KT Journal of Mechanical Engineering

ISSN: 3048-9563 (Online)

Key Tech Services Publication, India

http://www.ktjme.com
https://doi.org/10.64188/3048956325012
Vol.: 2, No. 2, 2025, Pages: 22-33

DESIGN AND ANALYSIS OF A DIE FOR AN AUTOMOTIVE COMPONENT

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Abstract

The present work focuses on the design and analysis of a closed die for forging an automotive crankshaft component. Forging is a preferred manufacturing process for such components due to its superior mechanical properties, high reliability, and material efficiency. Traditionally, die design relied heavily on trial-and-error methods, leading to high costs and longer development cycles. In this study, a systematic approach was adopted using CAD/CAE tools and finite element simulations to optimize the die design. Blocker and finisher dies were modeled and meshed, followed by iterative simulations using Forge Nxt software to analyze metal flow, under-filling, fold formation, force requirements, stress distribution, and die wear. A total of seven iterations were carried out to eliminate forging defects, after which the final die design was validated for stress and force limits within a 5000T press capacity. Die wear analysis indicated minimal high-wear zones, ensuring longer service life. A forging shop trial confirmed that the manufactured crankshaft dimensions were within the acceptable tolerance of ±1.5 mm. The results highlight that the integration of simulation in die design significantly reduces development time, material wastage, and trial costs while improving product quality and reliability. This study demonstrates the effectiveness of computer-aided die design in achieving defect-free forgings and meeting industrial requirements for precision, performance, and cost-effectiveness in automotive component manufacturing.

Received:15.05.2025 Revised: 13.07.2025 Accepted: 24.07.2025 Published Online: 31.07.2025

Keywords: CAD/CAE, crankshaft, Forge Nxt software, Die design,

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How to cite this article: Komal M. Garse, Ranjit R. Mali, Design and Analysis of a Die for an Automotive Component, KT Journal of Mechanical Engineering, 2(2), 2025, 22-33. https://doi.org/10.64188/3048956325012

1. Introduction

Due to the increasing competition in global markets, the profit in metal forming industries is pushed to the marginal or limit level. How to cut costs, improve productivity, and enhance product quality determines whether companies can maintain their leading edge and competitiveness in the severe competitive marketplaces. Modern forging is anything but a static science. The development of new methods, processes, tools, and dies is ongoing constantly. Production speeds are getting faster. In short, forging has left the village blacksmith far behind, racing ahead to maintain its leadership in our total industrial picture. The forging industry is alive with new trends. Some forgings are now combined into one, adding to the size and complexity of modern forged shapes. Other forgings are getting smaller, stronger, and are being made faster and to closer tolerances than ever before. In a miraculously short space of time, the industry learned how to precision forge complicated automotive components, due to the difficult steels and shapes required. With the ability to manufacture complex components degree of structural reliability, and a high strength-to-weight ratio achieved in the forging process, the forgings are the best choice for high-performance, high-strength, high-reliability, and long-term usage applications, where tension, stress, load, and human safety are critical considerations. Forging process has some added advantages, such as producing little or no scrap and generating the final part geometry in a very short time, usually in one or two strokes of the hammer or press. As a result, forging offers potential savings in materials and energy, so it is usually used in large or medium-sized manufacturing processes. Forgings find their application in various sectors such as the automotive industry, the defense ministry, marine industry and aerospace industry, agricultural machinery, off-highway and railroad equipment, fitting, petrochemical applications, industrial hardware, and hand tools. Consequently, the most significant objective of any method of analysis is to assist the forging engineer in the design of forging and or in the pre-forming sequences. For understanding and quantitative design and optimization of forging operations, it is useful to consider forging processes as a system and classify these processes in a systematic way. Talking about the forging process, Bharat Forge Limited is one of the leading forging companies. Throughout the years, a great deal of know-how and experience has been accumulated in this field, largely by trial-and-error methods. Nevertheless, the forging industry has been capable of supplying products that are sophisticated and manufactured to very rigid standards from newly developed, difficult-to-form alloys. In the past, forging die design procedure was based on the experience and intuition of the die designer and some empirical guidelines. The advent of using high-speed computers and their diminishing costs has made possible development of CAD/CAE/CAM of forging dies possible to a point where the forging process can be simulated and defects can be predicted. The dies can then be designed and manufactured for moderately complex shapes.

2. Literature Review

Bramley and Mynors [1] study briefly the origins of plasticity theory and its application to the forging process, including the demise of some procedures. Their paper then focuses on the use of numerical modelling simulation tools and their application and future potential for the forging industry. This includes the results of research by the authors and others into the usability aspects of these techniques. Some of the limitations of current commercial software are discussed, thus suggesting a future research agenda. Computer simulation of forging is a technique that enables the behavior of the workpiece material in a forging operation to be predicted. Caporalli et al. [2] in their research studied that planning of hot forging processes is a time-consuming activity with high costs involved because of the trial-and-error iterative methods used to design dies and to choose equipment and process conditions. Some processes demand many months to produce forged parts with controlled shapes, dimensions, and microstructure. The design of the tools for the forging of a respective component takes a lot of time. In their research, they showed how expert systems can help engineers to reduce the time needed to design precision forged parts and dies from machined parts. Lasne et al. [3] studied the objective of optimizing automatically industrial forming conditions to achieve a desired objective goal is now possible due to the continuous increase of fast and parallel computers. Optimization requires that the computer simulation is accurate enough, that the material behavior is precisely identified, and that the optimization parameters are properly selected. To achieve the first goal, the fundamental mechanical assumptions and the basic principles of three-dimensional finite element discretization are briefly recalled. Douglas and Kuhlmann's [4] study reveals that the economic pressures from alternative processes, international competition, and government regulation have made precision hot forging an attractive option for the forging industry. The forging process is exceedingly complex with many variables. However, new tools have made it possible to simulate and control the forging process to a degree not thought possible in the past. Forging has traditionally enjoyed an eminent position among the various methods of manufacturing because forged products, for good reason, have been looked upon as offering maximum reliability and superior properties. Equbal et al. [5] have found that optimization of the forging process is required to reduce the production cost of the die as well as the forged part, and to increase the accuracy of the die and the forged part. In the metal forging process, the performance of the die and, hence, product quality is heavily dependent on various parameters. In order to reduce the cost of the forging process and make it competitive with other production methods, it is essential to optimize these parameters that will facilitate a risk-free manufacturing environment, which can help to minimize the overall cost. Fujikawa's [6] research is related to the application of CAE for their hot forging plant. Since the late 1980s, the commercial-based forging analysis software has come into the market and brought some benefits for optimizing forging processes. Nissan Motor Co. has applied CAE (computer-aided engineering) mainly to hot-forging processes. The first example is a model experiment using Plasticine and FE (finite-element) simulation with analysis of variance using the orthogonal array to reduce the amount of input material for crankshaft forging. Pillinger et al. [7] in their research overviewed the recent research in the numerical simulation of forging, with an emphasis on applications rather than the mathematical formulations, which are well documented elsewhere. The research addresses several specific topics, including Process Modeling, Tool and Die Design, Interface Phenomena, Material Phenomena, and Computational Aspects. The paper also looks at recent developments in re-meshing and its importance in realistic forging modeling. While forging may be one of the most ancient of metalworking techniques, it remains today one of the most important manufacturing processes. Y-T et al. [8] studied the development of a design system for efficient and faster product development. The evolution of modern technology demands ever-increasing international competitiveness of manufacturing processes and products, requiring lower design and manufacturing costs. To achieve this goal, the design and manufacturing engineers work together as a team to come up with an economical solution meeting the given constraints. Jolgaf et al. [9] work is devoted to the development of a CAD/CAM system for the closed-die forging process. The application of computer-aided engineering (CAE), computer-aided design (CAD), and computer-aided manufacturing (CAM), is essential in modern metal forming technology. Thus, the process of modeling for the investigation and understanding of deformation mechanics has become a major concern in recent and advanced research, and the finite element method (FEM) has assumed increased importance, particularly in the modeling of deformation processes. In manufacturing operations, many parts are formed into various shapes by applying external forces to the workpiece by means of tools and dies. Jian et al. [10] investigated the hot forging process of micro alloyed steel. The crankshaft model was built according to the data, directly measured from the blocker crankshaft blank. The simulation of crankshaft forging was carried out by FEM software Ansys/ Ls-Dyna. The changes in structure and temperature field were simulated during hot forging. The relationships between the metal flow rules and the temperature field in the crankshaft were described. Kumbhar et al. [11] in their research found that new process development of a forging component requires a lot of process knowledge and experience. Even lots of trial-and-error methods need to be used to arrive at the optimum process and initial billet dimensions. But with the help of reliable computer simulation tools, it is now possible to optimize the complete process and billet dimensions without a single forging trial. This saves a lot of time, energy, and money Rathi and Jakhade [12] studied the various forging processes and the defects occurring within the processes. Initially, some important forging terms that are widely used in this field were discussed. A brief description of the classification of forging processes based on the temperature of work workpiece (hot, cold, and warm forging) and based on the arrangement of dies (open, impression, and closed-die forging) is given. Die design parameters, die material requirements, and the selection of proper die materials are briefly discussed. Shamasundar [13] has studied the use of computer simulation in the forging process for product development. During the research, he has made use of a simulation technique for the development of a crankshaft, an automobile component. In the paper, the authors discuss the application of FEM analysis-based process modeling of crankshaft forging for the analysis of grain flow and heat treatment. Tomov et al. [14] studied both open and closed-die forging processes are widely spread in the metal working industry for discrete part production. As a rule, this kind of process is are non-steady-state one, which makes its analytical investigation rather difficult. Due to that, some of the steps in the process planning and design depend on rules based on the experience gained in the forging practice. Zhanga et al. [15] studied the plastic deformation characteristics of 42CrMo steel in the upsetting process and found the feasibility of using computer simulation to analyze and research the upsetting process of the 42CrMo billet. By means of commercial and professional plastic forming software DEFORM-3D, the forging process of a 42CrMo billet was simulated [16-19].

3. Designing process for closed die forging

3.1 Introduction

Die design and manufacturing are important steps in metal forming product development. Without a suitable die, metal forming processes are often crippled or rendered totally inefficient. To have a die that has a long service life, the design and manufacture of the die must be well conducted. Many factors affect die service life, which may range from die design, die geometry, and material, heat treatment condition, billet conditions, and material, and further to manufacturing and tribological conditions between the die and workpiece. Therefore, how to systematically and integrally design of die together with the metal-formed product, forming process sequence, and the detailed process conditions is an important issue. Traditionally, die design is based more on heuristic know-how and experience acquired through trial and error than deep scientific analysis and calculation. This kind of product development paradigm cannot ensure that the die service life is optimally designed, as the interaction and interplay among the above-mentioned affecting factors on die service life is difficult to quantitatively represent and determine based on the traditional experiences and know-how. To have good die performance and service life, the die should be optimally designed and precisely fabricated. On the other hand, die materials need to be well selected and heat-treated. In die service stage, the working conditions and working processes need to be well determined. To realize this goal, industries and academia have made a lot of effort to conduct extensive research in this area.

Impression die forging is also called closed die forging. In closed die work, metal is placed in a die resembling a mold, which is attached to the anvil. The hammer is then dropped on the workpiece, causing the metal to flow and fill the die cavities. The hammer is generally in contact with the workpiece on the scale of milliseconds. Depending on the size and complexity of the part, the hammer may be dropped multiple times in quick succession. Excess metal is squeezed out of the die cavities; this is called flash. The flash cools more rapidly than the rest of the material; this cold metal is stronger than the metal in the die, so it helps prevent more flash from forming. This also forces the metal to fill the die cavity. After forging, the flash is trimmed off. In commercial closed forging, the workpiece is usually moved through a series of cavities in a die to get from a billet to the final form. The first impression is used to distribute the metal into the shape that resembles the final production. This impression is called a blocker die. The deformed metal then passes through the finisher dies to get the final impression. The design process can be expressed as follows:

3.2 Estimation

The first step in the CDFD department is the estimation division. Every new part development must have an estimation report that needs to be sent to the customer for reviewing the basic proposals of the company as per the requirement. This division estimates the whole forging process for the required customer part, including the machining and heat treatment processes. It takes the metallurgical data from the Metallurgical Quality Control (MQC) department.

The estimation division decides the following parameters for the forging of the component required:

- Line (Press/Hammer) Selection
- Development of Forged part drawing
- Process Requirement, etc.

3.3 Line Selection

The selection of the press depends on many factors, like:

- Weight of the forged part
- Size and dimension of the part
- Process Requirement
- Quantity Required

This gives an approximate idea about the unit that can be chosen from the available press and hammer. The size of the part also affects the press selection because of the limitation of the die size of the unit. The Eumoco 5000-tonne press was being selected for the forging of the dies.

3.4 Development of Forged Part Drawing

The first step is the modeling of the forge part as per the customer-supplied drawings or model. In consultation with the customer, many parameters need to be changed while modeling the part on the modeling software. For example, many times due to a lack of proper forging requirements, the draft angle supplied by the customer may be less than what may be required to forge the part. In this case, the required draft angle for forging of the part is reported to the customer for their approval. Many times, the machining allowances provided by the customer may be less than what is required to maintain the quality output by the company. The machining allowance is increased in such cases, which is again provided to the customer for final approval.

3.5 **Parting Line**

Die parting line is the plane that divides the top and bottom dies in a close die forging. This depends upon the ease of die filling, forging equipment, grain flow, and trimming facility. A proper parting line avoids deep impressions that might cause die breakage.

3.6 Draft Angles

Draft angles are necessary on all forgings to permit the removal of the forged part from dies and to assist in achieving the desired metal flow. Forging equipment also plays a vital part in ascertaining the draft angle. Draft angle is usually between 3 to 5 degrees.

3.7 Fillet and Corner Radii

Fillet and corner radii greatly affect the metal flow in a die. Good fillet radii smooth out the metal flow and avoid defects of overlaps. Bigger fillet radii increase the machining allowances and weight of the forgings. The choice of corner radii is also an important factor because small corner radii will cause die breakages.

4. Finite Element Method

4.1 Introduction

Computer technology became inevitable in the engineering and manufacturing industry as computing has become cheap and fast enough to simulate metal forming numerically in a useful timescale. The finite element (FE) method has been used to solve equations that describe solid metal flow. In the last 15 years, considerable efforts have been made, largely in a research environment, to apply FE modeling to the simulation of forging operations and to evaluate the results. The technique is now being adopted by the forging industry. As computer technology and FEM advance, wider and more complicated metal forming processes are being investigated. It is believed that the further development of FEM will be continuously challenged by the need from the industry to make the modeling more accurate, more practical, and more affordable. Since a decision made at the design process level has a profound effect on die and tool design, manufacturing, maintenance, mechanical properties, and life cycle, a great deal of effort is being made to reduce experience-based process development. According to recent remarkable advances in computer technology, the applications of computers in manufacturing have been growing rapidly and independently in computer-aided design/computer-aided manufacturing (CAD/CAM), computer-aided engineering (CAE), and rapid prototyping to aid design and manufacturing activities in present-day industries.

4.2 Designing and Modeling of Dies

4.2.1 Blocker Dies

A block die is used to give an initial shape. The blocker die is developed by making use of the 3D model of the blocker crankshaft. The parting line divides the dies into the lower and upper dies. Figures 1 and 2 show the Blocker Bottom and Top die, respectively.

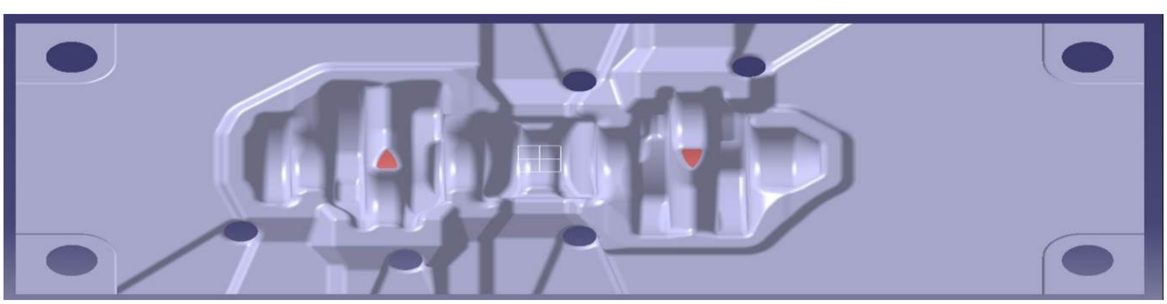

Figure 1. Blocker Die (Bottom Die)

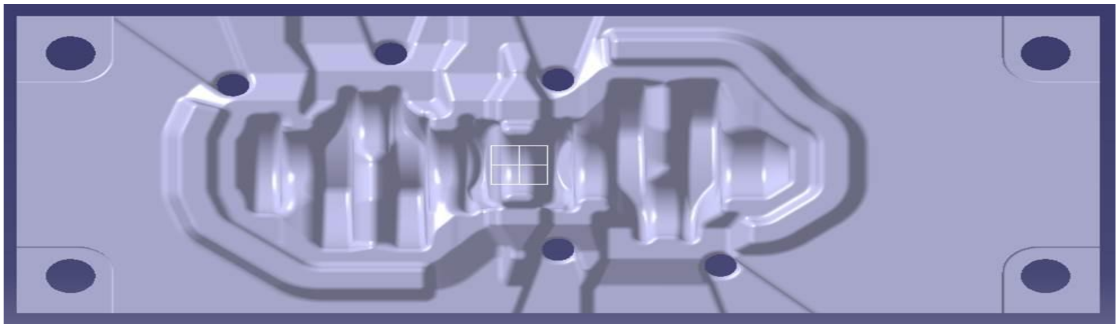

Figure 2. Blocker Die (Top Die)

4.3 Meshing of Dies

The meshing of the dies is done on the software by Altair called Hypermesh. The first step is Geometry clean-up, where all the red colored surfaces, which represent the free edges, are filled. Also, yellow-colored surfaces that represent three or more surfaces sharing a common edge also need to be removed. This is essential since die surface needs to be continuous. The mesh is just a surface mesh and not a volumetric mesh. This is to ensure that there is no deformation to the die. When analyzing the die stress in simulation, the dies are also volumetrically meshed so that they become deformable. The volumetric meshing of the dies is done in Forge itself, selecting a constant mesh size. Figure 3 shows the meshed Blocker Bottom Die. Table 1 shows the different mesh sizes used for the different regions.

Table 1. Variable Blocker Meshing

Region	**Mesh Size**
Impression sinking	1-2
Striking Face	2-8
Side walls	8-16

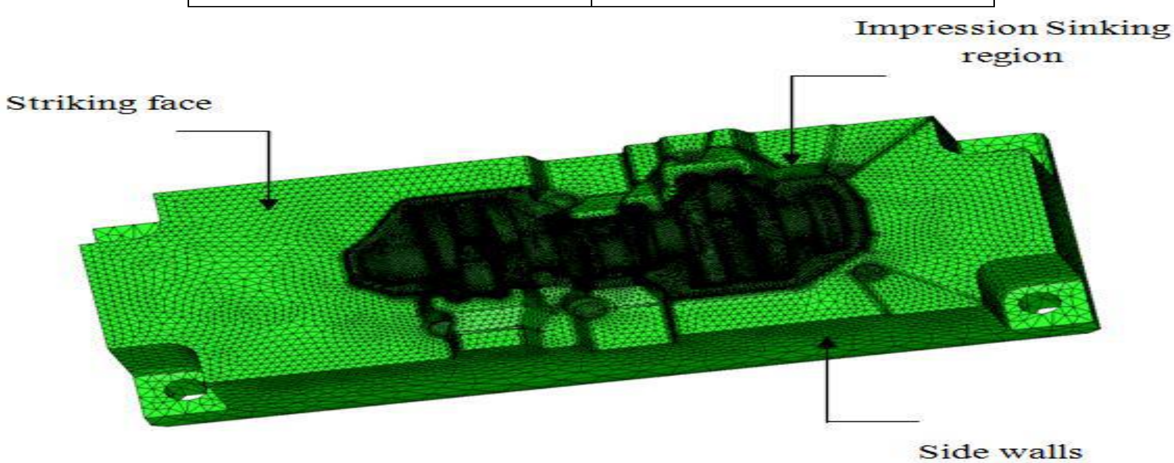

Figure 3. Meshed Blocker Bottom Die

Figure 4 shows the meshed Finisher Bottom Die. Table 2 shows the different mesh sizes used for the different regions.

Table 2. Variable Finisher Meshing

Region	Mesh Size
Impression sinking	1-2
Striking Face	2-8
Side walls	8-16

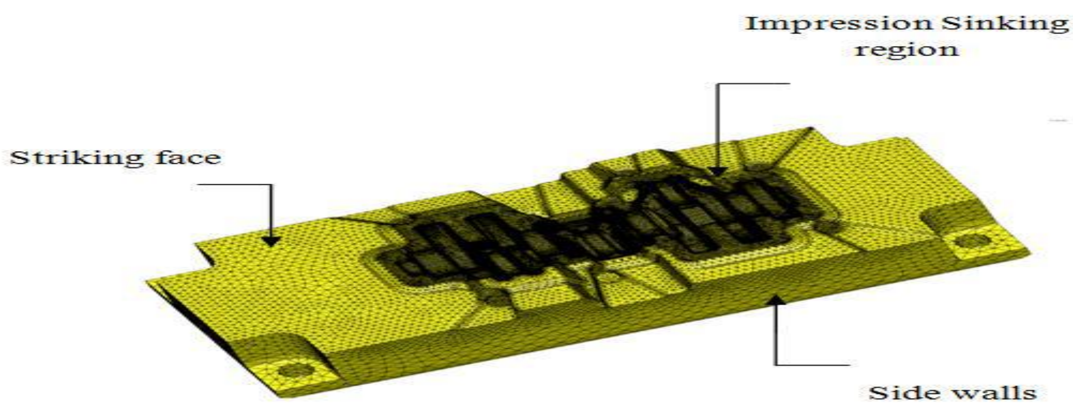

Figure 4. Meshed Finisher Top Die

5. Stress Analysis of Dies

During the analysis of the dies, once the defect-free blocker and finisher dies are obtained, the stress analysis of the dies is done. The Dies from the final iteration are then being checked for maximum stresses. The stress analysis is being conducted to predict the high stress zones and to check whether the stresses are within the limits. Depending upon the previous data, the die stress limits are being set for each of the presses. As discussed previously Eumoco 5000-tonne press is being selected, and the maximum stress limit for this press is 3200MPa shown in Figures 5 and 6.

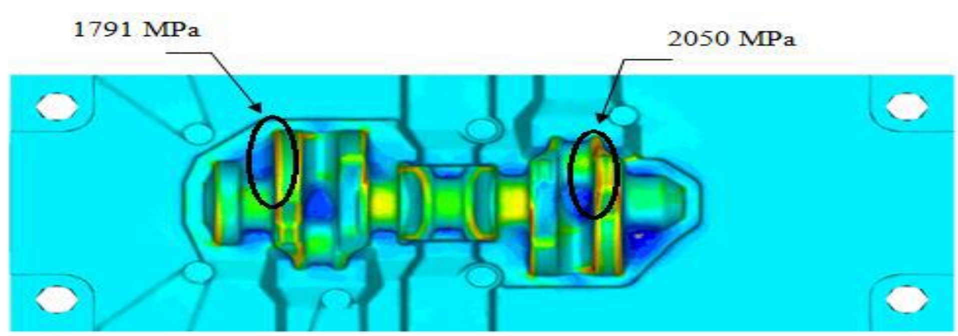

Figure 5. Blocker Bottom Die

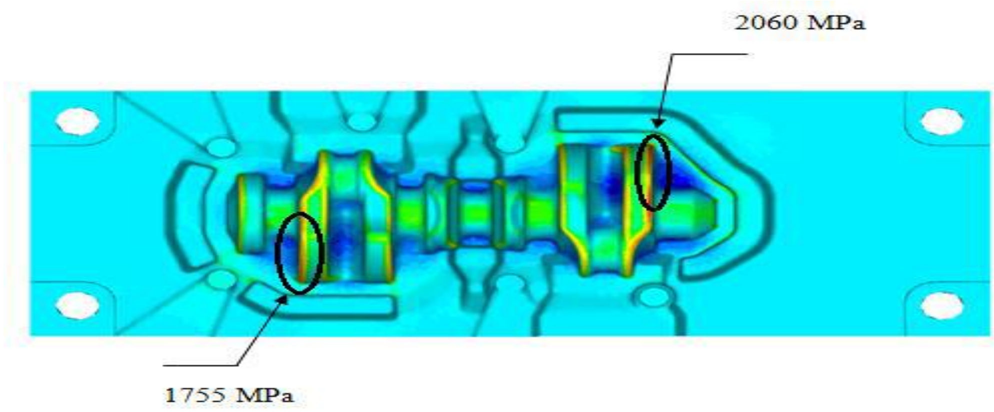

Figure 6. Blocker Top Die

4.1 Force Analysis

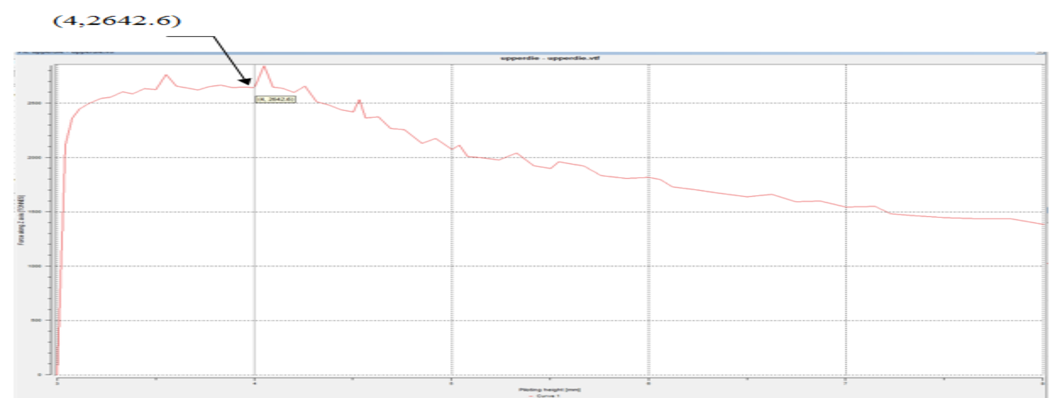

Figure 7. Force vs Piloting Height plot for Blocker Die

Figure 7 shows the force plot for the blocker dies. For the blocker dies, the force required to obtain a flash thickness of 4 mm was observed to be 2642.6 tonnes, which is lower than the available press capacity of 5000 tonnes. Hence, the design of the blocker dies was safe considering the capacity of the available press.

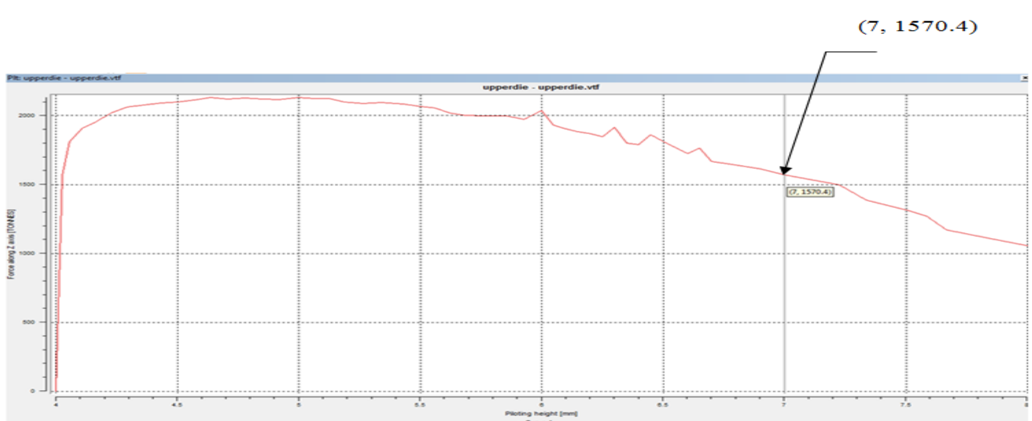

Figure 8. Force vs Piloting height plot for Finisher Die

Figure 8 shows the force plot for the finisher dies. For the finisher dies, the force required to obtain a flash thickness of 7mm was observed to be 1570.4 tonnes, which is lower than the available press capacity of 5000 tonnes. Hence, the design of the blocker and finisher dies was safe considering the capacity of the available press.

6. Conclusions

The use of Computer simulation could capture the defects occurring in the existing forging process. The simulation results gave insight into the forging process, enabled to find the defects before manufacturing the component, and helped in the prediction of the force required for the forging. Modified Blocker and Finisher Die designs were developed by an iterative computer simulation method. The forging defects (folds, under-fills) were removed using the simulation method. Results of the simulation are validated by shop floor trials. The entire exercise of computer simulation helped to arrive at an optimum forging process with no forging defects, which gave the benefits of reduction in time, cost, material wastage, and improved product quality.

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