4 Measuring the Heated Billet Temperature before Forging

Before placing the heated billet in to the die, lubrication is applied on the die cavity surfaces. For lubrication, graphite-oil based lubricant is used as recommended in [14]. In Fig. 6.5-6.11, the operation stages after the pre-heating of the dies can be seen. In Fig.6.5, the heated tube shaped billet can be seen. The heated billet on the die can be seen in Fig.6.6. The formed gear can be seen during the ejection stage as in Fig.6.7-Fig.6.8. For the first two forging attempts the billets with lower masses are used to avoid the excessive loads on the die. As expected, Sample 1 and Sample 2 could not completely obtain the gear geometry since their mass is less than 446 grams as discussed in Section 5.4. Samples 3-6 are above 446 grams and at the end of the experiments; with these samples, spur gear is successfully forged to the desired tolerances. The manufactured gear can be seen in Fig.6.9-Fig.6.11. The experiments have been realized only for first six billets and could not be continued due to the reasons explained in Section 6.3. The measured values for the dimensions of the forged gears are given in Table 6.3. The mass of the billets before and after the forging process are given in Table 6.4. The differences between the values for masses before and after forging are due to the scale formation which is cleared before forging.



Fig.6.5 A view of Heated Tube Shaped Billet inside the Heater



Fig.6.6 A view of Heated Tube Shaped Billet inside the Middle Die

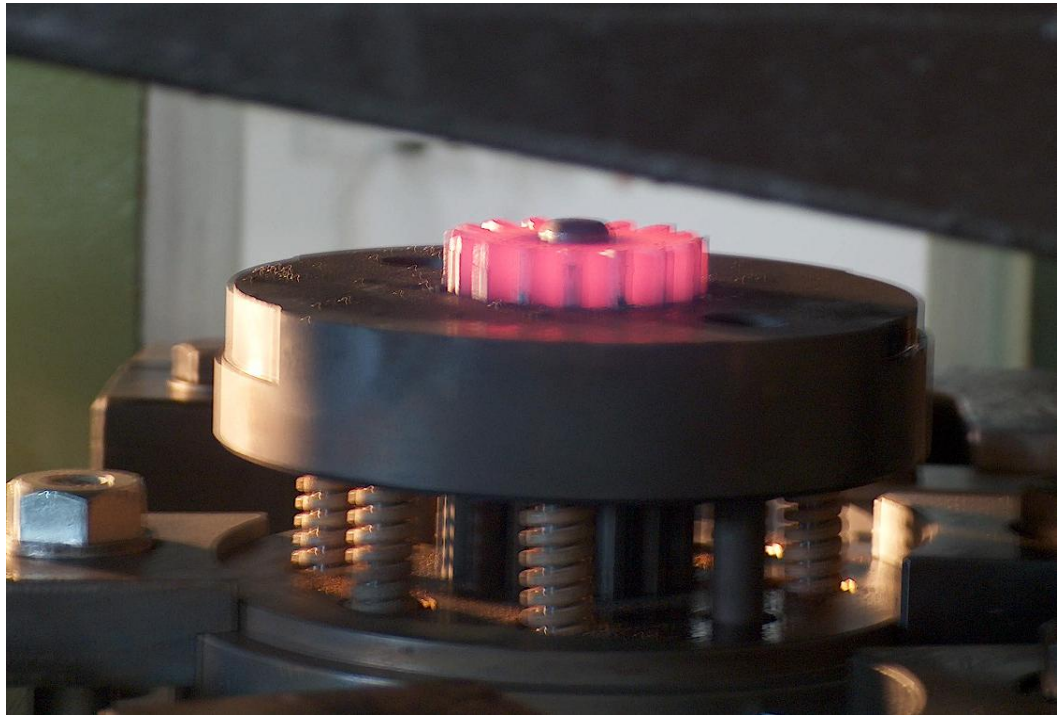


Fig.6.7 A view of Formed Gear at the Ejection Stage

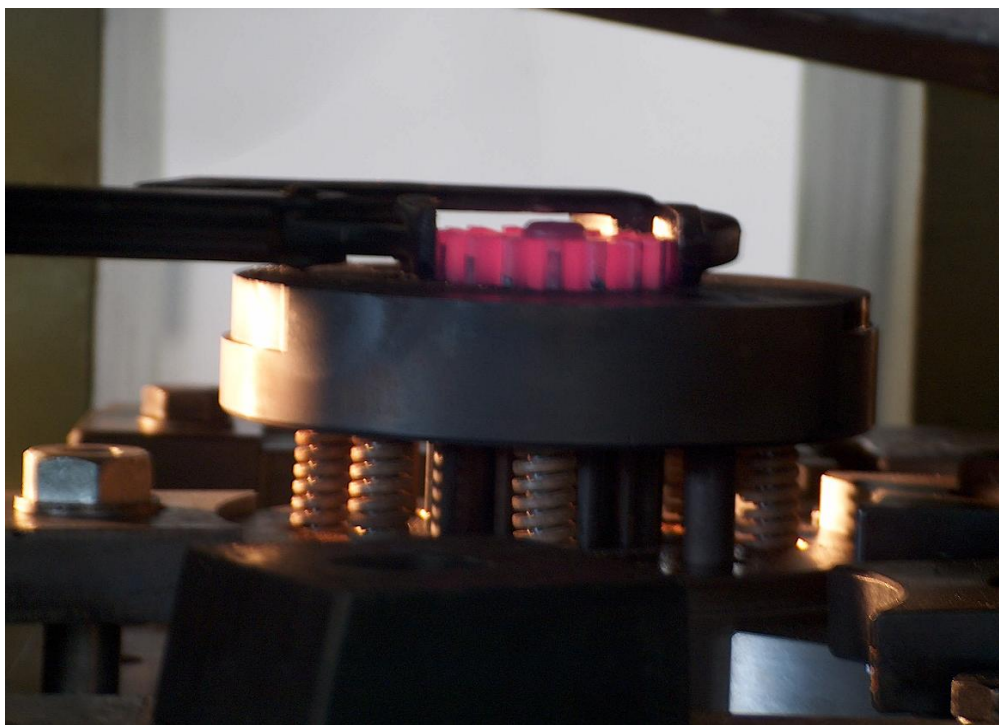


Fig.6.8 A view of Formed Gear during pulling out by Tong



Fig.6.9 A view of Formed Gear



Fig.6.10 Front View of the Formed Gear



Fig.6.11 Top View of the Formed Gear

Table.6.3. Dimensions of Forged Gear

	Outside Diameter (mm)	Inside Diameter (mm)	Face Width (mm)	Root Diameter (mm)
Obtained Spur Gear Sample 1	71,695	19,916	19,030	54,590
Obtained Spur Gear Sample 2	72,380	19,893	19,609	54,640
Obtained Spur Gear Sample 3	72,290	19,863	19,905	54,560
Obtained Spur Gear Sample 4	71,840	19,918	20,102	54,450
Obtained Spur Gear Sample 5	72,123	19,917	20,040	54,570
Obtained Spur Gear Sample 6	72,086	19,922	19,966	54,556

Table.6.4. Mass of the Billet and Forged Gear before and after Forging Process

	Mass Before Forging (g)	Mass After Forging (g)
Sample 1	421,84	420,53
Sample 2	441,86	440,92
Sample 3	448,37	447,36
Sample 4	447,95	446,12
Sample 5	448,07	446,84
Sample 6	447,56	445,62

6.3 Some Problems Encountered During Tests

Due to the simulations no error in the forming of the gears is expected during the real-life experimentation. On the other hand, after the forming process, the ejection of the formed gear from the middle die is expected to be a problem because of the ejection assembly of the die holder. Although the ejector stroke is supposed to reach 36 mm as written in the Smeral Die Holder Manual [49], it does not reach more than 20 mm and it causes the problem of ejecting the formed gear out of the die. To resolve this problem, the die holder is disassembled from the press frame and the ejector system is inspected. It is seen that design of the

ejector system of the die holder is faulty and it is impossible to increase the ejector stroke without doing a machining process on the die holder. This erroneous design of the die holder causes a big problem during the ejection process of the formed gears. The ejection of the formed gear out of the die took nearly two minutes causing the dies and accordingly the springs getting overheated. The overheated springs became inoperative during the forging process and the experiments are stopped before damaging the dies. From the results it is seen that, as mentioned in Chapter 3, if a spring with a high resistance to temperature and a die holder with a high ejection stroke is used, the die design is feasible for mass production.

In the test run, the sample temperature is measured with pyrometers as 1050°C at the induction heater exit, and 1010°C just before forging, moreover the die temperatures before and after the forging process are measured as 250°C and 405°C separately.

CHAPTER 7

GENERAL CONCLUSIONS

7.1. Discussion of the Results and General Remarks

General remarks have been summarized in the following subsections;

7.1.1. Remarks on the Design of Precision Forging Dies for the particular Spur Gear

In this study, “Near Net-Shape Hot Forging” of a particular spur gear has been realized in METU-BILTIR Center Forging Research and Application Laboratory. Alternative precision forging die sets in the literature have been evaluated before starting to design a precision forging die set. The designers have given only some clues about alternative precision forging die sets, but not the complete design in the literature [26-35]. Therefore, a new conceptual precision forging die set design for a spur gear has to be made to achieve a completely closed die forging operation which does not allow any excess material to escape outside of the die and so that no flash formation occurs. In this study, this has been successfully achieved.

The proposed die set consists of three dies which are upper die, middle die, lower die and auxiliary elements such as springs, ejector pins, etc. According to the proposed die set, the middle die and the lower die are assembled to each other by locating helical springs between them. During the forging process, the middle die moves by means of springs. The upper die does not enter into the die cavity, but pushes the middle die downwards, so that no teeth forms are needed on the upper die.

To increase the manufacturing tolerance requirements of the billets which are very high in precision forging, a chamfered section in the upper die has been designed.

To eject the formed gear out of the die, two ejector pins are present in the lower die. Other than ejecting the finished product from the dies, the ejector pins prevent the rotation of the gear section on the lower die. Also two restraining bolts have been integrated into the die set to prevent the dislocation of the middle die from the assembly. These restraining bolts are fixed in the lower die by nuts and the bolt head is free in the middle die assembly.

The proposed lower die is a modular design and it consists of three modules which are, mandrel, gear shaped section and the base. With the help of the modular design, the modules can be changed in the case of die wear or fracture without re-making the whole lower die. Due to the modular lower die design modifications can be easily made like; increasing the mandrel diameter or height, increasing the number of ejectors, etc. The mandrel which is integrated into the lower die is useful for aligning the billet in the precision forging dies and by this way, minimizes the eccentricity caused by the operator

7.1.2. Remarks on Finite Volume Simulation Results of the Particular Spur Gear

The finite volume analysis of the particular spur gear is performed for temperatures of 1000°C, 1050°C, 1100°C, and 1150°C by a commercially available finite volume program. In the simulations, the die temperature is assumed as 250°C. From the simulation results, it is seen that, all of the billet temperature values are resulted with complete die fill. Different billet diameters are simulated in the simulations to achieve the right billet diameter with a successful die filling. At the end of the simulations, it is seen that, the tube-shaped billets which have less wall thickness values are buckled and could not fill the die cavity. Consequently, the tube-shaped billet diameters which result with complete die fill and also adequate for mass production is selected for the real-life experiments.

Considering the metal flow, because of the existence of friction in the interface between the die and the workpiece, the movement of the die assists the metal flow downwards and the bottom corner is formed much earlier than the top corner. At the end of the process, the bottom is fully filled while a designed chamfer was formed at the top corner.

Moreover, the results are examined by considering forging loads and effective stresses. Considering the forging loads, the die forces start to increase at the start of the forging to a certain level and kept within a range while the material flows into the gear teeth section of the die cavity. Close to the end of the process, when the material reaches to the wall of the die cavity, the forces on the dies increase to the maximum value to form the complete teeth form. From the simulations it is seen that as the billet temperature is increased, the die forces decrease. The maximum die force obtained from the analysis is 134 tons at 1000°C. It is observed that the 1000 tons mechanical press which is available in METU-BILTIR Center Forging Research and Application Laboratory is appropriate for the hot forging of the particular spur gear.

7.1.3. Remarks on the Real-Life Experiments of the Particular Spur Gear

The ejection of the formed part from the die plays a very crucial role in precision forging processes. Very small (even zero) draft angles used in the processes makes the ejection stage even harder. Therefore, the press to be used in the precision forging process should have an ejection system with an adequate ejection stroke.

For the real-life experiments, 1050°C billet temperature is selected to achieve a better surface finish and a better dimensional accuracy with less scale loss and by using less energy.

According to the successful simulation results, the designed conceptual die set and the billets are manufactured in METU-BILTIR Research and Development Center CAD/CAM Laboratory. Finally, the experiments for the conceptual design of “Near Net-Shape Hot Forging” are conducted in METU-BILTIR Research and Development Center Forging Laboratory. The conceptual design is successful and flashless forging i.e. precision forging has been realized.

The comparison of the desired particular spur gear dimensions and the obtained spur gear dimensions are given in Table 7.1. As expected, Sample 1 and Sample 2 could not completely obtain the gear geometry since their mass is less than 446 grams as discussed in Section 5.4. Samples 3-6 are above 446 grams and at the end of the experiments; with these samples, spur gear is successfully forged to the desired tolerances. The experiments have been realized only for first six billets and could not be continued due to the reasons explained in Section 6.3. In Fig.7.1, the finite volume simulation results for 1050°C and the forged spur gear at the same temperature by using the proposed conceptual design can be seen. Therefore, a successful precision forging die set for the particular spur gear has been designed and by using the prototype die manufactured, it has been demonstrated that, the proposed conceptual design of precision dies have been successfully implemented in real-life application.

Table 7.1 Comparison of the Aimed and Obtained Spur Gear Dimensions

	Outside Diameter (mm)	Inside Diameter (mm)	Face Width (mm)	Root Diameter (mm)
Desired Particular Spur Gear	72	20	20	54,4
Obtained Spur Gear Sample 1	71,695	19,916	19,030	54,590
Obtained Spur Gear Sample 2	72,380	19,893	19,609	54,640
Obtained Spur Gear Sample 3	72,290	19,863	19,905	54,560
Obtained Spur Gear Sample 4	71,840	19,918	20,102	54,450
Obtained Spur Gear Sample 5	72,123	19,917	20,040	54,570
Obtained Spur Gear Sample 6	72,086	19,922	19,966	54,556

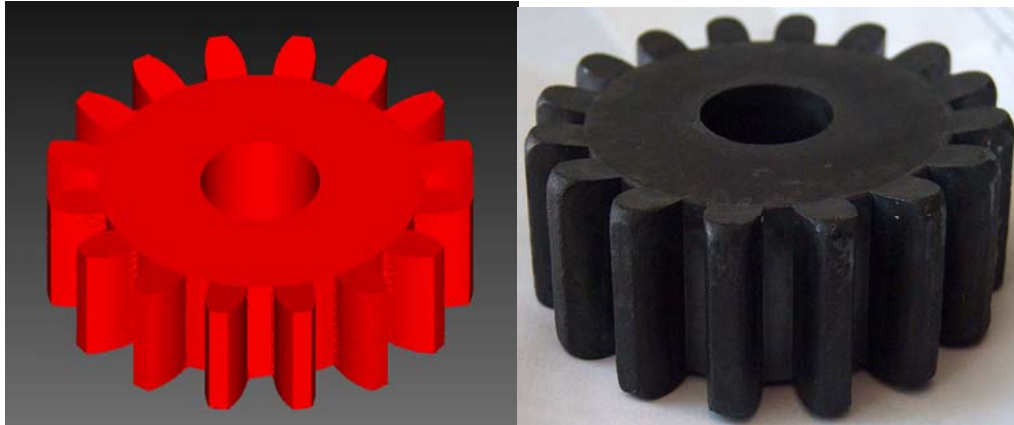


Fig.7.1. Simulated and Forged Spur Gear

7.2 Future Work

Suggested future works;

- The real-life experiments could be made on a different press with a high ejection stroke or using the same press but making appropriate machining modifications in the die holder. Moreover the real-life experiments could be made using a spring with a resistance to high temperature,
- The finite volume simulations could also be conducted by using a Finite Element Simulation program,
- Warm and cold precision forging of the spur gear can be analyzed,
- The study can be extended for different gear types such as bevel gears,
- Precision forging for spur gears with different sizes or and having different number of teeth can be analyzed,
- Precision forging for different geometries can be analyzed,
- Precision forging of spur gears with different materials can be studied.

REFERENCES

- [1] Boyer H., “Metals Handbook Forging and Casting”, ASM Handbook Committee, 8th Edition, 1971
- [2] Aktakka G., “Analysis of Warm Forging Process”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2006
- [3] Kalpakjian, S., “Manufacturing Processes for Engineering Materials”, Addison Wesley Longman Inc, 3rd Edition, California, 1997
- [4] Altan, T., Boulger, F, W., Becker, J, R., Akgerman, N., Henning, H, J., Forging Equipment, Materials and Practices, Batelle Columbus Laboratories Metalworking Division, Ohio, 1973.
- [5] Sabroff, A, M., Boulger, F, W., Henning, H, J., Forging Materials and Practices, Batelle Memorial Institute Columbus, Ohio, 1968.
- [6] V.Vazquez, Dr. T. Altan, “ Optimisation of Process Design in Forging”, <http://www.forgingmagazine.com/Techpapers/FEMSimulation/FEMSim.html>, June 2007
- [7] Alper, E., “Computer Aided Design of Axi-Symmetric Press Forgings”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 1989.
- [8] Kutlu, A, E., “Analysis and Design of Preforms for Non-Axisymmetric Press”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2001.

- [9] Karagözler, A. B., “Analysis and Preform Design for Long Press Forgings with Non-Planar Parting Surfaces”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2003
- [10] Gülbahar S., “Preform Design for Heavy Vehicle Steering Joint”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2004
- [11] Civelekoğlu B., “Analysis of Forging for Three Different Alloy Steels”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2003
- [12] T. Gulec, “ Computer Aided Design of Drop Forging Dies”, M. S. Thesis, Middle East Technical University, Ankara, Turkey, 1994
- [13] “DIN STANDARD 7523 Design of Drop and Press Forgings”, September 1986, Part 2
- [14] Private Communications with AKSAN Steel Forging Company.
- [15] R. Douglas, D. Kuhlmann, “Guidelines for Precision Hot Forging with Application”, Journal of Material Processing Technology, pp. 182-188, 2000.
- [16] A.N. Bruchanow, A. W. Rebelski, “Gesenshmieden und Warmpressen”, Verlag Technik, Berlin, 1955
- [17] Ding, P., Inoue, T., Ju, D. Y., Vries, E., “Forging Process Simulation Incorporating Strain-induced Phase Transformation by the Finite Volume Method”, Simulation of Materials Processing: Theory, Methods and Applications, Mori (ed.), 2001.
- [18] Mehta, Bhavin V., “Evaluation of MSC.SuperForge for 3D Simulation of Streamlined and Shear Extrusion Dies”, Ohio University, Ohio, USA, 2000.

- [19] Zuo, X., Wei, Y., Chen, J., Zeng, L., Ruan X., “3D FEM Simulation of Multi-stage Forging Process Using Solid Modeling of Forging Tools”, *Journal Materials Processing Technology*, Vol. 91, pp. 191-195, 1999.
- [20] Weronki, W. S., Gontarz, A., Pater Z., “Analysis of the Drop Forging of a Piston Using Slip-Line Fields and FEM”, *International Journal of Mechanical Sciences*, Vol. 39, No. 2, pp. 211-220, 1997.
- [21] MacCormack, C., Monaghan, J., “Failure Analysis of Cold Forging Dies Using FEA”, *Journal Materials Processing Technology*, Vol. 117, pp. 209-215, 2001.
- [22] Slagter, W., “Forging Simulation Tool Based on Breakthrough Technology”, 2nd International Conference on Design and Production of Dies and Moulds, Conference Proceedings, Kuşadası, Turkey, 2001.
- [23] Buijk, A. J., “Application of the Finite Volume Method to Upset Forging of Cylinders”, Forging Fair, Columbus, Ohio, 2000.
- [24] Vries, E., Ding P., “Simulation of 3D Forging and Extrusion Problems using a Finite Volume Method”, MSC Taiwan User Conference, Taipei, 2000.
- [25] Gökler, M.I., “Computer Aided Sequence and Die Design for Hot Upset Forgings”, Ph.D. Thesis, University of Birmingham, England, 1983.
- [26] Doege, E., Bohnsac,R., Closed die technologies for hot forging, *Journal of Materials Processing Technology*, Vol. 98, pp.165-170, 2000
- [27] Dean, T., A., Progress in net-shape forging, *Advanced Technology of Plasticity – Proceeding of the Fourth International Conference on Technology of Plasticity*, 1993

- [28] Vazquez, V., Altan, T., Die design for flashless forging of complex parts, Journal of Materials Processing Technology, Vol. 98, pp.81-89, 2000
- [29] Douglas, R., Kuhlmann, D., Guidelines for precision hot forging with applications, Journal of Materials Processing Technology, Vol. 98, pp.182-188, 2000.
- [30] Behrens, A., Doege, E., Reinsch, S., Telkamp, K., Daehndel, H., Specker, A., Precision forging processes for high-duty automotive components, Journal of Materials Processing Technology, 16-24, 2006
- [31] Yoshimura, H., Tanaka, K., Precision forging of aluminum and steel, Journal of Materials Processing Technology, Vol. 98, pp.196-204, 2000
- [32] Shan, D., Xu, W., Lu, Y., Study on precision forging technology for a complex-shaped light alloy forging, Journal of Materials Processing Technology, Vol. 151, pp.289-293, 2004
- [33] Dean, T., A., The net-shape forming of gears, Journal of Materials Processing Technology, Vol. 21, pp.271-278, 2000
- [34] Cai, J., Dean, T., A., Hu Z., M., Alternative die designs in net-shape forging of gears, Journal of Materials Processing Technology, Vol. 150, pp.48-55, 2004
- [35] Hua, C., Wang, K., Liu, Q., Study on a new technological scheme for cold forging of spur gears, Journal of Materials Processing Technology, Vol. 151, Issues 1-3, pp.289-293, 2007
- [36] Pro/Engineer Wildfire III User Guide, PTC, Release 2006
- [37] Tunç Mehmet., “Computerised Cost Estimation for Forging Industry”, M. Sc. Thesis, Middle East Technical University, Ankara, Turkey, 2003

[38] ISO 10243 Die Springs

[39] www.metrol.com [On-Line], Available at, <http://www.metrol.com/products/die-springs-faq.html>, June 2007

[40] A. Bramley; Forging Modelling. Proc. of the 9th Intern. Cold Forging Congress, pp 165-168, 1995.

[41] W. J. Slagter, C. J. L. Florie and A. C. J. Venis, "Advances in 3-D Forging Process Modeling", MSC.Software Corporation, Groningeweg 6, 2803 PV Gouda, The Netherlands.

[42] P. Ding, D. Ju, T. Inoue, E. Vries, "Numerical Simulation of Forging and Subsequent Heat Treatment of a Rod by a Finite Volume Method", ACTA Metallurgica Sinica (English Letters), Vol. 13, No. 1, pp 270-280, February, 2000.

[43] A. E. Tekkaya, "Current State and Future Developments in the Simulation of Forming Processes". Proc. 30th Plenary Meeting of the International Cold Forging Group ICFG, Den Bosch, September 1997, pp.1-10.

[44] W. J. Slagter, C. J. L. Florie and A. C. J. Venis, "Forging Simulation Tool Based on Breakthrough Technology", MSC.Software Corporation, The Netherlands.

[45] V. Bhavin Mehta, Ibrahim Al-Zkeri, Jay S. Gunasekera, "Evaluation of MSC.SuperForge for 3D Simulation of Streamlined and Shear Extrusion Dies", Ohio University, Athens, Ohio, USA, 2000.

[46] MSC.SuperForge, Material Library

[47] Lin, S., Y., "An Investigation of Die-workpiece Interface Friction during Upsetting Process", Journal of Material Processing Technology, pp. 239-248, 1995

[48] Personal Communication with Bias and MSC.SuperForge Authorities from USA

[49] Smeral QLZK UC Die Holder Manual

[50] TS 1845, February 1975

[51] www.uddeholm-tooling.com [On-Line], Available at,
http://www.uddeholm-tooling.com/english/files/dievar-english_061106.pdf, June 2007

[52] MSC.Superforge, Manual

[53] Private Conversations with Assab Korkmaz Company

APPENDIX A

MATERIAL PROPERTIES OF GEAR STEEL, 16MNCR5

Subcategory: Carbon Steel, Cementation Steel

Close Analog: DIN.1.7131

Composition (%):

C	Si	Mn	P	S	Cr
0,14-0,19	0,15-0,40	1,00-1,30	0,035	0,035	0,80-1,10

Physical Properties:

Density: 7850 kg/mm³

Hardness: 217 BHN, 94 HRc-B (Hot Rolled)

Mechanical Properties at Room Temperature:

Tensile Strength (Ultimate) : 590 MPa

Yield Strength : 880 MPa

Poisson's Ratio : 0.3

Thermal Properties:

Thermal Conductivity : 45.9 W/m-K

Coefficient of Thermal Expansion : $1.15 \cdot 10^{-5}$ W/m²K

APPENDIX B

MATERIAL PROPERTIES FOR TOOL STEEL, DIEVAR

Subcategory: Chrome-moly Steel; Ferrous Metal; Hot Work Steel; Tool Steel

Composition (%):

C	Si	Mn	Cr	Mo	V
0,35	0,20	0,50	5.00	2.30	0.60

Physical Properties:

Density: 7800 kg/mm³

Hardness: 160 HRB, 85 HRC-B

Mechanical Properties at Room Temperature:

Tensile Strength (Ultimate) : 1640 MPa

Yield Strength : 1380 MPa

Shear Modulus : 150 GPa

Poisson's Ratio : 0.22

Thermal Properties:

Thermal Conductivity : 31 Watt/m-K at 400°C

Coefficient of Thermal Expansion : 7.4 µm/m-°C between 25-400°C

APPENDIX C

HEAT TREATMENT

The expected mechanical properties of a tool steel can only be seen if a proper heat treatment is done after machining. Only after heat treatment has been completed, tool can be machined to finish size. In this study the precision forging die set is heat treated in vacuum furnaces available at a private company in Izmir [53]. As it can be seen from Fig.C.1, the precision forging die set is heated to austenitizing temperature which is 1000°C in three sub-stages of 450°C, 640°C and 830°C. When the vacuum furnace is reached to the austenitizing temperature, it is kept in the furnace for some more time until all the sections of the dies reach to the same temperature. Afterwards the dies are cooled rapidly with a cooling rate of 36°C/min. Then the tempering process is applied to the dies. This heat treatment results in higher toughness values, without sacrificing all of the hardness and tensile strength gained from the processes applied previously. The toughness and hardness values are inversely proportional. In this study the toughness, meaning that the impact absorbing ability of steel without fracture is more important than the hardness because of the hitting of the dies one to another. Taking into account to these, first tempering process is applied about 2 hours at 580°C. After the first heat treatment process the hardness values of the dies are measured as 52 HRc. Then the second tempering process is applied about 2 hours at 600°C and the hardness value became 48 HRc. Finally, the third tempering process is applied about 3 hours at 585°C and the hardness value is measured as 48 HRc.

To summarize;

1000°C Austenitizing (30min) – 36 °C/min rapid cooling rate – 580°C (2hour)
first tempering process (52 Hrc) - 610°C (2hour) second tempering process (48
Hrc) - 585°C (3hour) third tempering process (48 Hrc)

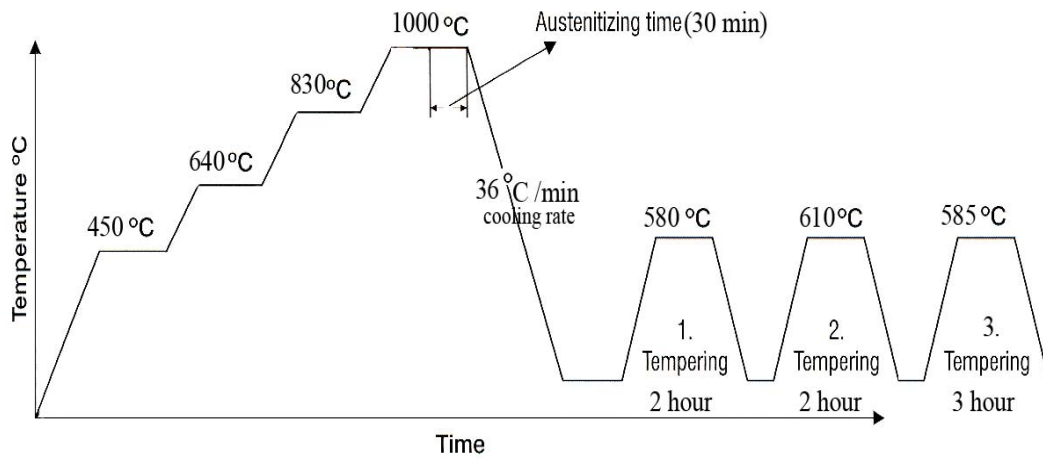


Fig.C.1 Heat Treatment Process

APPENDIX D

TECHNICAL DATA OF 1000 TON SMERAL MECHANICAL PRESS



Fig.D.1. Smeral 1000 ton mechanical press in METU-BILTIR Center Forging Research and Application Laboratory

Nominal Forming Force	: 10 MN
Ram Stroke	: 220 mm
Shut Height	: 620 mm
Ram Resetting	: 10 mm
Rod Length	: 750 mm
Crank Radius	: 110 mm
Number of Strokes at Continuous Run	: 100 min ⁻¹
Press Height	: 4840 mm
Press Height above Floor	: 4600 mm
Press Width	: 2540 mm
Press Depth	: 3240 mm
Press Weight	: 48000 kg
Die Holder Weight	: 3000 kg
Main Motor Input	: 55 kW
Max. Stroke of the Upper Ejector (without die holder)	: 40mm
Max. Stroke of the Lower Ejector (without die holder)	: 50 mm
Max. Stroke of the Upper Ejector (due to the die holder)	: 20 mm
Max. Stroke of the Lower Ejector (due to the die holder)	: 20 mm
Max. Force of the Upper Ejector	: 60 kN
Max. Force of the Lower Ejector	: 150 kN