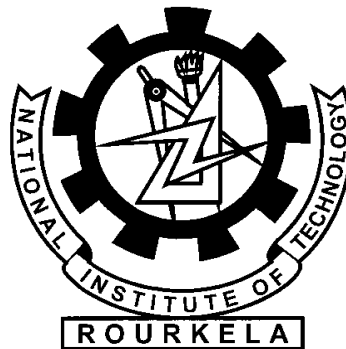


STUDY OF PROCESS PARAMETERS TOWARDS IMPROVING EFFICIENCY OF CLOSED DIE HOT FORGING PROCESS

**A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENT FOR THE AWARD OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN
MECHANICAL ENGINEERING
(SPECIALIZATION IN PRODUCTION ENGINEERING)**

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National Institute of Technology, Rourkela CERTIFICATE

This is to certify that the dissertation entitled, “**Study of Process Parameters towards Improving Efficiency of Closed Die Hot Forging Process**” being submitted by **Chandan Samal** to the National Institute of Technology, Rourkela, as a partial fulfilment of the requirements for the award of the degree of **Master of Technology in Mechanical Engineering (Production Engineering)**, is a record of bonafide research work carried out by him during the period July 2013 to May 2014 under our guidance and supervision.

To the best of our knowledge, this work has not been published/reported or submitted to any other university or institution for the award of any degree.

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*I am grateful to the Director, **Prof. S.K. Sarangi**, and **Prof. K.P. Maity**, Head of Mechanical Engineering Department, National Institute of Technology, Rourkela, for their kind support and encouragement from time to time.*

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ABSTRACT

Closed die hot forging process is one of the most adopted methods for forming complex shaped parts with satisfactory geometrical accuracy. Over sixty percent of the forgings are processed through this route. Forged parts, though required in many engineering sectors, play a vital role in the automotive sector. The majority of the crucial load bearing structural components as well as safety critical items are processed via the forging route. This is mainly due to the inherent strength to weight ratio and dimensional accuracy that can be combined into the components. Faster production of complex shapes with least wastage of material are some of the other benefits.

The metal flow analysis of the process is complex due to the involvement of a large number of parameters. A number of experimental testings and production-trials are being done in the industry in order to develop a robust manufacturing process. Such practices however involve huge investments in tooling and raw materials, including a great deal of development time and effort. In recent years, finite element method has emerged as a suitable tool for virtual process trials and simulation based design. This would lead to an improvement in overall efficiency of the process at a lower cost.

Through the present study, an attempt has been made to gain an insight into the process parameters influencing the closed die hot forging and their interaction. As a sample case, a real life automotive driveline component, a flange yoke, is taken for investigation. A simulation-driven approach using a commercial package (DEFORM), based on finite element method, was adopted. Trials were conducted using an industrial press, data generated were validated against those predicted. The correlation was found to be satisfactory.

Key words: *Automotive, Closed die forging, Finite Element Method, Hot forging, Process Parameter*

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Among all manufacturing processes, forging can be considered as one of the most adopted metal forming process. The properties generated in the product by the process, such as acceptable dimensional accuracy, higher strength to weight ratio, superior micro structure etc., make the forging process attractive. Other attributes such as faster processing and low material wastage, push down the cost of production of complex shaped parts.

1.1: Forged Components in Automotive

The application of forged parts, include most of the engineering sectors including automotive. The automotive sector is a major user of mass produced precision forging components. Their primary aims, is to manufacture reliable vehicles that can support load carrying at relatively higher speed; simultaneously should be lighter in construction to support fuel economy. Some of the advantages of forging that find favour with auto manufacturers are given below:

- The forged parts, if designed correctly, can take higher loads and greater stresses than same manufacture in another route.
- Due to the close tolerances achieved in the basic shape, further processing such as machining is reduced. So, productivity is improved with a reduction in overall cost.
- Saving in weight of parts can be achieved due to less material wastage and the inherent characteristic of higher strength to weight ratio.
- The deformation due to compressive load ensures reliability in internal structure.
- The grain flow characteristics give improved properties of strength, ductility and resistance to impact and fatigue.
- Lesser processing time supports productivity of the overall manufacturing process.

Typical vehicles contain over 200 separate forging parts, as shown in Fig.1.1. The area of application of such forging parts in automotive is summarised in Table 1.1.



Fig.1.1: Images of typical forged components used in automotive applications

(Image source: www.metalform.de)

Table 1.1: Application areas of forged parts in automotive

SI	Area of Application	Part Description
1	Engine assembly	Crankshafts, Cam shafts, Connecting rods, Rocker arms
2	Driveline assembly	Gear blanks, Drive shafts, Main shafts, Gear shifting levers, Propeller shaft components, Flanges, Yokes
3	Front axle assembly	Main beam, Stub axle, Spindle, Saddles, Anchor plate
4	Rear axle assembly	Drive shafts, Differential case, Crown wheel, Pinions, Gear blanks
5	Steering assembly	Steering shafts, Steering levers, Pitman arms
6	Suspension assembly	Shackles, Retainer
7	Brake/Clutch assembly	S-cam shaft, Callipers, Operating levers

1.2: Closed-die Forging Process: An Introduction

The forging process is deployed aiming at transforming the simple part geometry, into the desired final shape by controlling plastic deformation. In closed die forging (also known as impression die forging), the die imparts pressure on the material through the interface which results in the generation of cavity shaped component. The hot forging criteria together with closed die condition, can produce a higher degree of deformation with reasonable geometrical accuracy, making it a preferred process for mass production of parts with complex shape. A typical arrangement of closed die forging is shown in Fig.1.2.

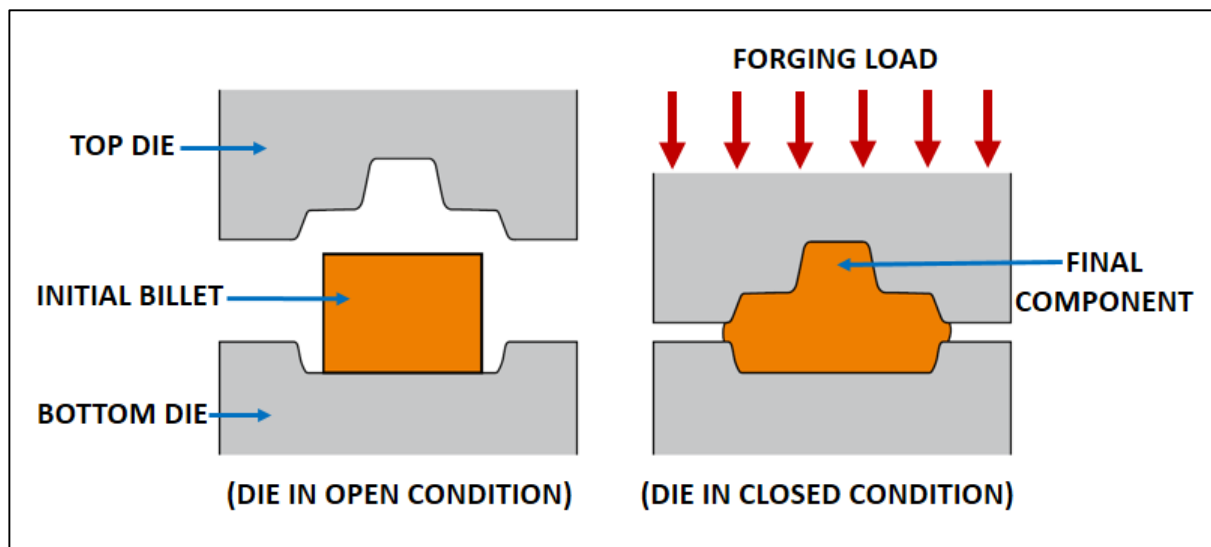


Fig. 1.2: Schematic arrangement of closed die hot forging process

1.3: Process Variables in Closed-die Hot forging (CDHF)

The physical phenomena defining a complex closed die hot forging operation are generally difficult to express in terms of quantitative relationships. A typical closed die hot forging process comprises many input variables that may be clubbed into the following groups. [1]

- i. Product variables
- ii. Material variables
- iii. Tooling parameters
- iv. Machine parameters
- v. Deformation zone characterisation
- vi. Tool and work interface behaviour

Each variable group could further be sub-divided into a set of parameters. A schematic diagram showing the broad parameters that can affect a complex CDHF process is illustrated in Fig.1.3.

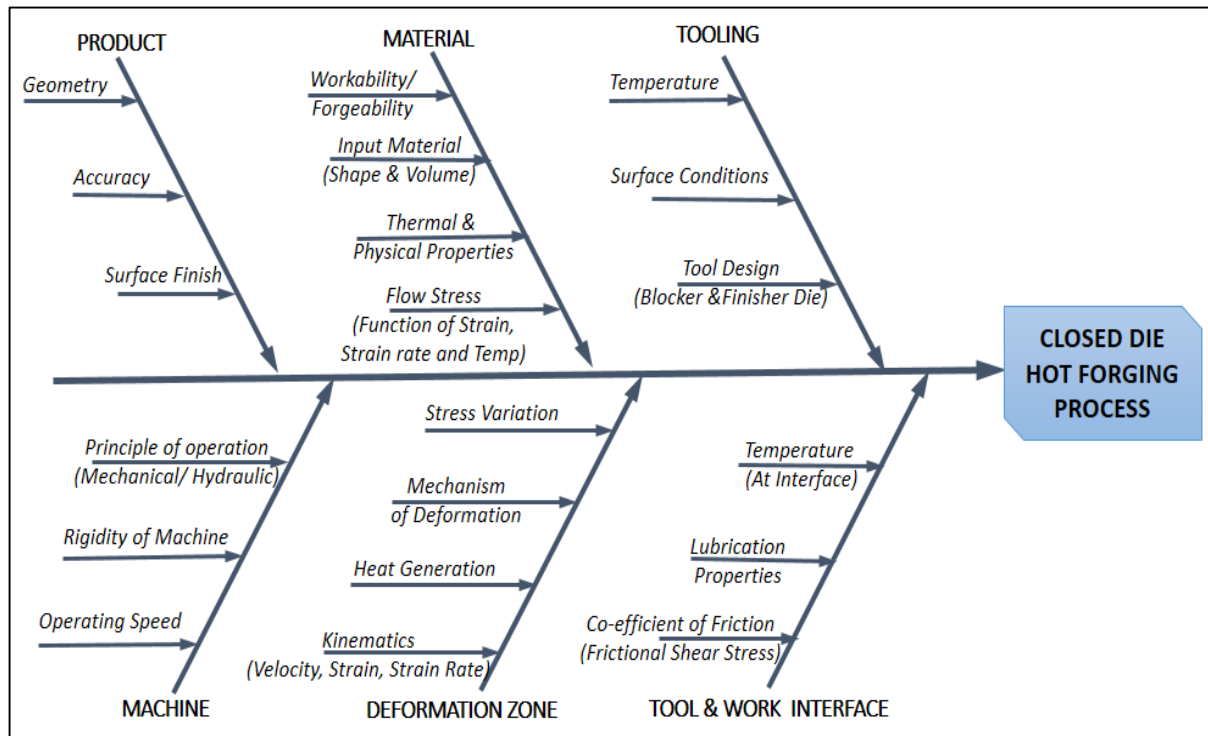


Fig.1.3: List of variables for closed die hot forging process

The input and output parameters, their interrelationship need to be studied along with their effect on product quality for improving the efficiency of the process. Along with this, an understanding of metal flow, its direction, the influence of the extent and rate of deformation in conjunction with the effect of temperature would be vital in controlling the process.

1.4: Major Factors influencing the Metal Flow

There are several factors that can directly influence the metal flow behaviour. They are as follows:

1.4.1: Forging Temperature

In general, increasing the hot forging temperature (which is far above the recrystallization temperature of the material) reduces the flow stress, the strain hardening coefficient and hence the resistance of the material to deform. It is expected that, the forging load requirement would go down.

It should also be noted that, additional heat is generated during the process due to the plastic deformation and friction. Indeed, an appreciable fraction of the mechanical energy involved during the process is converted to heat. This can contribute to an increase in temperature if the strain rate is reasonably high.

1.4.2: Flow Stress

The flow stress refers to the instantaneous value of stress, under the given condition of temperature which is required for continuous deformation or flow of material. This is the most vital material variable in the metal forming analysis. For a given material, the flow stress ($\bar{\sigma}$) is a function of degree of deformation or strain (ϵ), rate of deformation or strain rate ($\dot{\epsilon}$) and temperature of deformation (T). [5]

$$\bar{\sigma} = f(\epsilon, \dot{\epsilon}, T) \quad \dots \quad (\text{Eq.1.1})$$

As has been mentioned, at the temperature of forging the strain hardening is low; hence the rate of deformation or strain rate has a far greater effect on flow stress. The increase in strain rate, increase the values of flow stress, in most cases.

1.4.3: Friction and Lubrication

The forging load applied to the die is transmitted to the workpiece through the die interface. So, frictional conditions at the interface is vital to the metal flow. It can influence the metal flow, die stress and increase the requirement of forging load. Appropriate lubricants are used during metal forming operation to reduce friction, forging load and die wear, so as to improve the metal flow in the lateral direction.

The interface shear friction law is used in metal forming analysis. Mathematically, [1]

$$\tau = f \cdot \bar{\sigma} = \frac{m}{\sqrt{3}} \bar{\sigma} \quad \dots \quad (\text{Eq.1.2})$$

Where,

τ = Frictional shear stress

f = Friction factor

m = Shear factor

$\bar{\sigma}$ = Flow stress of the material

The value of shear factor, m lies between 0 to 1. The recommended value for steel forging with graphite based lubricant is 0.3. [1, 28]

1.4.4: Forgeability of the Material

The forgeability of a metal refers to the ability to undergo deformation without causing defects such as discontinuities or crack. The common tests for forgeability include upsetting and hot-twist. The test is recommended to be performed at similar operating condition as experienced in forging, such as temperature, strain rate. The forgeability also depends on material characteristics such as tendency for grain growth, oxidation and so on.

1.4.5: Shape factor of Component and Die

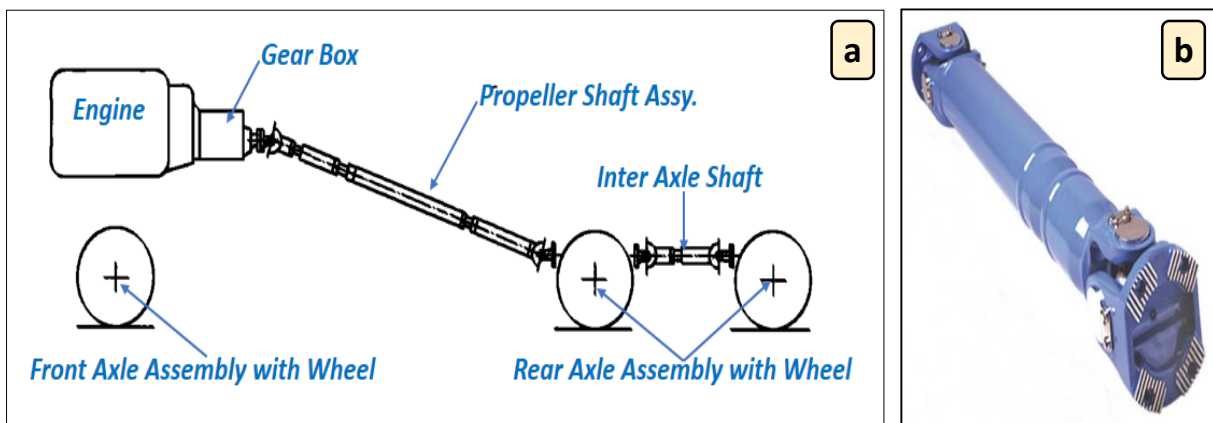
The metal flow in the die cavity is greatly influenced by the geometry of component and die. The simple shaped parts are easier to forge, compared to the complex shapes. The components having higher surface area per unit volume can be termed as a complex shape for forging. These parts with increased surface area are more critically affected by friction and temperature variation. As a result, forging load tends to increase for complete filling of the die cavity.

1.4.6: Die Temperature

Preheated dies are generally used in the hot forging process to avoid chilling effect at die and workpiece interface which hinders the metal flow at surfaces. The heated dies also facilitate die filling and reduce forging pressures. Typically, the die is heated in the range of 250-400 °C, based on complexity of workpiece.

1.5: Typical Forged Components in Automotive: A Note

A typical flange yoke, used in the propeller shaft of heavy commercial vehicles may be considered as a sample component. The propeller shaft is an important unit in the drive-line system of *the* vehicle. The primary role of this unit, is to effectively transmit engine power to rear axle. In cases of multiple rear axles, it is termed as inter-axle and transfers the power to the next axle. A schematic representation of these units in vehicle assembly is shown in Fig.1.4.



**Fig.1.4: a) Schematic layout of the propeller shaft assembly in the vehicle
b) Image of a typical propeller shaft assembly**

The propeller shaft and inter-axle shaft may contain several flange yokes at the universal joint. A typical arrangement of the assembly and its components are shown in Fig.1.5.

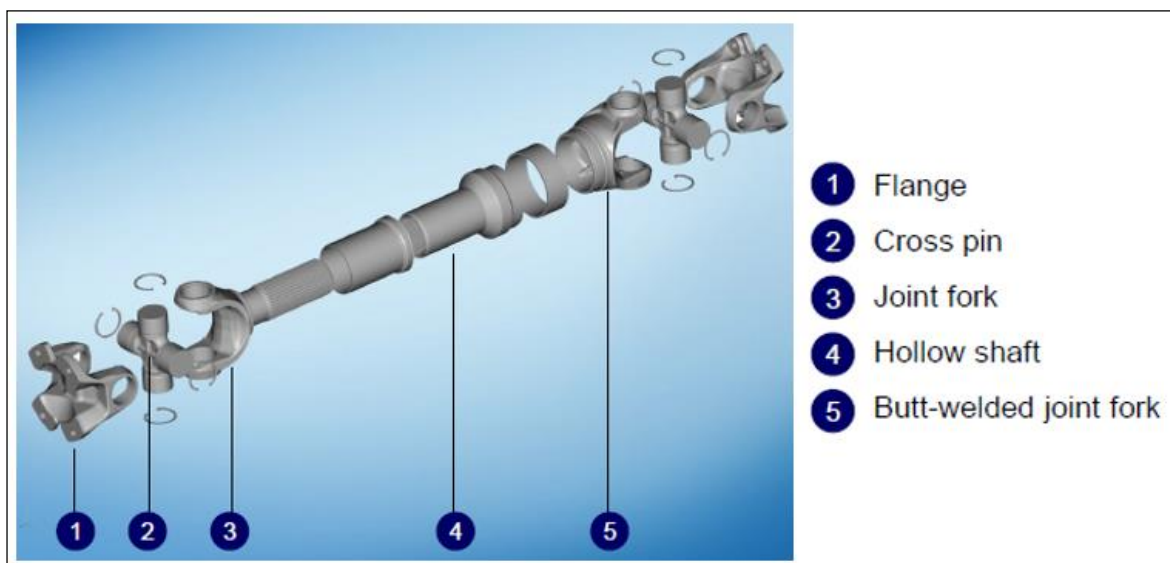


Fig.1.5: Typical arrangement of components in propeller shaft assembly

As the unit primarily transmits torque, all the components are continuously subjected to cycles of torsional fatigue. In actual service due to forward and reverse motion of the vehicle; the power transmission cycle works in both directions. Thus, practically the component is subjected to a reversible torsional fatigue cycle.

1.6: Analysis of Parameters Affecting a Closed Die Forging Process – An Overview

As has been mentioned in the foregoing, a number of process parameters and material characteristics are involved in the closed die hot forging operation that can influence the attributes of a product. Attempts were made in earlier times to adopt analytical techniques to analyse their effect; however, they had many limitations and the predictions were most of the time found unsatisfactory. With the advent of numerical methods the situation improved. Subsequently, in combination with computational techniques, the predictive capability showed appreciable enhancement. Equally important, such analysis can be completed rapidly and therefore optimisation, even on-line, is possible.

1.7: Present Work: Aim & Scope

The broad objective of the present work is to identify parameters influencing forming characteristics of a typical automotive component in the closed die hot forging process and critically examine their nature of influence. As *a sample*, an actual component used in the drive line assembly of automotive is considered, in this case. The finite element approach using a commercial software DEFORM-3D, was adopted for the analysis and experimental work. The validation of predicted values vis-a-vis actual findings was also planned. The work thus envisaged to gain an insight into the manner in which the various parameters influence the closed die forging process and its products.

1.8: Outline of the Report

In the foregoing pages, an overview of the background against which the present work was undertaken was given; one also got a glimpse of the broad aim of the study. Details about the relevant literature, modalities of experimentation, analysis of results, discussion etc. are dealt with, in a number of sections that follow. These are described below:

Chapter 2: Literature Survey

The current status of the field of closed die forging in general and methods of analysis of the process has been examined here.

Chapter 3: Analysis of Closed die Hot Forging Process: Use of Relevant Techniques

Here, critical aspects of finite element (FE) method and its suitability for complex metal forming analysis, such as that encountered in closed die hot forging process have been dealt with. The approaches of design by simulation for process analysis is also discussed.

Chapter 4: Design considerations for the process

Contains the method adopted for generating the pre-requisite steps required for the experimentation such as forging and die design specific to the component.

Chapter 5: Experimental work

Contains the details of experimental work done, including method of experimentation and validation for the same.

Chapter 6: Analysis of experimental data

Contains analysis performed on the experimental data and the findings there upon. It also contains discussion on the general observations.

Chapter 7: Conclusion and scope for future work

Includes the summary and concluding remarks. The scope for future work in this field is also included.

The broad objective of this chapter is to provide requisite background information relating to the proposed study from literature. The identified areas of the survey include:

- Closed die hot forging (CDHF) process and the process parameters
- Approaches for Analysis of the closed die forging process
- Finite Element (FE) Analysis for CDHF process.

2.1: Closed Die Forging Process and Process Parameters

The closed die hot forging process is most suitable for generating complex shaped work parts with reasonable profile accuracy. The process is quite complex from the analysis point of view as there exist several parameters, that can influence the process. These parameters in broader terms can be classified into two categories: design and process parameters.

The design parameters include the preform shape design and die design. The preform shape design is primarily dependent upon the number of stages involved. The die design includes parameters such as flash thickness, flash width, draft angle, corner and fillet radius, input billet geometry etc.

The process parameters include input temperature of billet and die, interface friction, speed of deformation etc. These have been studied in a number of publications; some of the major ones would be dealt with.

The hot forging process under closed die condition were studied in terms of flash formation by Tomov et al. [13]. A number of expressions proposed by earlier researchers for flash land calculation were compared using both analytical and numerical approaches. The best expression among the comparative work was identified so that it can be used as a first step for die design.

A novel approach for preform shape design, which is considered as an important design aspect in forging process planning was proposed by Sedighi and Tokmechi [14]. Here one starts with a primary preform selection and improves the geometry at a second stage. The shape

improvement phase is driven by simulation, using a finite volume method in association with parametric CAD tool. By defining the design variables as parameters, different sections of the part are mapped to an algorithm. At a next step, the defined criterion refines the dimensional values and the proposed model is generated.

Saniee and Hosseini [15] in their study showed that, input billet size and the flash dimension exercise a significant effect on both forging load and metal flow in the die. In a comparative experiment between two parts, it was observed that the die filling characteristic is more sensitive to size of billet, in case of component shapes having a horizontal axis of symmetry.

The importance of corner radius and friction in the closed die forging process were highlighted by Ab-Kadir [16] based on an exhaustive FE study. By conducting an iterative study on a bolt head forging, the effect of corner radius on die filling was compared. It was found that increased die radius in forging is favourable. Similar comparative study on friction showed that, the forging load and consequently die wear increases with increase in frictional value.

Using a thermo-mechanical simulator (i.e. Gleeble), the stress-strain behaviour of steel was determined under compressive load at varying temperature and strain rate by Lin et al. [17]. The temperature range is kept as 850-1150 °C and strain rates varied between 0.01-50 s⁻¹. It was observed that the flow stress reduced with increase in temperature and it increased with increased strain rate. The observed behaviour is shown in Fig.2.1 for a 42CrMo steel.

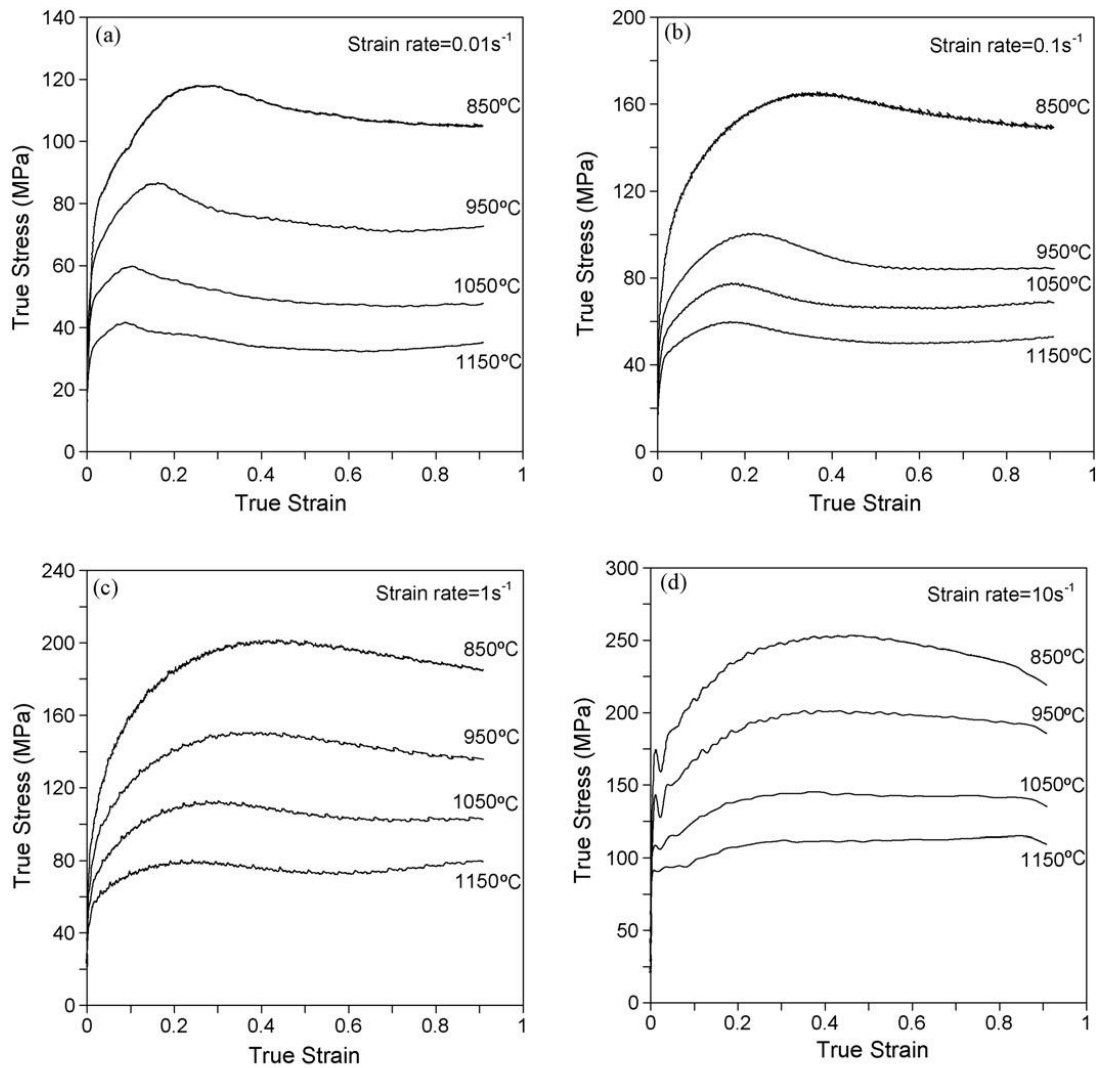


Fig.2.1: Effect of temperature and strain rate on flow stress (Material: 42CrMo steel)

Using a simulation based study Grobaski et al. [18] have shown that the forging die performance and die life are dependent on the forging load, speed of deformation and temperature of work/ die during the process. The forging load among them was found to be most significant.

From the above review, it can be observed that both the design and process parameters exert appreciable influence on the hot forging process.

2.2: Approaches for Analysis of the Closed Die Forging Process

Several methods, developed over time, exist for analysing the metal forming processes. The historical development, is summarised in the work by Osakada [19]. The methods can be broadly divided into Analytical Methods and Numerical methods.

The main objective of such analysis [1] is to:

- Establish a kinematic relationship between the undeformed part and formed part, so that the metal flow during the process can be predicted.
- Predict the process output parameters such as load, stress, strain, temperature etc.

2.2.1: Analytical Methods

The analytical methods known are mostly based on certain assumptions, which help simplify the formulation and an approximate solution is derived. Some of the common analytical methods and their approaches are as follows:

(a) Uniform Deformation Energy Method

This method is based on energy balance or ideal work concept. In this method, a homogeneous deformation is assumed without considering the effect of friction. An average value for the forming load and stresses can be estimated by using this method.

(b) Slab Method

In this method, the work-piece is assumed to be comprised of several small sections termed as slabs. Simplified assumptions are attributed for stress distribution in such slabs. The method of solving involves formulation of equilibrium equations and solving the same between the stress compatibility and boundary condition. The variation of temperature and flow stress are not included in the formulation. So, this method gives an approximate value for stress distribution and forming load prediction.

(c) Slip line Field Method

This method is mostly suitable for plane strain situations. Work material is assumed as rigid and ideal plastic in nature. The velocity fields are calculated using plasticity equations from the stress distribution. The effect of phenomenon such as strain

hardening is not included in the formulation. The variation in flow stress and its effects are also not considered. So, this method is not suitable for finding out the exact nature of distribution of stress throughout the work piece; as it occurs in the real life.

(d) Visio-plasticity Method

This method combines the experimental findings to the calculation. The work piece is practically deformed and velocity vectors are found out by comparing the flow pattern at different stages of deformation. The actual flow pattern is generated by imprinting grids on the surface of the workpiece. The load and strain rates are calculated based on velocity vector and the stress distribution is obtained by using appropriate plasticity equation.

(e) Upper Bound Method

In this method, a suitable kinematically admissible velocity field is assumed, so that it satisfies the velocity boundary condition. The calculation is based on limit theorem concept and can predict approximate load and velocity distribution.

A review of the above mentioned analytical methods reveals that, some of the idealised assumptions in calculation, limit their capabilities for handling complex metal forming cases such as closed die hot forging process. Moreover, none of the methods consider the effect of temperature gradient in work material and its effects during the processing, which is predominant with CDHF process.

2.2.2: Numerical Methods

Among the known numerical methods, the following methods have been mostly used:

(a) Finite Difference Method (FDM)

In finite difference method, the governing partial differential equations are formulated as difference equations. The temperature gradient can be modelled using this method. But the applicability of this method is limited to cases with simple boundary conditions only.

(b) Finite Element Method (FEM) [6]

In this method, the workpiece is split into a finite number of discretised elements over which the behaviour is described by differential equations. The elements are connected at common points termed as nodes. The discretization technique enable this method to handle complex geometrical shaped components in the analysis. The complex real life interaction effects can be coupled to the main analysis. So FE modelling technique can be concluded as the best method for analysis of complex forming situations such as CDHF process.

2.3: Finite Element Analysis for CDHF Process

Among the numerical methods, the finite element modelling technique is found to be adopted by many researchers for analysis of closed die forging process, in order that complex shapes could be handled. The development of hardware to support the high speed computing along with availability of reliable commercial software codes can be considered as a prime reasons for the adoptability of FE Method. The method of calculation is automated, in the available commercial simulation codes (e.g. DEFORM). The FE modelling software is normally used in conjunction with a CAD (Computer Aided Design) software, for accurate modelling of component and die. These models are imported into the FEM software for further processing such as discretization, application of boundary condition and computational analysis work. The solver used for analysis of CDHF process should be able to model both deformation and thermal analysis, as the actual processing is done at elevated temperature.

Oh et al. [20] dealt with different formulations used in FE codes for analysis of metal forming. The capabilities and application are discussed in details showing its suitability for process simulation and optimisation. The method of coupled formulation for heat transfer, including heat generation due to plastic deformation are also explained along with guiding equations. The major features of a commercially available software (DEFORM) and its approach to perform complex analysis is demonstrated. The significance of FE solution in steps for large deformation analysis and the role of an automatic mesh generator is highlighted. The post processing and use of predicted output in different real life application is presented as case studies.

The superiority of FE method compared to analytical methods such as slip line method in dealing with die forging analysis was shown by Tomov et al. [21]. This work also covers some of the critical design considerations, including pre-form and flash design analysis. The validation of results generated from numerical method using simulation is encouraging. Santos et al. [22] emphasised on simulation techniques for complex metal forming analysis and tool design in case of forging and sheet metal forming. Real life components are considered as a sample case for the study, to explain the advantages of simulation driven approach over traditional practices. Park et al. [23] worked out a detailed process analysis methodology for multistage forgings of complex shaped components. As a sample, the CV joint housing used in automotive transmission line was taken up, where both geometry and tolerance in manufacturing are crucial. Suitability and accuracy of the FE method for such complex component manufacturing is validated with actual trial. Gangopadhyay et al. [24] used three dimensional finite element analysis method to simulate the multistage forging process, adopted in manufacturing of railway wheel. A coupled thermo-mechanical analysis along with basic FE formulations for metal forming was used. The analysis was performed using DEFORM-3D software and the scope was extended to the final product production, including trimming operation. It was also observed that this method can be deployed for analysis of forging defects such as lap formation and under-filling of the die cavity, so as to improve product quality and productivity. The relevant mathematical formulations are also discussed. Satish et al. [25] used the simulation based approach to multi-stage hot forging process analysis of automotive front axle manufacturing. The approach was to optimise the preform design at the pad section of the axle using DEFORM software.

The simulation based approach in comparison to conventional approach was found more suitable for complex geometries.

2.5: Summary Observations and Directions for the Present Work

The detailed investigations of works done by different research groups in the area of metal forming reveal that both design and process parameters contribute to the forging process. It is also concluded that a generic solution cannot be worked out, for all shapes of components. Finite element method is found to be the best suited approach for analysis of complex shaped real life components.

In order to gain a deeper understanding of the closed die hot forging process for specific cases, it was considered appropriate to take up a typical automotive component. Thus, a flange yoke used in driveline for transmitting power was chosen for studying the influence of various parameters in its manufacture through closed die forging, based on FEM.

The details of the FEM approach used in this study, selection of variables, experiments conducted, results and analysis etc. are given in the next chapters.

ANALYSIS OF CLOSED-DIE HOT FORGING PROCESS: USE OF RELEVANT TECHNIQUES

As has been mentioned earlier, the numerical techniques are superior to other methods in analysing the influence of various parameters involved in a closed die hot forging process. The present approach has therefore been to make use of Finite Element method (FEM); which can handle more complex geometry of the work-piece. Further, complex interaction of factors can be coupled to the main analysis in FEM. Descriptions of the methodology to adopt FEM to closed hot forging would be made. Simulating the forging process would be an effective way of looking at various parameters and their influence in a virtual manner even without experiments; the process would be described in this section. There are commercial packages available today based on the FE-method, they would be looked into. One such, i.e. DEFORM, has been chosen for the current study; some details of the same would be provided.

3.1: FEM for Analysis of Closed Die Hot Forging Process: A Summary

The general advantages of FEM for dealing with deformation of metals have been noted in the earlier chapter. Specific aspects of the FEM in handling the complex analysis of closed die hot forging may be summed up as follows:

- i. Practically all shapes, including complex three dimensional, unsymmetrical geometries along with die geometry can be considered for analysis.
- ii. Localized phenomenon causing variations in parameter such as stress can be included in the analysis.
- iii. Variation in the flow stress occurring at different region, due to variation in temperature can be included in the analysis.
- iv. The phenomena of adiabatic heat (heat generated due to work done in forming) can be coupled to the analysis.
- v. Some of the redundant work done during the overall forming process can also accounted in the process. Such phenomenon is quite common in the mechanism of flash generation, bend formation etc.

- vi. The effect of varying strain rate can be included in the analysis.
- vii. Effect of tool and workpiece temperature and localized chilling at the interface can be included in the analysis.
- viii. Environmental effect such as heat transfer with the surroundings and its effect on forming can be considered.
- ix. Interpolation of result in different forms such as directional stress, strain, strain rate can be interpolated and the stored data can be reused for advanced analysis such as fatigue and die failure.
- x. With the availability of reliable commercial codes, analysis is continuously getting refined to generate more accurate and faster results.

3.2: Description of FE Process for Closed Die Forging

The basic approach here is to split the basic problem into small units (discretisation), so that suitable formulations for each can be made. The final solution is achieved by assembling the units and solving it.

The finite number of small units, which in combination represents the whole problem is termed as elements and the connecting points are known as nodes. The behaviour of the material along with operating boundary conditions are carefully embedded to the formulation by using different relational constraints to the elements and nodes. Basic finite element formulations and solving method are well documented in various textbooks. [9, 10]

The modified process for deformation analysis can be described as follows:

- The total solution is achieved in a set defined steps, so that the actual nature of deformation can be captured.
- At each step a smaller increment of the die travel is considered, and the relevant calculation is performed. This is repeated until the specified distance or stopping criteria is not achieved. The general stopping criterion is die distance, limiting value for load or minimum values for velocity or strain etc.
- In case of complex shapes, there is a drastic change while moving from the initial shape to the final geometry. This is addressed by frequent re-initiation of meshing cycle, as and when the element shape integrity is lost beyond the defined value. This is known as re-meshing cycle, which can be manual or automatic.

The global stiffness equation for the workpiece is generated by assembling the individual elemental equation. The governing equation defining the relation is [24]:

$$K\Delta v = f \quad \dots\dots \quad (\text{Eq.3.1})$$

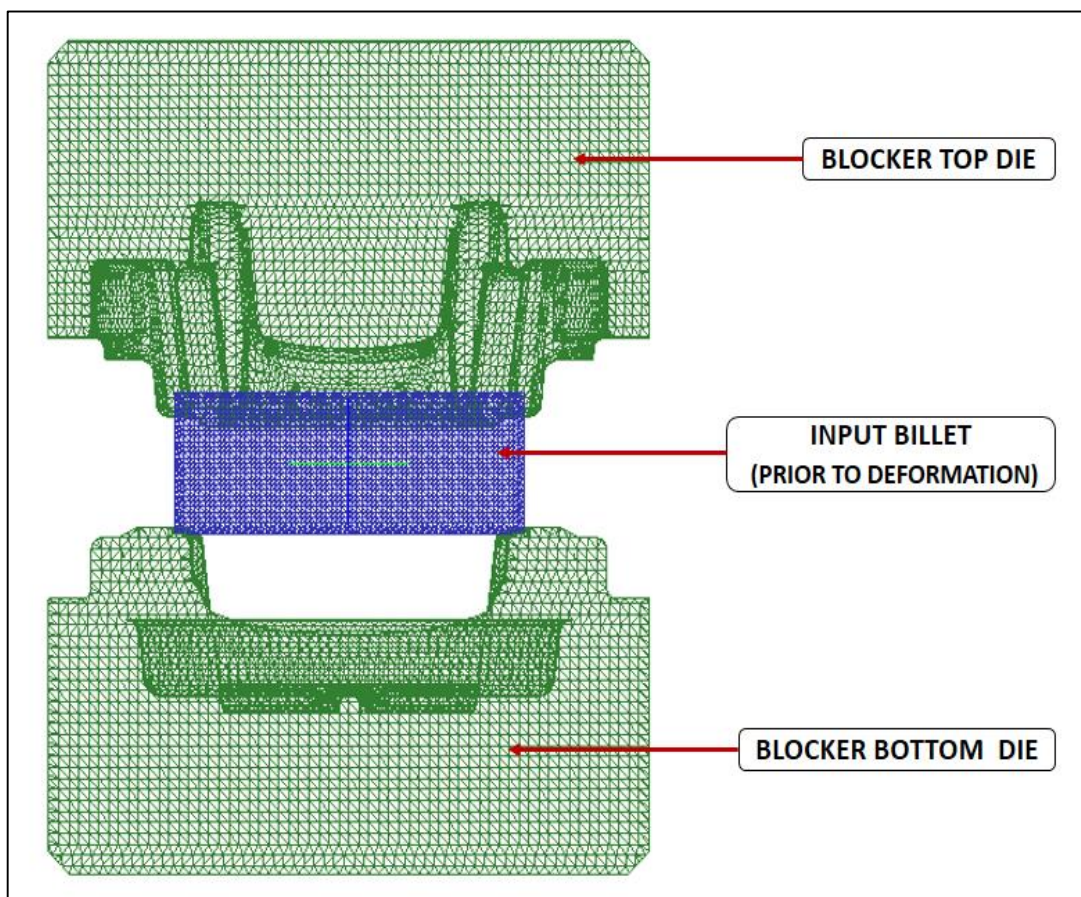
Where,

K represents the global stiffness matrix

Δv = incremental velocity

f = global force vector

The discretised model generated during the project work is shown in Fig. 3.1.



**Fig. 3.1: Discretised model of die and billet assembly
(Initial contact between die and billet shown)**

3.3: FE Formulation for Metal flow in Hot Forging:

In case of closed die hot forging, the primary interest is to track the material flow, through the die cavity. For deciding metal flow and its direction, minimum work rate principle is followed. Consequently, the velocity distribution which predicts lowest work rate is chosen for deciding the flow direction. This principle is based on the practical phenomenon that the material will always flow in the path of least resistance.

The method of formulating and solving metal forming problem is performed by using the variational approach where the proper function is dependent on specific constitutive relations. The velocities are solved, keeping the variation of the function as stationary. [6, 20, 24, 28]

The functional (function of function) considering rigid-viscoplastic FE formulation is as follows:

$$\pi = \iiint E(\dot{\epsilon}_{ij})dV - \iint F_i u_i dS \quad \dots \quad (\text{Eq.3.2})$$

Where,

$E(\dot{\epsilon}_{ij})$ is work function

F_i is the surface traction.

The constraint for material incompressibility on the admissible velocity fields is removed using the large positive penalty constant K:

$$\sigma\pi = \iiint \bar{\sigma} \delta \dot{\epsilon} dV + K \iiint \dot{\epsilon}_v \delta \dot{\epsilon}_v dV - \iint F_i \delta u_i dS = 0 \quad \dots \quad (\text{Eq.3.3})$$

Where,

$\dot{\epsilon}_v$ is volumetric strain rate

The first integral defines the plastic work due to deformation

The second term maintains volume constancy by multiplying the change in volume with a large penalty constant

The third integral defines the work due to surface traction

The metal flow criterion is governed by J_2 flow theory; as the yielding of the material is assumed to begin, when the second deviatoric stress invariant reaches the critical value. The formulation neglects the effect of first set of stress variant as hydrostatic component of the stress tensor do not contribute to the deformation of metal. This is also alternatively known as von Mises yield criterion.

For Von Mises yield criterion,

$$\text{Effective stress, } \bar{\sigma} = \frac{1}{\sqrt{2}} \cdot \sqrt{(\delta_1 - \delta_2)^2 + (\delta_2 - \delta_3)^2 + (\delta_3 - \delta_1)^2} \quad \dots \quad (\text{Eq.3.4})$$

$$\text{Effective Strain, } \bar{\epsilon} = \frac{\sqrt{2}}{3} \cdot \sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2} \quad \dots \quad (\text{Eq.3.5})$$

In case of hot forging, heat energy and thermal effects are embedded to the formulation as coupled analysis as their effects are significant. The major portion of the heat is generated due to the plastic work and the friction at the interface. Some amount of the heat is lost at a varying rate due to the contact with the die at lower temperature in physical phenomenon such as convection and radiation by the exposed surfaces.

The adiabatic heat generation rate in the workpiece can be determined by

$$\dot{r} = \kappa \sigma_{ij} \dot{\epsilon}_{ij} \quad \dots \quad (\text{Eq.3.6})$$

Where,

κ = fraction of mechanical work converted to heat (0.9 to 0.95 is considered for forging)

σ_{ij} is component of stress tensor

$\dot{\epsilon}_{ij}$ is component of strain rate tensor

The inclusion of the thermal consideration such as heat transfer and heat generation as coupled analysis to the main formulation makes the mode as non-isothermal in approach.

3.4: Design by Simulation

Simulation is the process of conducting virtual computer based experiments, founded on mathematical and logical modelling techniques. The finite element based modelling is the most adopted simulation technique for engineering analysis. Design by simulation is a systematic approach where the objective is to perform virtual iterative trials to understand the effect of parameters on the output and the overall behaviour of the system as a whole. In case of a bulk forming process such as forging, the simulation technique can be used both for process analysis and die design.

3.4.1: Purposes of Design by Simulation:

The purpose of process modelling through simulation aims at the followings:

- To gain a comprehensive insight into the process to understand different mechanism and phenomena involved.
- The study can be performed in isolation, so that actual setup is not disturbed.
- Reduces effort on expensive trials, thus reduce overall development time.
- Testing the effectiveness of new concepts before actual implementation.
- Reduced effort on analytic requirements.
- To find out the results in easily demonstrable models, which can be further scaled to advanced analysis, such as die wear, die life estimation etc.

3.4.2: Precautions in Design by Simulation:

There is a set of cautions which should be borne in the mind during performing simulation driven process analysis. They are as follows:

- i. Simulation is majorly based on finite element analysis, which is an approximate method by itself.
- ii. The method of formulation decides the accuracy of the output, such as element size.
- iii. The exactness of the input parameter to the formulation decides the accuracy of the output result. So, process input parameters should be correct and reliable.
- iv. It is always recommended to verify the initial study with actual trial to find out the correlation.
- v. For new development the results can be benchmarked with a similar known case.

vi. Simulation by itself cannot solve engineering problems. Based on the output results, suitable inference for problem solving can be initiated. However a confirmatory test on the decided solution can be verified before actual implementation.

3.5: Commercial FE-Packages Suitable for Closed Die Forging: Introduction to DEFORM

Rapid development in high speed computing and processing hardware, has enabled FEM codes be used in many engineering analysis. There are a number of reliable general purpose FE modelling packages available such as ANSYS, NASTRAN, DYTRAN, MARC, LSDYNA that can predict stresses in both tool and work piece.

Customised FEA packages are also available which are tailored, specifically to address the requirements of metal forming analysis. A list of such specialised FE modelling software, capable of simulating closed die hot forging process is shown in Table 2.1.

Table 2.1: List of commercial FE software, suitable for analysis of CDHF process

SI	Commercial Name of Software	Company/ Team Developed the Code
1	DEFORM (Design Environment for Forming)	Scientific Forming Technologies Corporation (SFTC)
2	FORGE	Transvalor S.A.
3	SIMUFACT	Simufact Engineering GmbH
4	QForm (Quantor Form)	Quantor Form Ltd

DEFORM (Design Environment for Forming) is one of such customised FEM- codes, tailored to address analysis requirements of the entire deformation and allied processes. In this project DEFORM-3D module is extensively used for the FE modelling and analysis work.

3.5.1: Features of DEFORM Suitable for Closed Die Hot Forging Process

Some of the main characteristics of DEFORM that make the package appropriate for CDHF are:

- Coupled modelling of deformation and heat transfer can be performed
- Extensive material property database at high temperature are pre-built with the system along with provision to include user defined input.
- Rigid, elastic and plastic models are included, which can be directly applied to the die and work-piece based on type of analysis.
- Integrated equipment models of various types are pre-built into the system, which can be easily reconfigured. (Such as Hydraulic press, Mechanical cranked press etc.)
- Point tracking system to track the exact flow is available.
- The flow net technique can assist to predict grain flow behaviour.
- Contact element pattern can ensure die filing characteristic.
- Information on metal flow, resulting flow velocity, strain rate, strain, stress, load, temperature and die stress can be found out.
- Contoured plot of the output parameter in post processing along with animation can help to understand, complex behaviour during actual processing.

3.5.2: Simulation Steps for CDHF process in DEFORM™:

DEFORM-3D module possesses specifically designed templates for process simulation of bulk forming analysis. This can handle complex 3-dimensional geometries of both work piece and die by incorporating solid elements. The Automatic Mesh Generator (AMG) produces optimized mesh based on user input. The auto remeshing feature keeps on modifying the mesh when the acceptable criteria are violated due to deformation. The rules for such criteria can be defined by the user, prior to starting the simulation study. Most of the settings can be manually overridden, in case need arises. The three functional segments in the module are [28]:

- (a) Pre-Processor
- (b) Simulation Engine/Solver
- (c) Post Processor

(a) Pre-Processor:

The pre-processor assists and compile the input data for the simulation. In some of the cases, it helps the user to visualise and analyse the input data using the graphical user interface. The type of input includes:

Object Description: The data associated with geometry, object type, mesh definition, temperature, die movement, boundary condition etc.

Material Data: Material property data for both work piece and die. The data should be sufficiently describing the behaviour of the material, which it will reasonably experience during the entire deformation cycle.

Inter-object Conditions: Data describing the interaction between the workpiece and die including contact, friction and heat transfer criteria.

Simulation Controls: Data related to control the numerical behaviour of the solution including solving algorithm type, formulation type, remeshing criteria, stopping criteria, sub stepping method, data storing steps etc.

(b) Simulation Engine/ Solver:

The actual FEM based calculation is performed by the simulation engine or solver. Based on the input data, necessary formulations are initiated by the solver and the required calculations are performed sequentially. The total deformation is calculated in a series of steps and the results are stored for such steps. Several remeshing cycle may be initiated during the solving cycle based on the defined criteria. The stored simulation results can accessed by the user through the post -processor. The type of formulation available for forging include heat transfer, isothermal and non-isothermal simulation.

(c) Post Processor:

The Post Processor is generally deployed to visualise and analysis the result. The stored result by the solver can be plotted graphically or in alphanumeric form by the post-processor. The graphic interface is extensively used for such interpolation of result. The graphic representation includes mesh, contour plots of distribution of strain, stress,

strain rate, temperature and velocity vectors in various forms. The load / stroke curves can also be interpolated from the stored data. The other useful capabilities in the post processor include generation of point-tracking and flow net. This helps in visualisation of metal flow pattern and predict grain flow orientation.

DESIGN CONSIDERATIONS FOR THE PROCESS

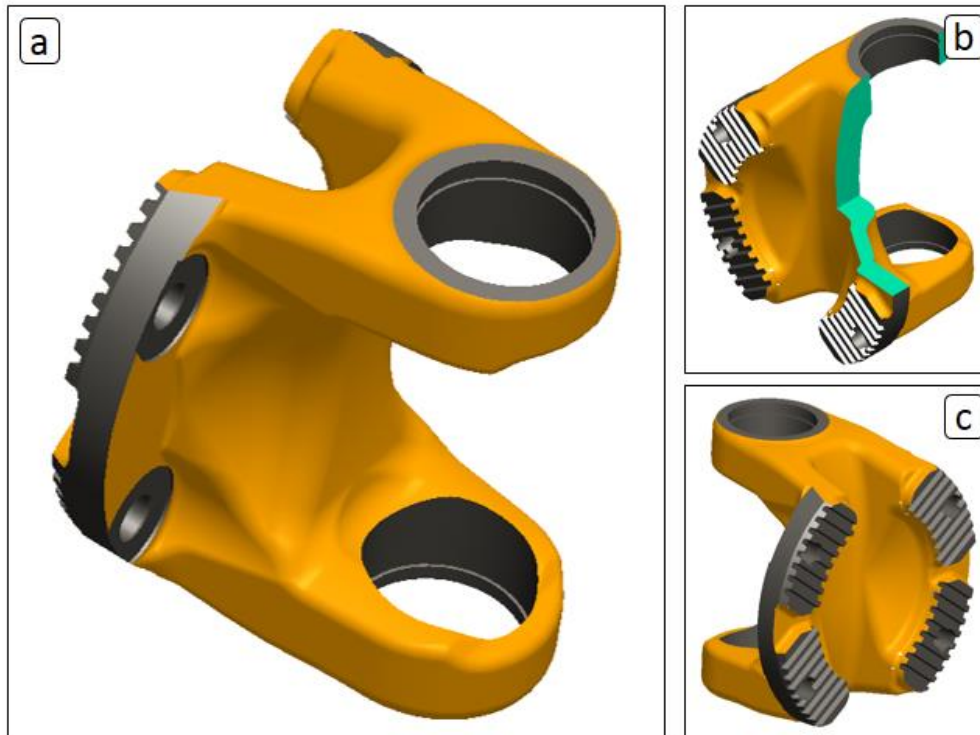
The broad objective of this chapter is to deal with some of the design guidelines, appropriate to the intended component, including die design, so that the prerequisite steps can be performed for the analysis of the process. The manufacturing route for the component is finalised as closed die hot forging based on the complexity of the geometry, tolerance requirement for the component, the extent of deformation required to form the shape, and mass production requirement of the component.

The involved design phase can be broadly divided into two stages: Product Design Stage and Die Design Stage

4.1: Product Design Stage:

The engineering design team finalise the geometry, dimension, tolerance and material requirement for the final component. This is based on intended application in service, including the desired performance characteristic for the particular part. The typical output is a machine drawing of the final required part; which include post forging operations such as machining, tolerance and surface finish requirements. The machine drawing of the considered component is shown in Fig.4.1. A 3D model displaying different views is shown in Fig.4.2.

The first step for a production engineer to convert the machine drawing into forging part drawing. Understanding of the function of actual part in service can be considered as a prerequisite to efficiently handle this conversion phase. This understanding also improves the decision making ability for the subsequent design stages. The selected component is a part of the universal joint used in propeller shaft for heavy commercial vehicle application. The component is known as “Flanged Yoke” in automotive terminology. It is mostly subjected to torsional loadings; as the whole propeller shaft is designed to efficiently transmit the engine torque to the rear axle.



**Fig.4.2: 3D Model of the final machined component; a) Isometric view
b) Cut sectional view showing the web thickness; c) View showing the rear details**

4.2: Die Design Stage:

There are no fixed rules for designing the dies for forging. The design method adopted is majorly dependent on the geometry of component and the processing conditions. There are, however, a set of recommended guidelines and principles for design, which can be adopted based on a particular situation. They are mostly empirical, and are developed from years of practical experience.

With the recent developments in virtual process simulation using finite element method; these adopted guidelines can be further refined to suit the exact scenario.

In case of closed die hot forging, the design phase follows the following steps:

4.2.1: Determination of Parting line and Axis of Product for Manufacturing:

This step is crucial as it impacts both component quality and the method of die design. As per the stated guidelines [7, 8], the selection of parting line should be such that:

- a) Deep impressions in the die are avoided to improve die life.

- b) Die side thrust is minimised, to avoid die shift during the forging cycle.
- c) Largest periphery is preferred to be placed around the parting line; so that it is easier to force metal laterally to spread into the cavity. Putting the largest flat surface on the parting line is the other variation of this criterion.
- d) Desired grain orientation is achieved for the part to be manufactured.

Reviewing the application of the component reveals that, the component is continuously subjected to torsional fatigue cycle. The torque is transmitted to the body, as a coupling force acting through the holes present in the yoke. The net effect can be summed up as constant bending forces acting on the sections of the yoke.

In order to improve the mechanical properties of the component, it is desirable that the grain flow orientation is perpendicular to the loading direction. This will improve the fatigue resistance of the component.

Thus, reviewing the actual application of the component, one could select the parting line.

4.2.2: Designing the Forging Part

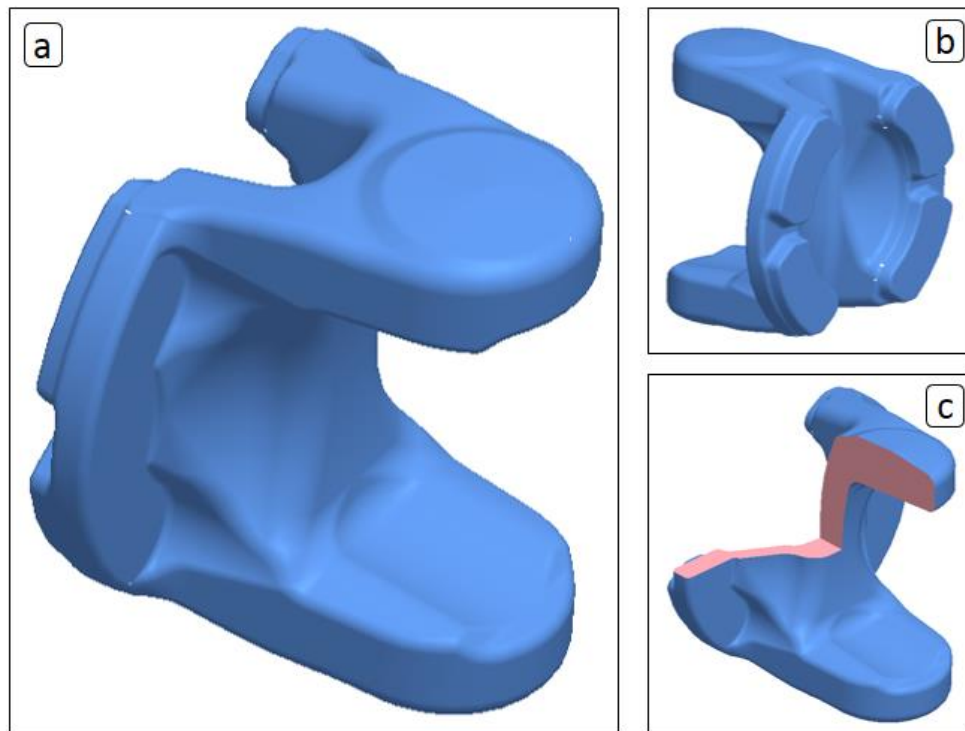
The first step here is to initiate necessary design changes in the forging part design so that the component can be formed with the decided parting line. Consequently some of the geometry needs to be simplified or modified. In case of the considered component, the holes in the yoke lie in the perpendicular axis of forming; so the yoke is to be formed as solid in forging and the hole will have to be generated afterwards by machining.

The next step is to add up the required allowances to the forging part design. The considered tolerances are:

- i. Machining allowances
- ii. Straightness or uneven allowances
- iii. Contraction allowances

The standard charts and formulae, recommended in IS 3469-1974 (Indian Standard) is referred to finalise the allowances to the forging part design.

The images of forging part model is shown in Fig.4.3.



**Fig. 4.3: 3D Model of the generated forged component; a) Isometric view
b) View showing the rear details; c) Cut sectional view showing the web thickness**

4.2.3: Incorporating the Draft Angle in Design

Draft refers to the taper generated in the internal and external sides of a closed die forging to facilitate easy removal of components from the die cavity. In the actual practice, the draft is generally modelled in the forging component design and the replica is generated in the die by machining. The selection of draft angle should be optimal, as excess draft angle increases allowances in component; thus increasing the final weight of component.

The draft angle is included in the vertical walls with respect to the axis of forming. Normally draft provided on the inner surface is larger than the outer surface drafts, as upon cooling the forging shrinks both radially and longitudinally.

Draft angle value also is greatly dependent on the type of equipment used and complexity of forging. The draft angle value is decided as 3° for external 5° for internal surface based on recommendation table, considering mechanical crank press and steel as forging material. [7]

4.2.4: Flash and Gutter Design

Flash refers to the excess metal normally attached at the periphery of the workpiece that is subsequently trimmed in a separate die. It is formed in the flash land, normally adjacent to the die impression cavity. The flash design is crucial, as it performs two contradictory, yet important roles during the actual shaping of metal.

(a) Acts as a restriction to the outward flow of the metal during the first phase of forming, so that remote corners and deeper cavities can be filled up.

(b) Pushes out the excess metal from the cavity in the second phase, after complete filling of the cavity so that the excess pressure is relieved.

Apart from this it also acts as a cushion from impact blow generated at high strain rate forming.

Most of the finisher forging dies are designed to accommodate flash. However, in industries, flash provision is given to the blocker dies also, if:

- Less numbers of stages of forming is desired
- Complex shaped workpiece with large multi-directional deformation is to be achieved

The optimum value of flash thickness has been always desirable; as smaller value will necessitate greater energy for bringing forging to size, while bigger value may cause inadequate die filling.

Flash Gutter is the cavity designed to accept the excess metal extruded out through the flash land. Mostly the gutter cavity is placed adjacent to the flash land.

4.3.5: Design Considerations for Fillet and Corner Radii

Design of fillet and corner radii affect grain flow, forging load, die wear, grain flow and the amount of metal to be removed during machining. So, proper selection of the fillet and corner radii is a vital aspect in the forging die design. As a rule, all possible sharp corners must be avoided in forging design as they tend to weaken both the dies and finished forgings. It also hinder the smooth flow of metal causing under-fill, excess load and die wear. In the present design of the blocker die, the radius and fillets are maintained in the range of 5- 12 mm.

4.3.6: Deciding the Number of Stages for Forging:

Practical industrial forging is generally consists of multiple stages. The number of stages is dictated by the complexity in geometry, nature of metal flow and the expected accuracy of the component. Considering the geometry of flange yoke a three stage forming is felt both adequate and economical. The planned stages are as follows:

- a) Upsetting : Primarily to remove the oxide layer and prepare the initial billet for subsequent processing.
- b) Blocker stage : To give the primary shape to the component along with attaining maximum critical metal flow.
- c) Finisher stage : To achieve the final dimensional requirements of the component.

The next subsequent step is trimming, to remove the generated flash is not included in the scope of this project.

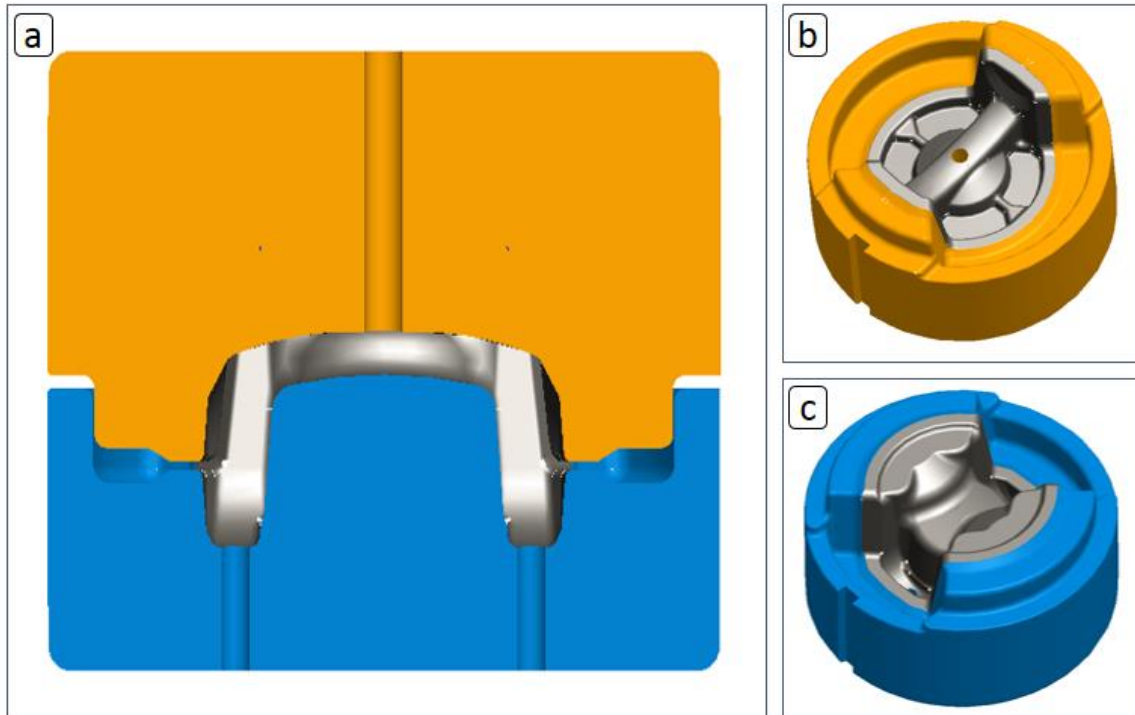
Considering the component design, the preferred practical way to approach stages of die design, is to design in the reverse order. This means the first finalise the design of finisher stage and then blocker.

a) Finisher Die Design

As discussed, the finisher stage gives the final desired geometry and dimension to the component. The steps followed for design, are as follows:

- i. Die block shape is considered as round and the overall dimensions are considered to suit existing die holding block.
- ii. As per parting line the top and bottom die design is finalised.
- iii. The die cavity is in both halves, by taking forged part design as reference.
- iv. Shrinkage allowances is added to the die cavity considering steel as the work material.
- v. Flash land and gutter design are included.
- vi. The round circumferential die lock is introduced to encounter side thrust to the die.
- vii. Pin ejection mechanism is added at suitable locations for assisting removal of the component after forming.

A typical arrangement of the finisher die designed for this project is shown in Fig.4.4.



**Fig.4.4: a) Sectional view of Finisher die set assembly with ejection holes
 a) Top die model, c) Bottom die model**

b) Blocker Die Design

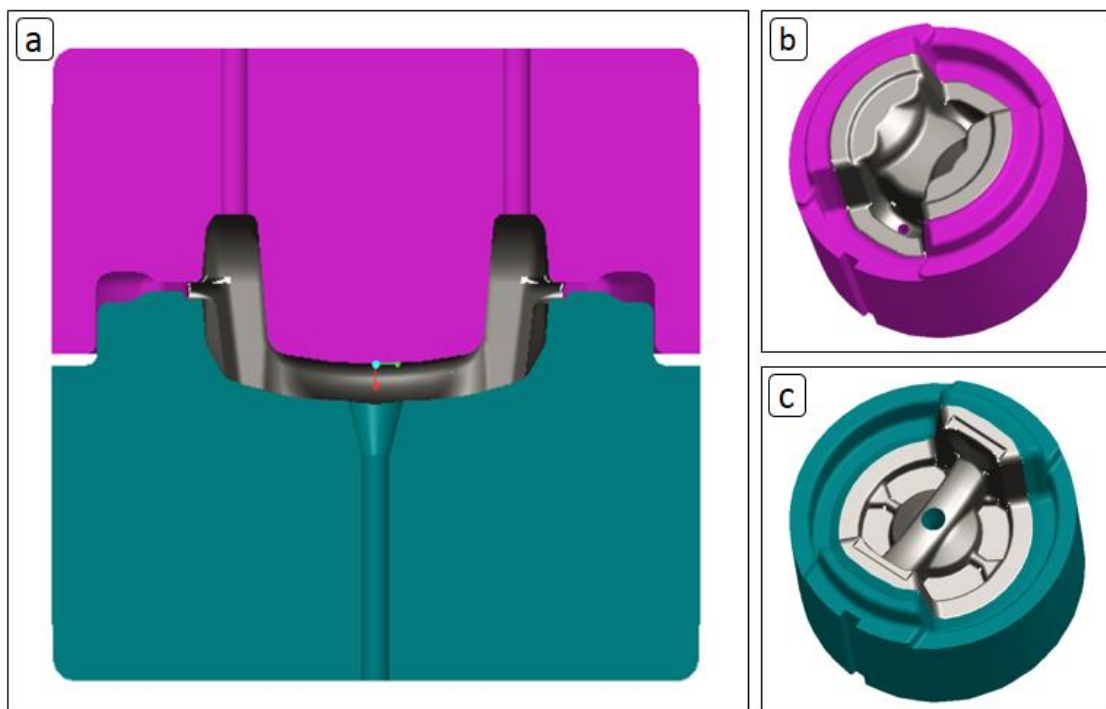
The major role of the blocker stage is to achieve desired metal distribution from the simple shaped billet, so as to supplement complete die filling at finisher stage. This is the crucial stage, where maximum metal flow is expected; so as to achieve production of component in less number of stages. It is consciously decided to add flash at this stage also, as otherwise controlling the metal flow in such complex shaped cavity will be difficult to be achieved in one stage only.

The step followed for the design is as follows:

- i. As like finisher, the die block shape is inherited to suit the existing die holding block.
- ii. As there is no fixed rule, a conscious target of achieving around 70% of the forming at the blocker is decided. The primary objective is set as to avoid major forming in finisher stage, so that the sharp radius and stringent dimensional requirement of the final component can be met.
- iii. A shape for the blocker stage is worked out, considering it resembling to H-section.
- iv. Overall forming height at yoke is reduced by 20% and fillet radius values are made larger (2 to 3 times) aiming reduction in the forging load in blocker stage.

- v. Based on the shape, the die cavity in both halves are generated.
- vi. Shrinkage allowances is added to the die cavity considering steel as the work material.
- vii. Flash land and gutter design are included.
- viii. Cavity for the initial location of billet in the die is incorporated in the design.
- ix. The round circumferential die lock is introduced to encounter side thrust to the die.
- x. Pin ejection mechanism is added for assisting removal of the component after forming.

A typical arrangement of the finisher die designed for this project is shown in Fig.4.5.



**Fig. 4.5: a) Sectional view of Blocker die set assembly with ejection holes
b) Top die model, c) Bottom die model**

c) Upsetter Die Design:

As the main objective at this stage is to remove the scale or oxide layer present in the surface and prepare the billet material for subsequent operation; the upsetting die is decided to be kept as flat for simplicity. This stage is not well documented in texts, but still is an essential step for dealing hot rolled billet materials as input. The oxide layer is detrimental to the die life and tends to produce defects in the component such as scale pit. Its presence at the die-workpiece interface also adversely affects the metal flow. A vertical upsetting of 4 mm is decided for the considered component.

This chapter includes the experimental work done on the chosen component, data generation from simulation driven process design and validation with real forgings.

5.1: Determination of Stock/Billet Size for the Experiment

As the first step, the machine drawing of the component was studied and model for the same was generated using the PTC Creo solid modelling software. It is then converted to into the forging model by introducing simplification of features and adding up allowances; as discussed in Chapter-4. The next step is to decide the input billet size for the processing. Referring to the data generated from model, we can find the followings:

1. *Net weight of the finished component*

= volume of the finished component (from model) x density (steel)

Volume of forging = 465391 mm³

Density of material = 7.86×10⁻⁶ kg/mm³

Therefore, the net weight of the component is 3.66 kg

2. *Net weight of the forging component*

= volume of the forged component (from model) x density (steel)

Volume of forging = 613641 mm³

So the net weight of the component is 4.82 kg

3. *Estimated flash loss*

= (15 to 20) % of the net forging weight based on complexity of geometry

= 0.96 kg (considering the upper limit)

4. *Required input billet weight*

= Net weight of the forging + Flash loss

= 5.78 kg

5. Approximate yield of production

$$= (\text{Net weight of the forging} / \text{Billet input weight}) \times 100$$

$$= 83.4 \%$$

In general, square, rectangular shaped billets are preferred over round; for forging such complex shapes. The flat side of such billets ensures proper seating in the cavity, and less attention on operating required.

Considering square billet with rounded corner of 65mm dimension: (Corner radius = 4mm)

$$\text{Cross-sectional area} = 4211.27 \text{ mm}^2$$

$$\begin{aligned} \text{Length of billet required} &= (\text{Required weight} / \text{density of material}) / \text{Cross sectional area} \\ &= 174 \text{ mm (Approx.)} \end{aligned}$$

So, the derived input billet dimensions are (SQ 65 x L 174) mm.

5.2: Determination Flash Land Dimensions

The primary role of flash land is to generate desired restriction to undesired metal flow. It is characterised by the width to thickness ratio (w/t). The calculation for the flash land are mostly empirical, developed by different researchers. As flash design is an important input to the process, calculation is done using different method [7]. The result of the same is summarised in Table.5.1.

Table 5.1: Summarised result of flash thickness calculation

Reference Work (Author)	Method of Calculation (Flash thickness)	Calculated Value (*)
1. Vieregge	$t = 0.017D + \frac{1}{\sqrt{D+5}}$... (Eq.5.1)	2.8 mm
2. Neuberger & Mockel	$t = 0.89\sqrt{W} - 0.017W + 1.13$... (Eq.5.2)	3 mm
3. Teterin & Tarnovski	$t = 2\sqrt[3]{W} - 0.01W - 0.09$... (Eq.5.3)	3.2 mm

(*) – Calculated values are rounded off to the closest suitable values

As per the design, D= Equivalent diameter = 160 mm

W= Forging weight = 4.82 kg

Considering different method and calculation, the average recommended flash thickness for the considered component is found out as 3 mm

Similarly, for calculation of the flash width, the following empirical equation is used [1]

$$\frac{w}{t} = \frac{30}{\sqrt[3]{D + \left[1 + \frac{2D^2}{h(2r+D)}\right]}} \dots\dots \text{(Eq. 5.4)}$$

As per the design, D= Equivalent diameter = 160 mm

h= Height of rib = 100 mm

r= Radial distance from centre to rib = 60 mm

t= Flash thickness (Calculated) = 3 mm

The calculated flash width is found out to 16 mm (Approx.)

The calculated flash dimensions are used for the initial die design.

5.3: Actual Experimental Setup:

The actual trial was taken at the forging division of M/s RSB Transmission (I) Ltd., located at Mania, Cuttack. The following facilities of the plant were used for the experimental work:

- I. Mechanical cranked press of capacity 2500T was used for the forging operation. In Image of the setup is shown in Fig.5.1. The inline induction heating arrangement was used for heating the billet to required temperature.
- II. CNC Vertical Milling machine was used for manufacturing of dies.

The other specification/ trial condition are as follows:

- I. H13 grade material was used for manufacturing of the dies.
- II. As per design specification, 37 C15 material was used as the billet material.
- III. Colloidal graphite solution along with water, (In a ratio 1:20) was used during the process as lubricant.

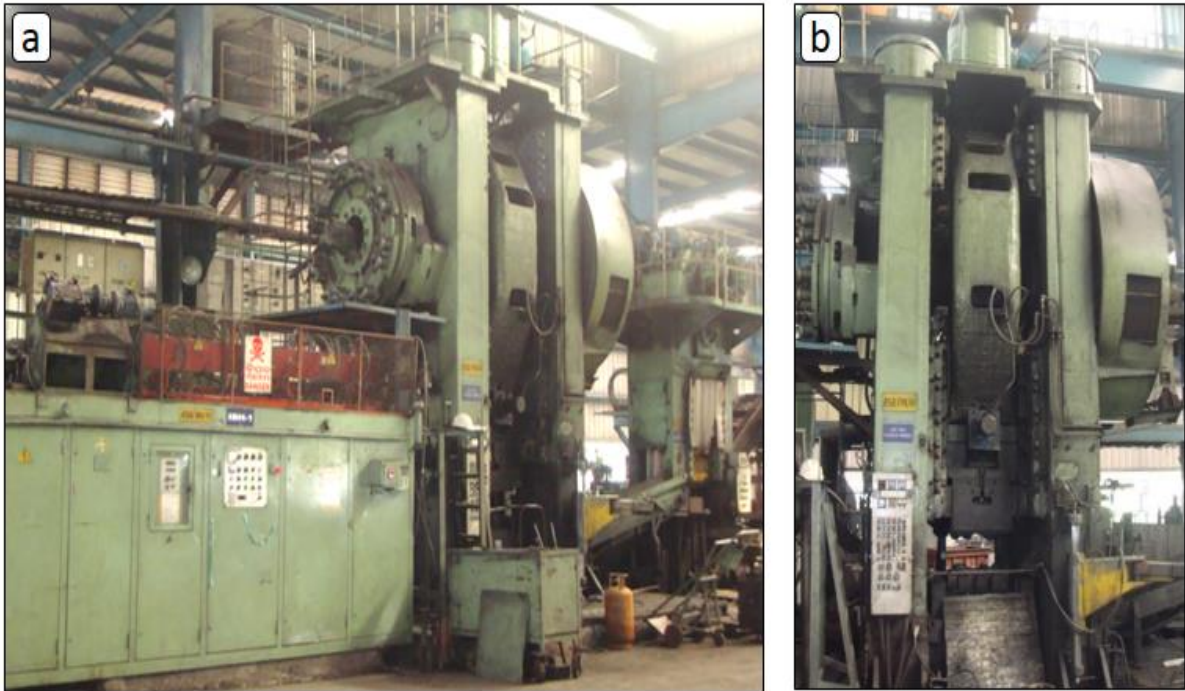


Fig.5.1: Machine used for experimental trial; a) Mechanical cranked press with automated induction heating arrangement b) Front view of the press machine

5.4: Verification and Validation of Experimental Procedure:

The selected method for metal forming analysis is simulation driven. A simulation predicts the desired behaviour, based on mathematical and computational models. In this particular experimental model extensive finite element formulations are used.

Verification in general terms, refers to checking the correctness of the formulated model. Whereas validation refers to checking the exactness of the model to predict the real life situation. So, the validation of the initial set results is found essential to:

- Ensure that the input values and assumptions made are correct or justified.
- The model is adequate to predict actual behaviour.
- Correlation between the predicted value and the actual findings.

To validate the adequacy of the model, an actual trial was conducted on the machine. The input parameters were measured during the process. These input values were fed to the simulation model, along with some suitable assumptions.

The validation criteria were set as:

- Mapping the generated flash pattern and its dimensions at the last forging stage. (i.e. finisher stage)
- Grain flow pattern mapping, to ensure that the metal flow direction is identical.

In the absence of direct load measurement device on mechanical cranked press used, it is believed that the above two criteria should be acceptable to check the model adequacy.

In the actual trail the billet material is processed through all the three stages of forging. (i.e. - upsetting, blocker and finisher stage). Similarly a three stage trial is performed using DEFORM-3D software. The generated flash pattern in both the actual and the simulation result was found identical. The metal flow pattern is also found similar. The comparison between actual and predicted flash pattern is shown in Fig.5.2. The comparison of the metal flow pattern at central cross section is shown in Fig.5.3.

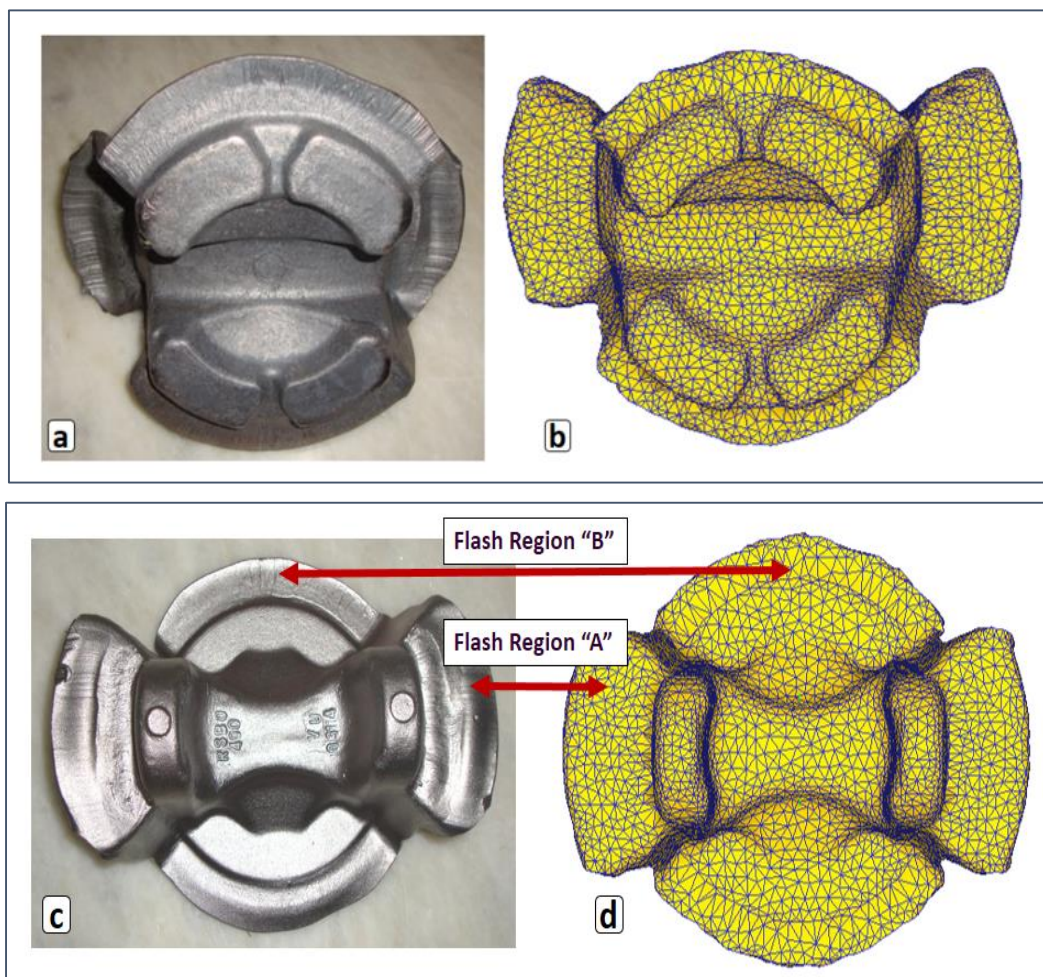
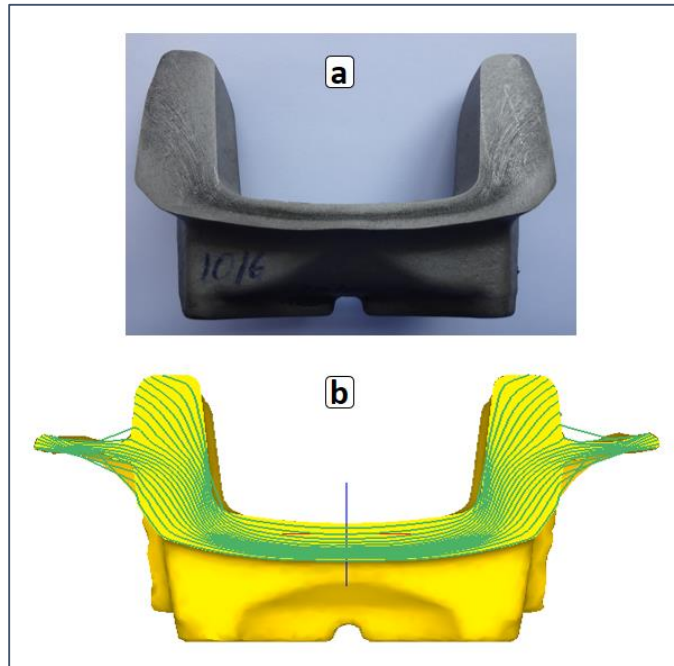


Fig.5.2: Comparison between Actual Vs. Predicted Flash Pattern; Different Views (a,c- Actual Component; c,d- Simulation Prediction)



**Fig.5.3: Comparison of Metal flow Pattern; a) Cross section of Actual component
b) Predicted pattern by Simulation along with flash**

The dimensional comparison of actual finding vs. predicted value of flash width is compared in Table 5.2.

Table 5.2: Dimensional validation table for flash width/pattern (Actual/Predicted)

Sl	Region of Observation	Actual trial findings		Prediction by simulation		Variation in % w.r.t actual trail findings
		Observed values (mm)	Mean	Observed value (mm)	Mean	
1	Region-A (Flash generated at yoke area)	32.44	32.692	32.82	34.828	6.53%
		32.62		34.86		
		32.94		34.78		
		32.78		34.84		
		32.68		34.84		
2	Region-B (Flash generated at flange area)	11.62	11.436	12.22	12.144	6.19%
		11.92		12.12		
		11.46		12.18		
		11.22		12.08		
		10.96		12.12		

It can be observed from the table that, there exists a variation of 6% between the actual findings and predicted value. Considering the complexity of the geometry, multistage forging and the amount of metal flow involved, this correction can be considered good enough to proceed further experimentation.

So as a first step, the all the inputs and assumptions are needed to be recorded, for further experiment aiming to adopt design by simulation route. They are as follows:

(A) Material definition:

1. Material designation : AISI 1043
(Alternate equivalent grade to 37C 15, from the available material database)
2. Size of billet : 65 RCS (Length 172 mm)
3. Input billet temperature : 1250 °C

(B) Tooling definition:

1. Material designation : AISI H-13
2. Die preheating temperature : 300 °C
3. Flash thickness : 4 mm

(C) Machine specification:

1. Type of machine : Mechanical cranked press
2. Maximum capacity : 2500 T
3. Maximum stroke length : 350 mm
4. Operating stroke length : 250 mm
5. Stroke per second : 1 cycle
6. Connecting rod length : 2350 mm

(D) FE Modelling strategy:

1. FE Model construction : Symmetric boundary condition in half section
: Half cut section billet on the longitudinal axis
: Half cut section of top and bottom die
(To suit billet cut orientation)

(E) Meshing definition:

1. No of element (billet) : 50,000 (With fine internal mesh)
: 78,000 (Approx. generated element)
(Based on convergence test with respect to effective stress in workpiece)
2. No of element (for die) : 65,000 (Without fine internal mesh)

(F) Boundary condition:

1. Environmental temperature : 35 °C
2. Coefficient of friction : 0.3
3. Operating step increment : 0.5 mm (For step simulation)
4. Heat transfer co-efficient [28] : 11 N/Sec/mm/C
(Between die and billet interface: Forming)
5. Convection co-efficient : 0.02 N/Sec/mm/C
(Free convection of still air 2 W/m²/°C)

5.5: Stage-wise Simulation Results:

The simulation results are interpreted by using post-processor. The output parameters can be customised to suit the problem definition and to improve the overall understanding of the process. The stage wise deformation and the resulting metal flow behaviour are shown in Fig.5.4-5.6. It captures the transformation of simple billet geometry; into the complex shaped component along with the effective stress distribution during the process.

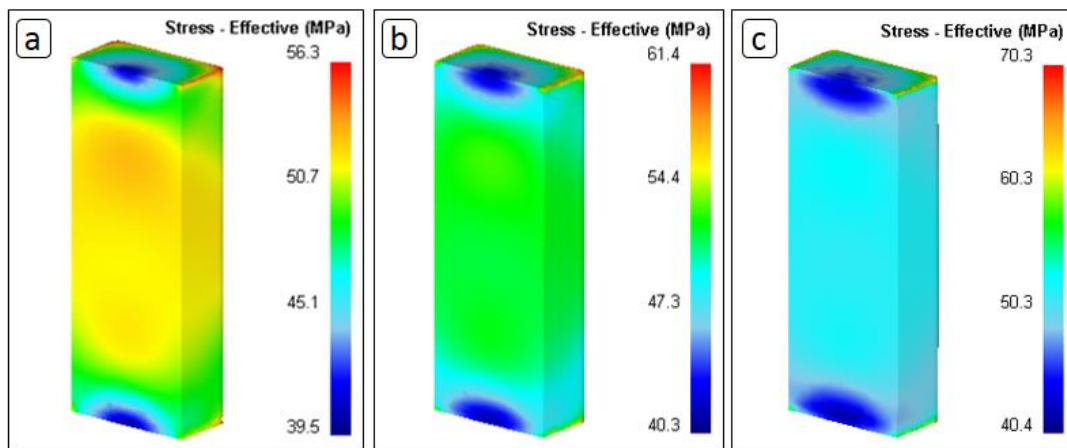


Fig.5.4: (a-c) Step wise simulation result of upsetting stage; Effective stress plot

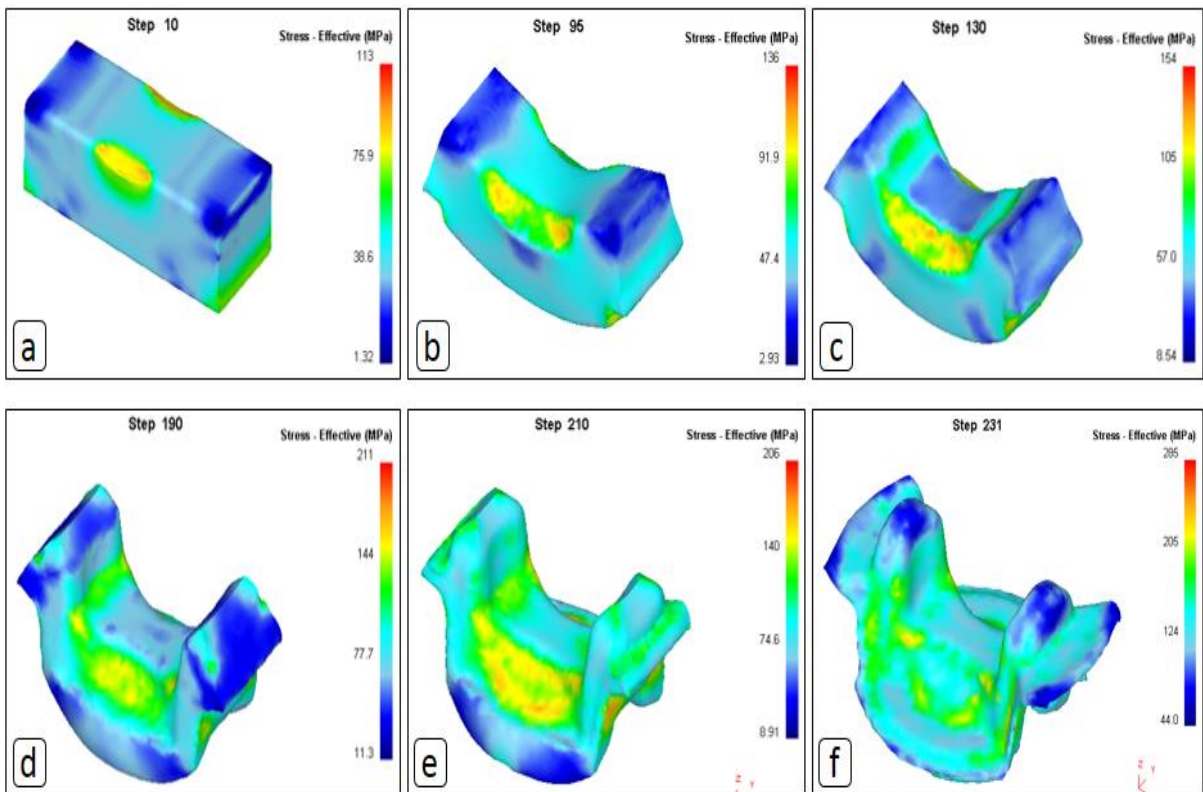


Fig.5.5: (a-f) Step- wise simulation result of blocker stage; Effective stress plot

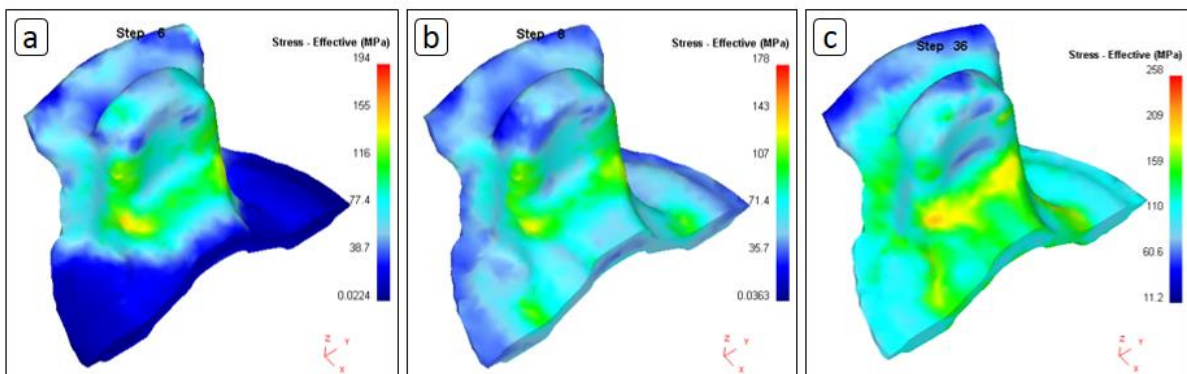
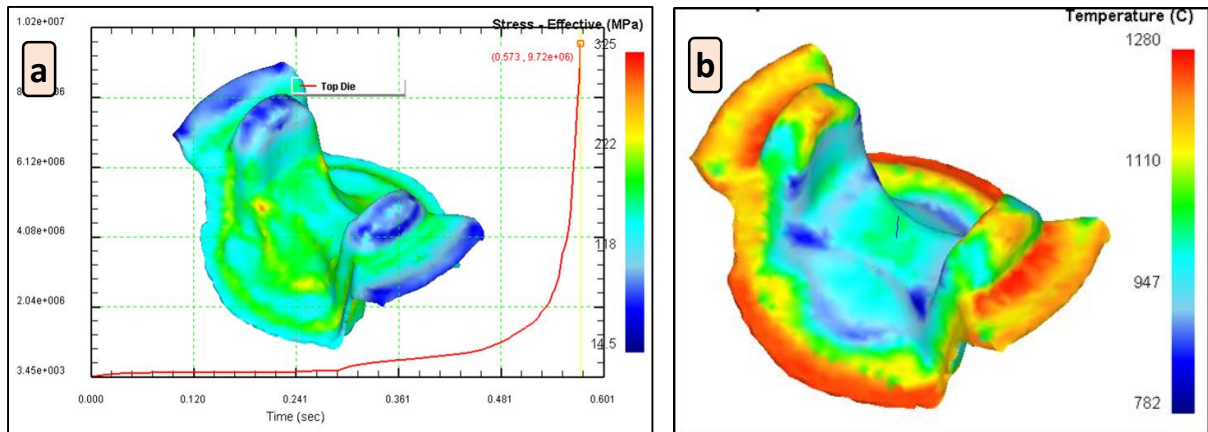


Fig.5.6: (a-c) Step wise simulation result of finisher stage; Cut sectional view

The result shows that, the metal flow at the finisher stage is limited; whereas it is maximum at the blocker stage. This is desirable and in line with the criteria for die design adopted.

The predicted load stroke curve and temperature distribution for the blocker stage is shown as a sample Fig.5.7. An upsurge in temperature (to 1280°C) is observed, at the end of deformation process from initial input value (to 1250°C). This can be attributed to the conversion of mechanical work into heat energy, during the process of deformation.



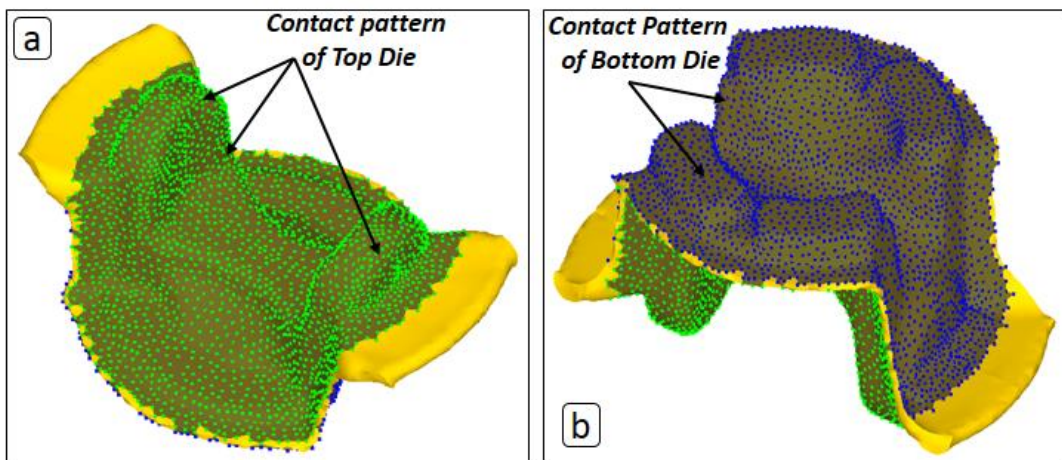
**Fig.5.7: Simulation predicted results for load and temperature.
(a – Load stroke graph for the process; b - Temperature distribution plot)**

The result obtained from the solver, can also be transformed into different forms of output such as effective stress, effective strain, velocity distribution etc. For this study, we will be focusing our attention to the forming load.

5.6: Determination of Die Filling during Analysis

In closed die forging process, the component shape and dimensions are derived from the die cavity. Therefore, as an essential requirement, the die cavity should be completely filled.

In FE analysis, interaction at the face of die and workpiece is modelled using contact elements. The load transfer and interaction behaviour at the interface is taken care by such elements. So, the behaviour of the contact elements at final step ensures the filling of the die. A typical contact pattern of such elements is shown in Fig.5.8. For all the experimental trials, the die filling is ensured at the final step.



**Fig.5.8: Contact element display showing the complete die filling.
(a - Contact pattern of top die shown in green coloured dots; b - Contact pattern of the bottom die is shown in blue coloured dots)**

The material and the die set used for the actual experiment is shown in Fig.5.9.



Fig.5.9: Actual set up showing billet and die used for experimental trial
a) Input billet material, b) Blocker bottom die, c) Blocker top die

The image of actual component is shown in Fig.5.10.



Fig.5.10: a-c Different views of the actual component without flash

5.7: Experimental Details Aiming Design of Experiments:

As discussed earlier, the closed die hot forging process has many process variables. As an outcome of the process, the forging load can be considered as a vital response characteristic. The forging load as an output parameter:

- Decides the selection of equipment for the process.
- Affects equipment and die wear characteristic, including die life.
- Influences the economy of manufacturing

It is evident that the lower forging load is desired in the processing cycle.

Considering the component selected and with defined set of workpiece material, machine specification, die design; the following factors are expected to mostly influence process characteristic:

- Input billet temperature
- Flash thickness
- Friction factor at the interface of die and workpiece

A set of experiments with varying level of these parameters were planned via simulation to capture the effect on forging load. The selected levels are as shown in Table 5.3

Table 5.3: Various input parameters and their levels for the experimentation

Parameter/Description	Unit	Level		
		I	II	III
Billet temperature	° C	1150	1200	1250
Flash thickness	mm	3	3.5	4
Friction factor	--	0.3	0.4	0.5

5.8: Experimental Results:

Experimental run were performed considering different combination of levels and the corresponding predicted forging load value for both blocker and finisher stage were recorded. The summary of the simulation trial is shown in Table.5.4.

Table 5.4: Experimental finding of the forging load at different levels of input parameter

RUN	A	B	C	A Temp (°C)	B Flash Thk (mm)	C Friction	Upsetting Stage Forging Load (in N)	Blocker Stage Forging Load (in N)	Finisher Stage Forging Load (in N)
1	1	1	1	1150	3	0.3	3.29E+05	9.21E+06	7.88E+06
2	1	1	2	1150	3	0.4	3.30E+05	9.35E+06	8.07E+06
3	1	1	3	1150	3	0.5	3.31E+05	1.03E+07	8.62E+06
4	1	2	1	1150	3.5	0.3	--	7.04E+06	6.01E+06
5	1	2	2	1150	3.5	0.4	--	8.22E+06	6.88E+06
6	1	2	3	1150	3.5	0.5	--	8.58E+06	7.18E+06
7	1	3	1	1150	4	0.3	--	6.17E+06	5.01E+06
8	1	3	2	1150	4	0.4	--	6.95E+06	5.58E+06
9	1	3	3	1150	4	0.5	--	8.03E+06	6.49E+06
10	2	1	1	1200	3	0.3	2.87E+05	8.00E+06	6.69E+06
11	2	1	2	1200	3	0.4	2.89E+05	8.57E+06	7.12E+06
12	2	1	3	1200	3	0.5	2.92E+05	9.38E+06	7.85E+06
13	2	2	1	1200	3.5	0.3	--	6.52E+06	5.52E+06
14	2	2	2	1200	3.5	0.4	--	7.27E+06	6.10E+06
15	2	2	3	1200	3.5	0.5	--	8.27E+06	6.89E+06
16	2	3	1	1200	4	0.3	--	5.63E+06	4.82E+06
17	2	3	2	1200	4	0.4	--	5.89E+06	5.01E+06
18	2	3	3	1200	4	0.5	--	6.87E+06	5.79E+06
19	3	1	1	1250	3	0.3	2.46E+05	6.53E+06	5.64E+06
20	3	1	2	1250	3	0.4	2.47E+05	7.16E+06	6.12E+06
21	3	1	3	1250	3	0.5	2.48E+05	7.48E+06	6.44E+06
22	3	2	1	1250	3.5	0.3	--	5.89E+06	5.08E+06
23	3	2	2	1250	3.5	0.4	--	6.13E+06	5.31E+06
24	3	2	3	1250	3.5	0.5	--	6.89E+06	5.94E+06
25	3	3	1	1250	4	0.3	--	4.85E+06	4.32E+06
26	3	3	2	1250	4	0.4	--	5.21E+06	4.62E+06
27	3	3	3	1250	4	0.5	--	5.88E+06	5.20E+06

ANALYSIS OF EXPERIMENTAL WORK

This chapter includes the analysis of data generated from the experimental work performed. After validating the process, the experimental trials are done in FE method based simulation software DEFORM-3D. The major focus was to:

- Understand the metal flow behaviour.
- Find out the effect of selected parameter and their significance.
- Identify combination of parameters to achieve lowered forging load.

6.1: Data Analysis on Effect of Parameters:

It has been observed that the blocker stage is most crucial in the multi stage forging process; as the maximum metal flow take place at this stage. Hence, this stage can be identified as the ideal stage for optimization. The forging load at the blocker stage with various combinations of input parameters are plotted graphically to note the effect of parameters.

The effect of variation of temperate in the input billet, at constant flash thickness and friction factor is shown in Fig.6.1.

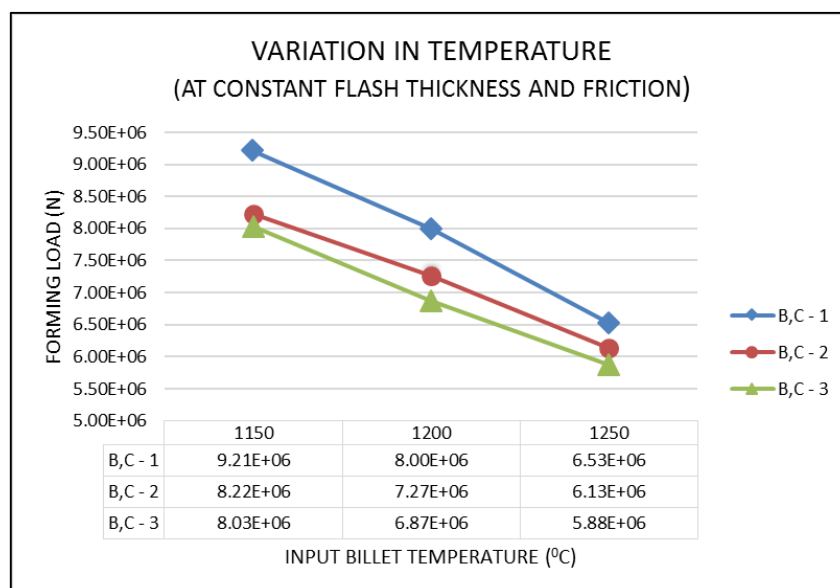


Fig.6.1: Effect of variation of billet temperature

It is observed that, forging load at blocker stage is reduced drastically with the increase in input billet temperature. This behaviour can be explained from the following facts:

- The value of flow stress, which accounts for the metal flow; reduces with increase in temperature.
- The reduction in flow stress values, causes better metal flow due to lesser resistance.

This in in turn, reduces the forging load requirement at higher temperature.

The effect of variation of flash thickness, at constant billet temperature and friction factor is shown in Fig.6.2

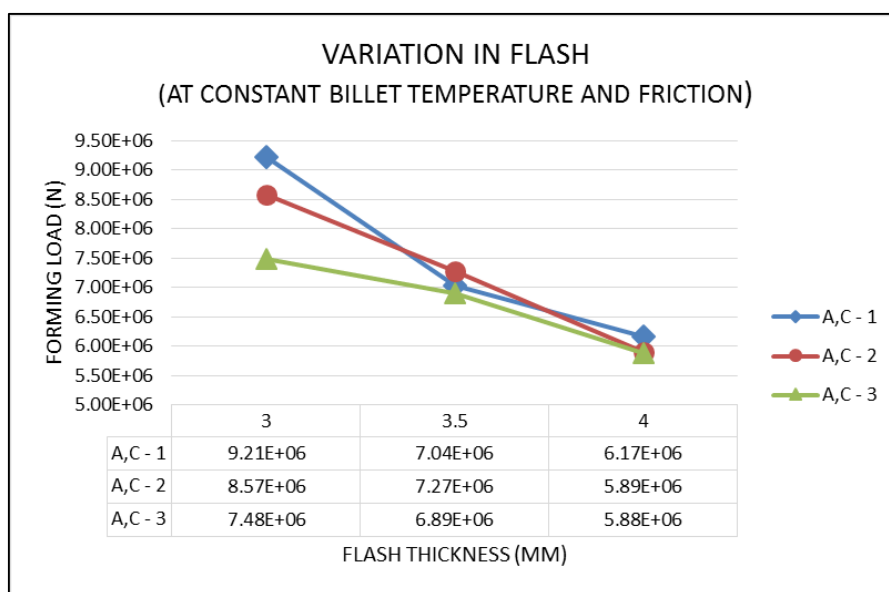


Fig.6.2: Effect of variation of flash thickness

It is noticed that the forging load in the blocker stage is also reduced with increase in flash thickness. This behaviour can be explained from the following facts:

- A lesser value in flash thickness adds up the extra squeezing load at the flash land area.
- A higher load is required in the transverse direction; when the excess material tries to escape from the die cavity, after the complete filling stage is reached. The lesser available cross section will create a restriction to flow and in terms increase the demand of additional load.

Hence, it is desirable to have a flash thickness in positive side to reduce the forging load. It should also be noted that, a very high value of flash thickness is also not desired, as it can

restrict the complete filling of the die. Higher flash thickness can also cause difficulties in trimming stage and leaves a deep trim mark on the finished component; apart from adding to the cost due to consumption of a greater amount of input material (billet) for the same size of the finished product.

The effect of variation of friction factor, at constant billet temperature and flash thickness is shown in Fig.6.3.

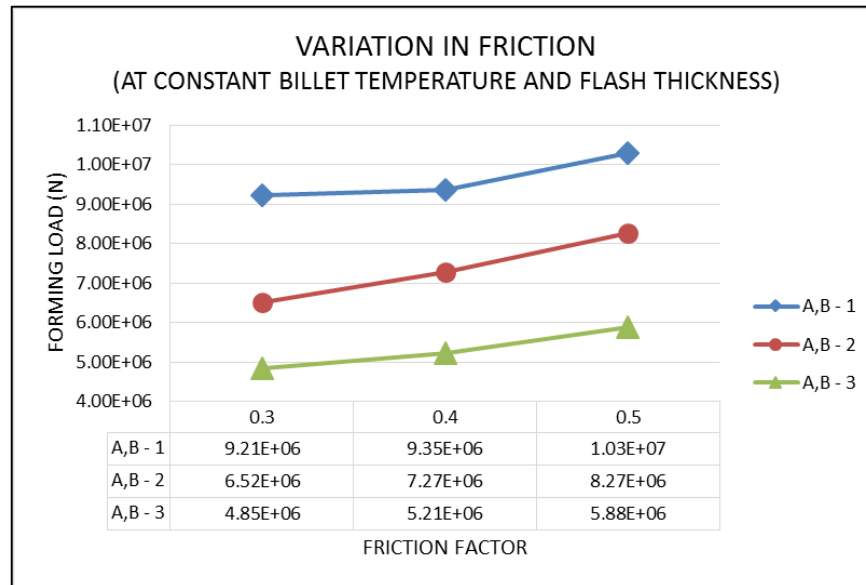


Fig.6.3: Effect of variation of friction factor

It is observed that the forging load at blocker stage is increasing with the increase in frictional value. This behaviour can be explained from the following facts:

- The interface friction between the die and the workpiece restricts the metal flow, causing the requirement for additional force to overcome, in comparison to an ideal frictionless situation.
- It also causes variation in the distribution of applied load to the workpiece.

So, the overall forging load requirement increases, at higher values of friction factor.

6.2: Design of Experiment Trial

In order to determine the most desirable combination of parameters along with the significance of each, Taguchi method is adopted. Unlike other design of experiment tools, Taguchi method adopts the orthogonal array (OA) approach [11, 12]. This method is effective and more popular in industries, as the OA approach considers the entire parameters with lesser number of trials or experiments, as compared to other methods. The method considers both controlled and noise factors in the design.

Additionally, the Taguchi method uses the loss function approach for the measurement of the performance characteristics deviating from the desired value. These values of loss functions are converted to S/N (Signal to noise) ratio.

Broadly, three methods are available for of calculating the S/N ratio, and the appropriate method is decided based on end objective or outcome desired. Considering the forging load as response, minimisation criteria (Smaller is better) is selected.

The formula for calculating the S/N ratio in decibel is as follows: (Smaller is better)

$$S/N \text{ Ratio} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad \dots \quad (\text{Eq.6.1})$$

Where,

\bar{y} = average of observed data

y = is observed data

s_y^2 = Variance of y

n = no. of observations

It should be noted that, the larger value of S/N ratio indicates better performance characteristics. So the desired level of the process parameters is identified by the highest value of S/N ratio.

For the data analysis, considering three factors with three levels, a L9 orthogonal array was constructed and the S/N ratios were calculated considering the “Lower is better criteria”. The L9 orthogonal array is shown in Table 6.1.

Table 6.1: L9 Orthogonal array with parameters, response and calculated S/N Ratio

Run No	Reference			Combination of factors			Blocker load (N)	S/N Ratio
	A	B	C	Temp.	Flash Thk	Friction		
1	1	1	1	1150	3	0.3	9.21E+06	-139.285
2	1	2	2	1150	3.5	0.4	8.22E+06	-138.297
3	1	3	3	1150	4	0.5	8.03E+06	-138.094
4	2	1	2	1200	3	0.4	8.57E+06	-138.660
5	2	2	3	1200	3.5	0.5	8.27E+06	-138.350
6	2	3	1	1200	4	0.3	5.63E+06	-135.010
7	3	1	3	1250	3	0.5	7.48E+06	-137.478
8	3	2	1	1250	3.5	0.3	5.89E+06	-135.402
9	3	3	2	1250	4	0.4	5.21E+06	-134.337

The main effect plot for S/N ratio, for billet temperature, flash thickness and friction factor are plotted graphically as shown in Fig.6.4.

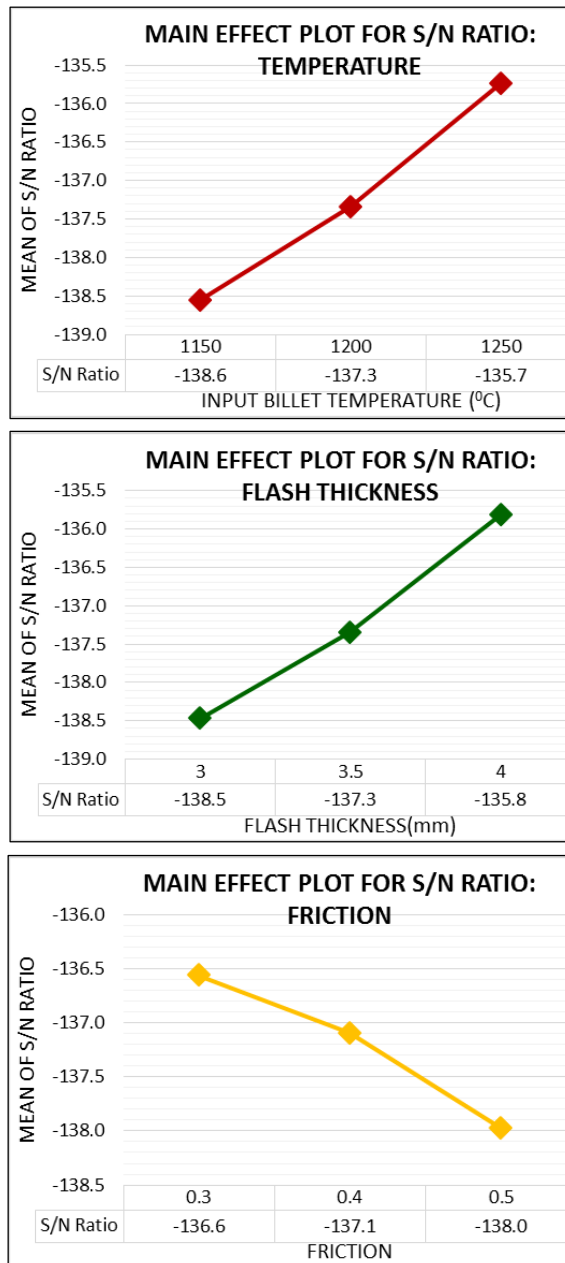


Fig.6.4: Main effect plots for S/N ratio for different parameters

The graphical representation reveals that the combination (3, 3, 1) is the best combination for getting lowest forging load. This corresponds to forging at 1250 degree billet temperature, 4 mm die gap with 0.3 operating friction factor. The prediction is matching with the experimental trial.

For establishing the significance of each parameter, a response table for S/N ratio is constructed. The mean S/N ratio at each level is calculated. The difference between the maximum and minimum is termed as Delta. The calculated value of delta for the different

parameters are compared to find out the significance of each parameter. The response table for S/N ratio along with rank is shown in Table.6.2.

Table 6.2: Response table for S/N Ratio

Level	Temperature	Flash Thickness	Friction Factor
1	-138.6	-138.5	-136.6
2	-137.3	-137.3	-137.1
3	-135.7	-135.8	-138.0
Delta	2.8	2.7	1.4
Rank	1	2	3

It was earlier observed that the temperature, flash thickness and friction are crucial parameters for the process and its variation has a major impact on the forging load. **From the response table, it can be concluded that, the temperature of the input billet is the most significant parameter followed by flash thickness.**

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1: Conclusion:

In this work, an automotive driveline component (Flange Yoke) is taken as a reference sample, to study the metal forming behaviour during closed die forging. The effect of selected input (forging) parameters on forging load is determined. The Taguchi method is used to find out the best possible combination for the desired response. The conclusion drawn from the work is as follows:

- I. Finite element method is quite suitable for analysing complex metal forming characteristics in a closed die hot forging process.
- II. Using the FE method, other phenomena associated with metal forming, such as heat generation due to deformation, heat transfer etc. can be coupled with the basic deformation analysis, so that the solution is close to the real life.
- III. A good amount of agreement is observed during validation of the FE output with actual manufacturing data, in terms of flash pattern and dimension prediction.
- IV. The metal flow prediction agrees well with the grain flow in actual component.
- V. The die filling prediction in terms of contact element behaviour is found useful in real life situation.
- VI. The billet temperature, flash thickness and friction are found to have a significant effect on the forging load. Among the three, the temperature of the input billet is found to be the most significant parameter followed by flash thickness and friction factor, in that order.

7.2: Scope for Future Work:

The primary aim of the present work was to develop a methodology for the analysis of real life components processed via closed die hot forging process. With level of understanding developed in this work, the future scope of work can be envisaged as follows:

- I. The aspects associated with design parameters for forging can be studied for effects on response.
- II. Develop prediction for prediction of the time and die-gap at which filling of cavity takes place so that over-squeezing (hence avoidable extra work) is minimized.
- III. Predict temperature rise in work-piece (through adiabatic heat) so that energy of heating can be reduced.
- IV. Optimum blocker stage design based on FE analysis.
- V. Die life prediction and improvement, based on die stress analysis.
- VI. Other complex component shapes can be undertaken for metal flow analysis.
- VII. Forging stage reduction in complex components processed in multiple stages.

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