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

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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 loads 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 productions 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 testing's 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.

In this paper, 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

1. INTRODUCTION

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. 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.

1.1. Closed-die forging Process:

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.1.1.

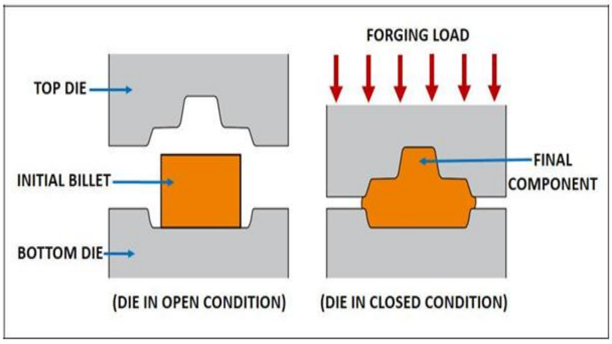

Fig. 1.1: Schematic arrangement of closed die hot forging process

2. 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. Product variables
2. Material variables
3. Tooling parameters
4. .Machine parameters
5. Deformation zone characterization
6. Tool and work interface behaviour

2.1. MAJOR FACTORS INFLUENCING THE METAL FLOW

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

2.1.1: 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.

2.1.2: 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 ($\dot{T}$)and temperature of deformation $\left(\bar{\varepsilon}\right)$

$$\bar{\sigma} = f\left(\varepsilon \quad \bar{\varepsilon} \quad T\right)\text{------------} \qquad \text{(Eq.1)}$$

2.1.3: Friction and Lubrication

The forging load applied to the die is transmitted to the work piece through the die interface. So, a frictional condition 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.

$$\tau = f.\bar{\sigma} = \frac{m}{\sqrt{3}}.\bar{\sigma}\text{----------} \qquad \text{(Eq.2)}$$

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.

2.1.4: 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.

1.3.5: 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.

2.1.6: Die Temperature

Preheated dies are generally used in the hot forging process to avoid chilling effect at die and work piece 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 ^{o}C, based on complexity of work piece.

3. OBJECTIVE OF WORK

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.

4.ANALYSIS OF CLOSED-DIE HOT FORGING PROCESS:

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.

4.1: FEM for Analysis of Closed Die Hot Forging Process:

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.

4.2: Description of FE Process for Closed Die Forging deformation analysis can be described as follows:

1. The total solution is achieved in a set defined steps, so that the actual nature of deformation can be captured.
2. 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.
3. 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 work piece is generated by assembling the individual elemental equation. The governing equation defining the relation is

$\mathrm{K}.\Delta v = f$ --------------------- (Eq.3)

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. 4.1.

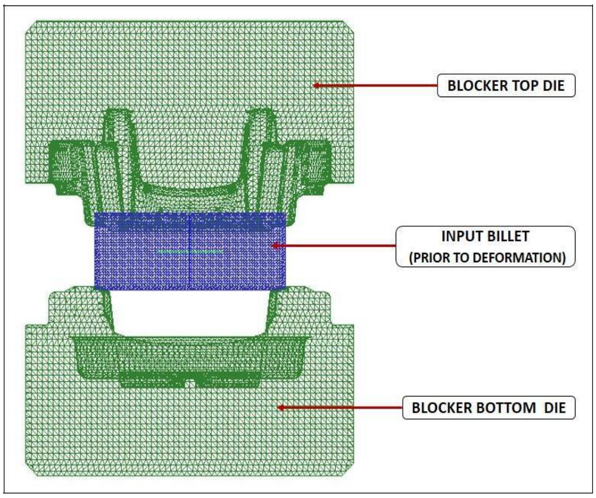

Fig. 4.1: Discretised model of die and billet assembly

(Initial contact between die and billet shown)

4.3: 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-visco plastic FE formulation is as follows:

$\pi = \iiint (\dot{\epsilon}_{ij}) dV - \iint F_i u_i dS$ ----------------(Eq.4)

Where,

$(\dot{\epsilon}_{ij})$ 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:

$\sigma\pi = \iiint \bar{\sigma}\delta\dot{\bar{\varepsilon}}\, dV + K \iiint \epsilon\dot{v}\ \delta\ \epsilon\dot{v}\, dV - \iint F_i \delta u_i dS = 0$-------- (5)

Where,

$\dot{\epsilon}_v$ = 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,

Effectivestress,

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\delta_1 - \delta_2)^2 + \ (\delta_2 - \delta_3)^2 + \ (\delta_3 - \delta_1)^2} \text{ ---------(Eq.6)}$$

Effectives,strains,

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + \ (\varepsilon_2 - \varepsilon_3)^2 + \ (\varepsilon_3 - \varepsilon_1)^2} \text{ -(Eq.7)}$$

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 work piece can be determined by

$\bar{\tau} = \mathrm{K}.\sigma_{ij}\varepsilon_{ij}$ --------------------- (Eq.8)

Where,

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

σ_{ij} =component of stress tensor

ε_{ij}= component of strain rate tensor

4. EXPERMENTAL WORK

4.1: 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 Pro-E solid modelling software. 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 mm^3

Density of material = 7.86×10-6 kg/mm^3

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 mm^3

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

= (Net weight of the forging/ Billet input weight) x 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)

Cross-sectional area = 4211.27 mm2

Length of billet required = (Required weight/density of material) /Cross sectional area

= 174 mm (Approx.)

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

4.2: 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 is mostly empirical, developed by different researchers. As flash design is an important input to the process, calculation is done using different method .The result of the same is summarized in Table.4.1.

Table 4.1: Summarised result of flash thickness calculation

Reference Work (Author)	Method of Calculation (Flash thickness)	Calculated Value (*) (mm)
1. Vieregge	t=0.017D+ $\frac{1}{\sqrt{D+5}}$	2.8
2. Neuberger & Mockel	t=0.89 $\sqrt{W}$ +0.017W+1.13	3
3. Teterin & Tarnovski	t= $2^3\sqrt{W}$ -0..01W-0.09	3.2

(*) – 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

$$\frac{W}{t}=\frac{30}{\sqrt[3]{D+\left[1+\frac{2D^2}{h(2r+D)}\right]}}$$

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.

4.3: ACTUAL EXPERIMENTAL SETUP:

The actual trial was taken at the forging division of M/s RSB Transmission (I) Ltd., located at Mania, Hyderabad. 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.H13grade 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.4.1: Machine used for experimental trial; a) Mechanical cranked press with automated induction heating arrangement b) Front view of the press machine

4.4: VERIFICATION AND VALIDATION OF EXPERIMENTAL PROCEDURE:

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:

1. Ensure that the input values and assumptions made are correct or justified.
2. The model is adequate to predict actual behaviour.
3. 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:

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

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.4.2. The comparison of the metal flow pattern at central cross section is shown in Fig.4.3.

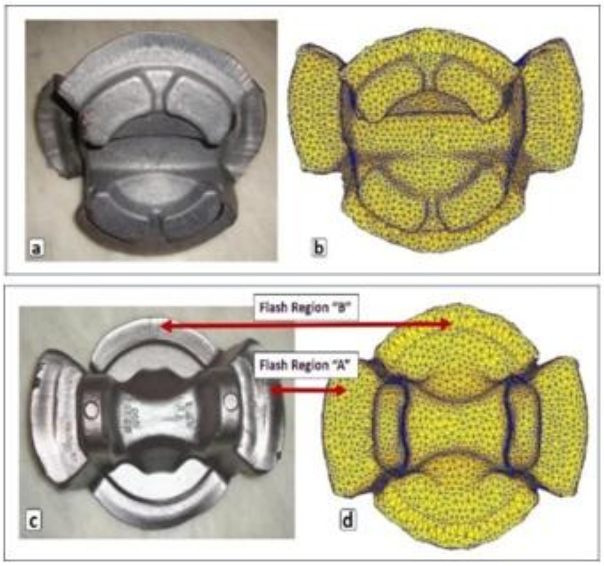

Fig.4.2: Comparison between Actual Vs. Predicted Flash Pattern; Different Views (a,c- Actual Component; c,d- Simulation Prediction)

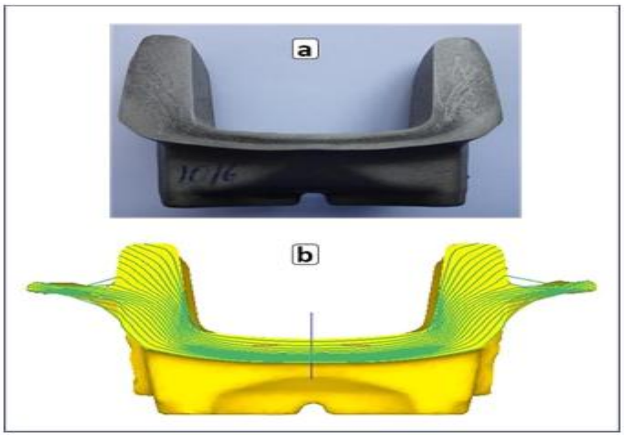

Fig.4.3: Comparison of Metal flow Pattern; a) Cross section of Actual component b) Predicted pattern by Simulation along with flash

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

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:***

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

(B) ***Tooling definition:***

Material designation	AISI H-13
Die preheating temp	300 °C
Flash thickness	4 mm

(C) ***Machine specification:***

Type of machine	Mechanical cranked press
Maximum capacity	2500 T
Maximum stroke length	350 mm
Operating stroke length	250 mm
Stroke per second	1 cycle
Connecting rod length	2350 mm

(D) ***FE Modelling strategy:***

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

(E) ***Boundary condition:***

Environmental temperature	35 °C
Coefficient of friction	0.3
Operating step increment	0.5 mm (For step simulation)
Heat transfer co-efficient [28]	11 N/Sec/mm/C
Convection co-efficient	0.02 N/Sec/mm/C

4.5: 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.4.4-4.6. It captures the transformation of simple billet geometry; into the complex shaped component along with the effective stress distribution during the process.

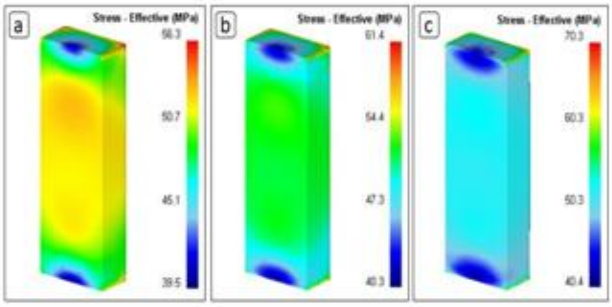

Fig.4.4: (a-c) Step wise simulation result of upsetting stage; Effective stress plot

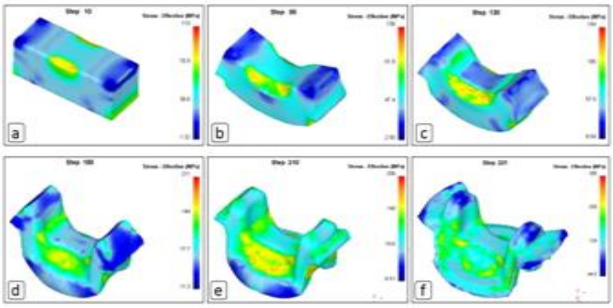

Fig.4.5: (a-f) Step- wise simulation result of blocker stage; Effective stress plot

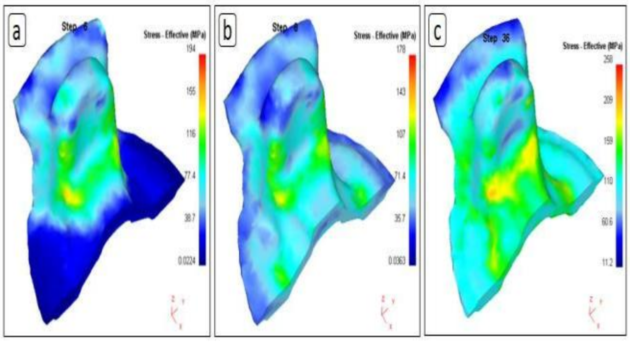

Fig.4.6: (a-c) Step wise simulation result of finisher stage; Cut sectional view

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.4.7. 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.

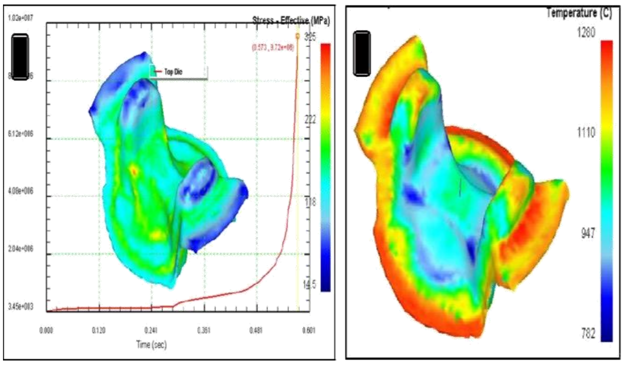

Fig.4.7: Simulation predicted results for load and temperature.

(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. ANALYSIS OF EXPERMENTAL WORK

5.1 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 5.1

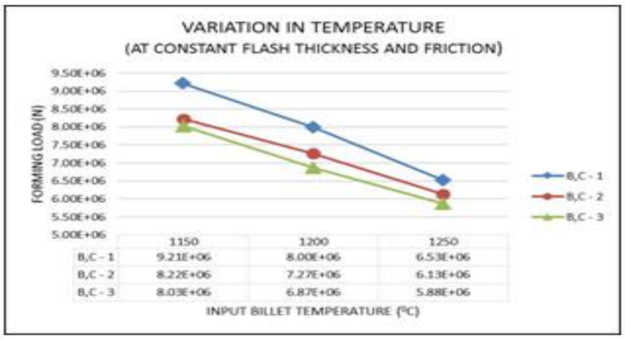

Fig.5.1: Effect of variation of billet temperature

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.

The effect of variation of flash thickness, at constant billet temperature and friction factor is shown in Fig.5.2

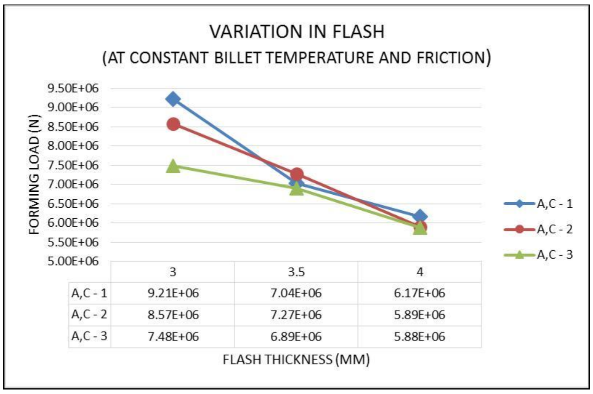

Fig.5.2: Effect of variation of flash thickness

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.

The effect of variation of friction factor, at constant billet temperature and flash thickness is shown in Fig.5.3

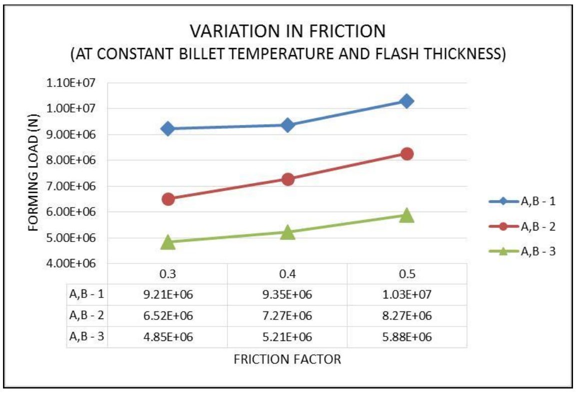

Fig.6.3: Effect of variation of friction factor

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 work piece 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

5.2: 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.

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

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

Where,

$\bar{y}$ = average of observed data
y = is observed data
$sy2$ =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.

The main effect plot for S/N ratio, for billet temperature, flash thickness and friction factor are plotted graphically as shown in Fig.5.4.

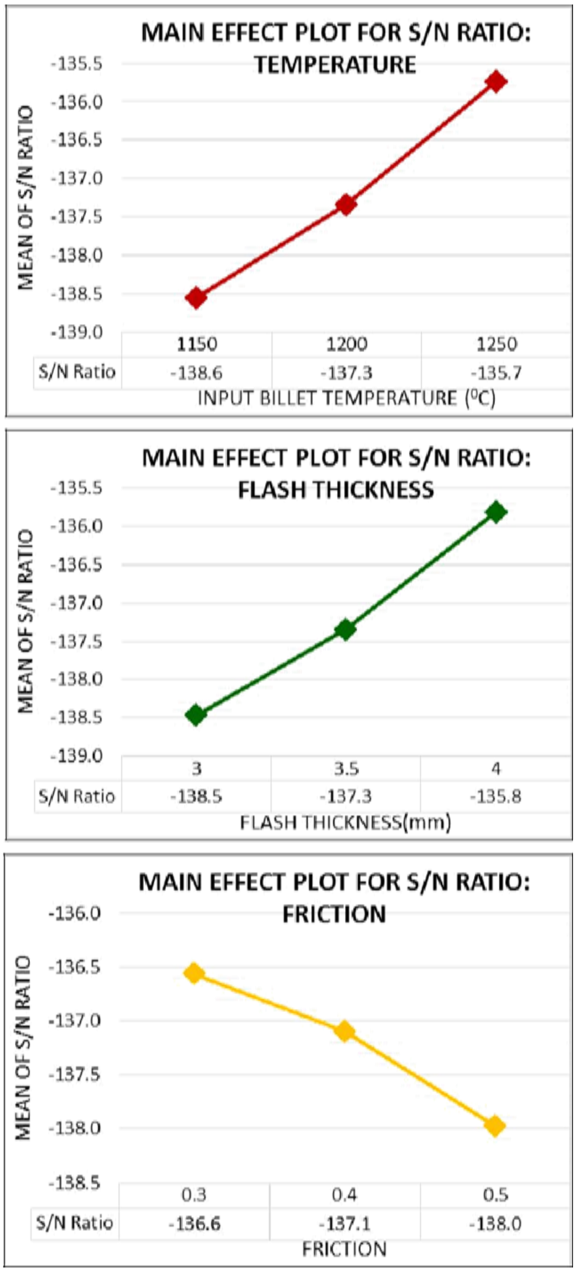

Fig.5.4: Main effect plots for S/N ratio for different parameters

Table 5.2: 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.**

6. CONCLUSION AND SCOPE FOR FUTURE WORK

6.1: 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:

- 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.
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- 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.

6.2: 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.

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