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Preform Shape Optimization of Connecting Rod Using Finite Element Method and Taguchi Method

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ABSTRACT : *Preform design in forging processes is an important aspect for improving the forging quality and decreasing the production cost. The objective of this paper is to obtain an optimal perform shape in the consideration of the influence of the metal flow deformation in closed die forging process. Finite element method based DEFORMTM 3D software in conjunction with Taguchi method has been used to simulate the closed die forging process and then performing a series of optimization iterations in order to obtain the optimal shape of the billet based on forging load minimization. The goal of the simulation and optimization process is to minimize the forging load and produce defect-free forgings. The optimal shape of the billet that gives minimum forging load with complete die filling was obtained after several optimization iterations. The approach used in this study could be extended to the optimization of more complicated forging products.*

Keywords: *Preform, Hot forging, Optimization, Finite element analysis, Taguchi method.*

I. INTRODUCTION

In the forging process of complicated parts, the selection of appropriate preform shapes is crucial. The preform design in metal forging plays a key role in improving product quality, such as ensuring defect-free property and proper metal flow. In addition, it may produce more uniform strain distribution through the final forging product. Thus, the metallurgical and mechanical properties reduce the material waste and less die wear may be achieved [1]. In designing this process, preform shape, final shape and material behaviour should be contemplated in a way to fill the die cavity completely. Furthermore, the designer should regard the process not causing any defect or undesirable properties. Main purpose of the preform design process is achieving the following:

- Assuring the metal flow without any defect and appropriately filling of the die.
- Minimizing the material wastes in the flash.
- Minimizing the die wear.
- Obtaining the desirable grain flow and suitable mechanical properties.

Traditionally, forging process design and forging process plan has employed trial & error methods which are a time consuming process and expensive. However, in the recent years a significant increase of computer and numerical simulations are reported based on finite element (FE) analysis of forging process. Moreover, traditional techniques have been substituted into numerically based analysis. Therefore, more robust and efficient computer based approaches has been introduced recently. As a result, a large number of investigations have been reported by different scientists in the preform design field.

Zhao G. et al. [2] apply a method, which employs an alternative boundary node release criterion in the FEM simulation of a backward deformation of forging processes. The method makes use of the shape complexity factor, which provides an effective measure of forging difficulty. Bramley [3] initiated a reversed method by Upper Bound Elemental Technique (UBET) and has attained the preform shape by reversing the velocity field direction to a minimum amount for whole of the energy distribution rate which optimized by contact conditions. Biglari et al. [4] succeed to design optimum axisymmetric forging preforms by combining the backward tracing and fuzzy logic concepts. A new approach is introduced by Yiguo, L., et al. [5] for pre-form design called Simulation Block Technique (SBT) in which, the two half-parts of the forging die is imaginarily separated from their closed position, they move backward from each other in opposite direction of the forward (normal) forging process, so that the initial billet or a pre-form can be obtained, the model incorporates the use of UBET. Kang, B., S., et al. [6] presented pre-form shapes design in forging of rib-web shaped plane-strain parts were designed using rigid-plastic finite element method in order to obtain flash-less part. The preform was obtained by changing the aspect ratio- the height to width ratios of the rib geometry used in the analysis. An optimization approach for the design of intermediate forging die shapes using backward deformation simulation and design optimization was developed by Han, C., S., et al. [7]. This approach could determine the pre-form die shapes from the final part shape by imposing constrains on the plastic deformation of the material. In this paper computer simulation of the connecting rod using DEFORM (Design Environment for Forming) is adopted for the purpose of optimizing the perform shape. Deform is a Finite Element Method (FEM) based process simulation system designed to analyze various forming and heat treatment processes used by metal forming and related industries. By simulating manufacturing processes on a computer, this advanced tool allows designer and engineers to

- Reduce the need for costly shop floor trails and redesign of tooling and process.
- Improve tool and die design to reduce production and material costs.
- Shorten lead-time in bringing a new product to market.

II. METHODOLOGY

The main objective of closed die forging are complete die filling without defects viz. cracks, fold-over, wrinkles with minimum forging load. The goal of the simulation is to find out the shape of the billet that leads to a minimum forging load and complete die filling without any defects. Taguchi's experimental method is utilized to design the process parameter combinations to identify the relative influence of each parameter considered in the study. Study of the influence of design related variables on output performance characteristics are time consuming and costly during the real-time forging process.

Whereas finite element method (FEM) based simulation software permits simulation of the system in solving linear and non-linear problems in a cost effective and timely manner. In this paper the effect of design parameters viz. flash thickness, flash width, corner radii and fillet radii on perform has been studied in order to obtain minimum forging load with complete die filling along with minimum material loss by using FEM based DEFORM^{TM} 3D V6.1 to simulate and validate the optimum result. For simulation purpose 3-D modeling software CATIA V5 is used to model part and dies. Final part and its die are as shown in Fig. 1 and Fig. 2. Dies and billets are drawn in such a manner that they are *Z*-axis aligned. As DEFORM^{TM} accepts only *'.STL'* files, upper die, lower die and billets are saved with *'STL'* extension.

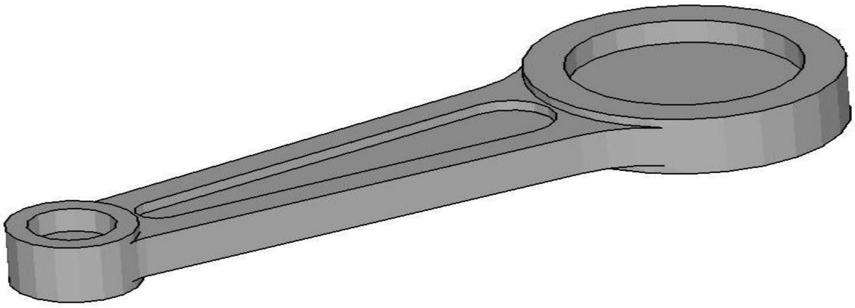

Figure 1: 3D CAD model of connecting rod

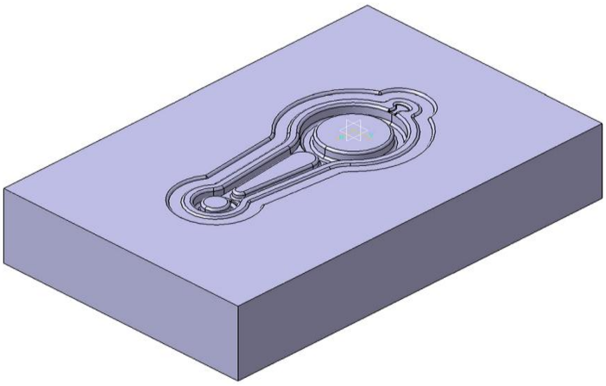

Figure 2: Die of Connecting rod

The material of connecting rod is AISI 1045 alloy steel, whereas AISI-H-13 die steel is used as die material and their properties are given in Table I.

Table I: Material Properties

Property	Component	Die	Units
Density	7870	7800	Kg/m^3
Poisson'^{s} Ratio	0.29	0.3	---
Elastic modulus	200	210	GPa
Tensile strength	585	1990	MPa
Yield strength	505	1650	MPa
Hardness	84	45	HRC
Thermal conductivity	51.9	24.6	W/m-K

III. DESIGN CONSIDERATIONS

3.1 Determination of Stock Size

The factors in estimating the stock size include the size and shape of the forging, method of heating and method of forging.
The terms used in weight calculation are
Net weight – it is the weight of forging as per the given dimension of the component.
Net weight = volume of forging × density of material
Volume of forging = 45700 mm^3

Density of material = 7.86×10^{-6} kg/mm^3
Net weight = 0.36 kg
Flash loss – it is the loss of extra material comes out when the top and bottom die block has filled. It is determined by flash thickness and flash width.
Flash loss = 15 to 20 % of the net weight
= 0.20× 0.36
= 0.072
Gross weight- the amount of material required to fabricate a forging.
Gross weight = net weight +losses
= 0.36+0.072kg
= 0.43 kg

3.2 Design of Flash

The purpose of the flash is to control the metal flow within the die cavity. The flash normally cools faster than the main body of the forging and hence results resistance in metal flow outwards. The consequence of this flow restriction, metal is forced to take an alternative route, the path of least resistance, which normally results in filling dipper die cavities. The flash thickness and width is directly related to the amount of waste material, acts as a pressure release valve for the almost incompressible work metal and restrict the outward flow of the metal so that remote corners and deeper cavities can be filled up. The finisher impression generally includes as provision for flash. The flash depression can be in either die or in both dies.

Thus design of flash dimensions plays a vital role in metal filling. While designing for flash, care must be taken in selecting flash thickness, as thickness being small will necessitate greater energy or extra blows to bring forging to size, on the other hand thickness being more may cause inadequate die filling. Thus a balanced condition is needed with just enough volume of metal to ensure that the flash thickness provided would force the work-metal to fill the impression properly without causing excess wear and pressure. Flash thickness is calculated by using the various formulas as given in Table II.

Table II: Design of Flash

Author	Flash thickness	Result
Bruchanov & Rebelskii [8]	$t = 0.015\sqrt{A}$	1 mm
Thomas [9]	$t = 0.016D$	1.25mm
Vieregge [10]	$t = 0.017D + \frac{1}{\sqrt{D+5}}$	1.5 mm
Neuberger & Mockel [11]	$t = 0.89\sqrt{W} - 0.017W + 1.13$	1.67mm
Teterin & Tarnovski [12]	$t = 2\sqrt[3]{W} - 0.001W - 0.009$	1.4 mm

Here,
A= plan projected area including flash land = 3950 mm^2
D= equivalent diameter = 72 mm
W= forging weight = 0.36 kg

3.3 Fillet and Corner radii

Fillets and corners are curved surface connecting ribs, bosses and webs, and are defined by their transverse section. A corner is a convex arc, which joins two intersecting sides at an external angle of more than 180°, whereas fillet is a concave arc, which joins two intersecting sides at an external angle of less than 180°. Design of fillet and corner affect grain flow, forging pressure requirement, die wear, grain flow, amount of metal to be removed during machining, amount of cut grain at junction and cost of dies and forgings. Proper selection of fillet and corner radii is vital in designing dies for forgings. Sharp corners must be avoided in forging design as they weaken both the dies and finished forgings. A sharp internal corner or very small fillet in forging introduces a danger of cracking in heat treatments while the corresponding sharp external corner on the die prevents a satisfactory flow of metal in impression and may result in a defective forging.

3.4 Press selection

The main requirement selecting the press to produce a given forging is an estimate of the forging load. This will depend on the material, forging temperature, forging complexity and flash and land dimension.
For non circular forging

$$P^1 = P \times [1 + 0.1 \times \sqrt{\frac{2}{b}}] \qquad (1)$$

$$P = 8 \times (1 - 0.001 \times D_{reduced}) \times (1.1 + \frac{20}{D_{reduced}})^2 \times S_1 \times \sigma \qquad (2)$$

Where, $D_{reduced}$ = Reduced diameter of Non- Circular forging including flash land = $1.13(S1)^{1/2}$=72mm
S_1= Plan projected area of Non-Circular forging including flash land = 6130 mm^2

σ= Tensile strength at forging temperature=6.5 kg/mm^2
b= Average width of forging including flash land = S_1/L_{max} =39.3 mm
L_{max} = maximum length of forging at parting plane including flash land= 156mm
P=8x(1-.001x72)x1.898x6130x6.5=561526 kg
$P^1 = P \times [1 + 0.1 \times 0.225]$ = 574 ton
For simulation work press capacity is taken 574 ton

IV. TAGUCHI EXPERIMENTAL DESIGN

Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance characteristics. The most important stage in this method lies in the selection of control factors. An exhaustive literature review reveals that the optimized preform shape largely influenced by flash thickness (F_T), flash width (F_W), corner radius (R_C), fillet radius (R_F). These parameters each at three levels are considered for the present study. The operating conditions under which test are carried are shown in Table III.

Table III: Factors and their levels

Factors	Symbol	Level			Unit
		1	2	3	
Flash thickness	F_T	1	1.5	2	mm
Flash width	F_W	6	8	10	mm
Corner radius	R_C	1.5	2	3	mm
Fillet radius	R_F	2	3	5	mm

The total degree of freedom (DOF) for four factors each at three levels is 8. Therefore L_9 orthogonal array [13] is selected for experimental design and is shown in Table IV.

Table IV: Taguchi Design for Preform (All dim. are in mm)

Flash thickness	Flash width	Corner radii	Fillet radii
1	6	1.5	2
1	8	2	3
1	10	3	5
1.5	6	2	5
1.5	8	3	2
1.5	10	1.5	3
2	6	3	3
2	8	1.5	5
2	10	2	2

V. PREFORM DESIGN

Preform design is one of the most important aspects in metal forming process design. Pre-form impression allows adequate metal distribution in the final impression. Thus, defect-free, complete die fill and small metal loses into flash can be achieved by a properly designed perform. If the component has varied cross-section as in case of spanner, connecting rod, break, pedal lever etc. it is necessary to reduce or increase cross sectional area of the bar at desired points with a view to improve die life. This will necessitate the preforming operation before finishing. For better quality forging productions, care must be taken that in the finishing impression to minimize deformation to achieve final shape. Traditionally, the preform design is based on empirical or approximate analysis, requiring time consuming and expensive trial-and–error. Hence it is necessary to optimize the perform design in order to minimize the above drawbacks.

The following procedure is used to design preform impression from forging drawing.

- The plan and the elevation of forging are laid out to full scale.
- An estimated outline of the flash of the forging preside is than laid out.
- The forging is then divided into various element based on geometric shape.
- Vertical lines are drawn through largest and smallest cross sectional area of each element found as above.
- The area of the above cross section is calculated and to each such area, cross sectional area of flash is added (flash width× flash thickness).
- From the base line of above measurement are plotted and connected with smooth line, then the cross sectional area of perform at each line is determined.
- The diameter “D” of the perform is evaluated at each element using the equation 3.

$$D= (4xA/\pi)^{(1/2)} \qquad (3)$$

Where *D* – equivalent diameter
A - Total area (flash area + job section area)

Thereafter, the dimension D is symmetrically plotted about the reference line. These points are finally connected with a smooth curve as shown in Fig.3. A perform impression having this as an approximate contour can provide smooth flow of metal from blank into perform and finally finisher impression. For the present work 9 such performs and their dies were designed for different values of flash thickness, flash width corner and fillet radii [14].

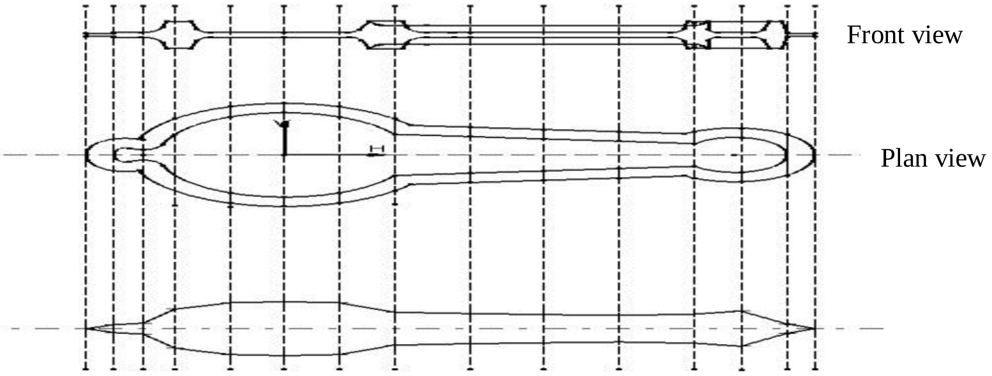

Figure 3: Preform shape of Connecting rod

VI. COMPUTER SIMULATION AND ANALYSIS OF THE FORGING PROCESS

Main objective of this study is to investigate the effect of design parameters on preform shape. The computer simulation of hot forging process has been done to obtain the optimum perform shape. The DEFORM™-3D V6.1 software package was employed in the present research for the simulation and analysis of results. So far most FE based software that simulate billet forming processes that consider only plane-strain or axis symmetric deformations. Since many industrial parts such as connecting rods have very complex geometries, the metal flow is three dimensional and cannot be properly modelled with a two dimensional approximation. Therefore, a three dimensional simulation of the manufacturing process must be performed to get adequate results. The commercial package DEFORM™-3D V6.1 offers the possibility of simulating three dimensional material flows of complex geometries.

Main objective of this paper is to investigate the effect of process and design parameter to die performance and quality of the forged part. In this study, computer simulation of hot forging process has been done to obtain the optimum design and process parameters. The DEFORM™-3D V6.1 software package was employed in the present research for the simulation and analysis. DEFORM essentially consists of three parts, described below.

6.1 Pre-processor

The pre-processor includes (i) an input module for iterative data input verification, (ii) an automatic mesh generation program which creates a mesh by considering various process related parameters such as temperature, strain, strain-rate as well as die and work piece geometry; and (iii) an interpolation module that can interpolate various simulation results of an old mesh onto a newly generated mesh. The combined and the automated use of the modules for automatic mesh generation and interpolation, called automatic remeshing, allow a continuous simulation of a forming process without any intervention by the user, even if several remeshings are required. This automatic remeshing capability drastically reduces the total processing time of finite element analysis. All the input data generated in the pre-processor can be saved (i) in a text form which enables the user to access the input data through any text editor; and /or (ii) in a binary form which is used by the simulation engine explained below.

6.2 The simulation engine

The actual FEM-based analysis is carried out in this portion of DEFORM. This simulation engine is based on a rigid – plastic FE formulation and can handle a multiple number of billets (either dense material or porous material, or combination of these materials) and dies (either rigid or linear elastic) with non-isothermal simulation capability. The simulation results are stored in binary form and accessed by the user through the post – processor.

6.3 Post processor

The post processor is used to display the results of the simulation in graphical or alphanumeric form. Thus, available graphic representations include (i) FE mesh; (ii) contour plots of distributions of strain, stress, temperature etc, (iii) velocity vectors, and (iv) load – stroke curves. Two other useful capabilities in the post –processor are (i) ‘ point tracking’, which provides deformation histories of selected points in the workpiece throughout the deformation; and (ii) ‘flownet’, which allows the user to observe the deformation of circles or rectangles ‘inscribed’ on the undeformed workpiece for any desired step through the simulation [15].

There are some assumed models in this paper, including that the plastic material model and the rigid die model are assumed. The velocity of the moving ram is kept constant. The strain rate at the first of deformation is equal to 2 S^{-1}. All the simulations started with 45000 elements. Table V shows the assumed models.

Table V: Operation parameters assigned to complete the simulation

Problem Type	Closed die hot forging
Forging Equipment	Mechanical press
No. of elements	45000
Mesh type	Tetrahedral
Simulation mode	Isothermal
Primary die	Top die
Const. Envir. Temp.	20^0c
Billet Temp.	1050^0c
Die Temp.	300^0c
Friction Coeff.	0.3 with lubrication
Die velocity	1.5 mm/s

VII. RESULTS

Simulations are run as per Taguchi experiment plan based on the experimental layout depicted in Table 4, and respective value of forging load for each simulation run are converted into their respective S/N ratios as per equation 1 and are given in Table VI.

Table VI: L9 orthogonal array with their response

Exp. No.	Parameters				Response		
	F_T	F_W	R_C	R_F	Forging load(N) (10^6)	S/N Ratio	Complete filling
1	1	6	1.5	2	7.86	-17.9085	No
2	1	8	2	3	7.29	-17.2546	No
3	1	10	3	5	9.73	-19.7623	No
4	1.5	6	2	5	3.82	-11.6413	Yes
5	1.5	8	3	2	7.53	-17.5359	No
6	1.5	10	1.5	3	6.25	-15.9176	Yes
7	2	6	3	3	3.17	-10.0212	Yes
8	2	8	1.5	5	3.47	-10.8066	Yes
9	2	10	2	2	4.01	-12.0629	No

After conducting the experiments according to Taguchi's experimental design we observed that in experiment no. 1, 2, 3 and 5 the problem of underfilling occurred and the forging load was also very high. This is due to small flash thickness and improper value of corner and fillet radii. While during experiment no. 9 problem of underfilling occur because it has been observed that material is going out in the form of flash without filling die cavity completely.

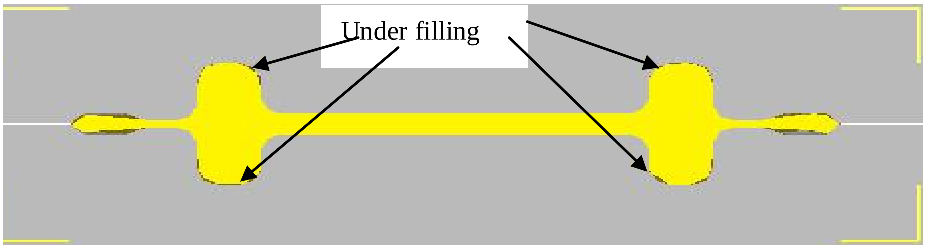

Figure 4. Critical areas of underfilling during Simulation

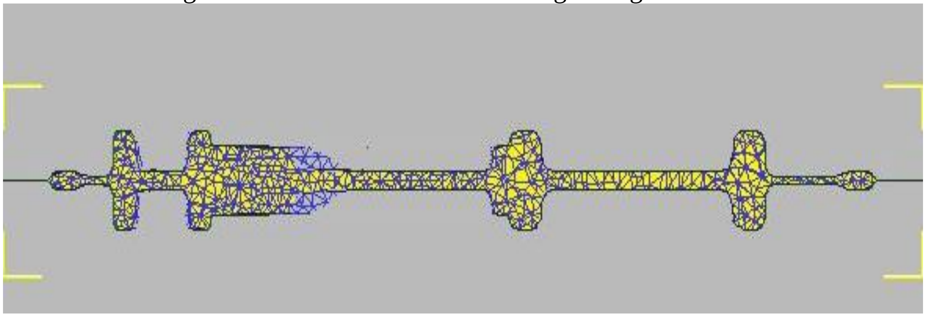

Figure 5. Comple die filling achieved during simulation

VIII. DISCUSSION

Data analysis is made using MINITAB R14 software at 95% of confidence. Main effect plot (Fig. 6) is used to determine the optimum factor levels for minimum forging load, which F_T3, F_W1, R_C1 and R_F2 are corresponding to the largest values of S/N ratio for all control parameters. Relative influence of each factor is determined by analysis of variance method (ANOVA) presented in Table VII.

Table VII: ANOVA Table for forging load

Parameters	Degree of freedom	Sum of square	Variance	% Contribution	F- value
Flash thickness	2	81.234	40.617	77.1526	6.72
Flash width	2	11.966	5.983	11.3648	0.99
Corner radii	-	6.797*	-	-	-
Fillet radii	-	5.293*	-	-	-
Error	4	12.09	6.045		
Total	8	105.29			

*pooled

ANOVA depicts that the process parameter namely Flash thickness and Flash width are the most significant parameters affecting the Forging load. Fillet radius and corner radius shows the least contribution. It is necessary to mention that confidence level of 95% is used for analysis purpose, so p-value less than 0.05 will establish the significance of factor.

Adequacy of analysis is carried out using Anderson–Darling (AD) test and results are illustrated in Fig. 7, which shows that data follows normal distribution and develop procedure is suitable enough to explore the design space.

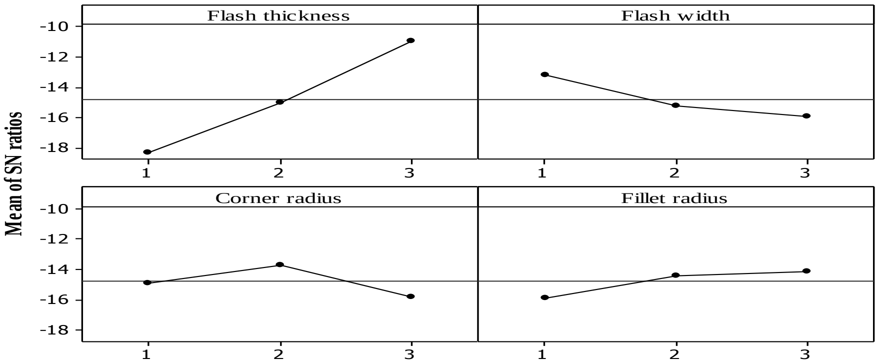

Figure 6: S/N ratio response graph for forging load

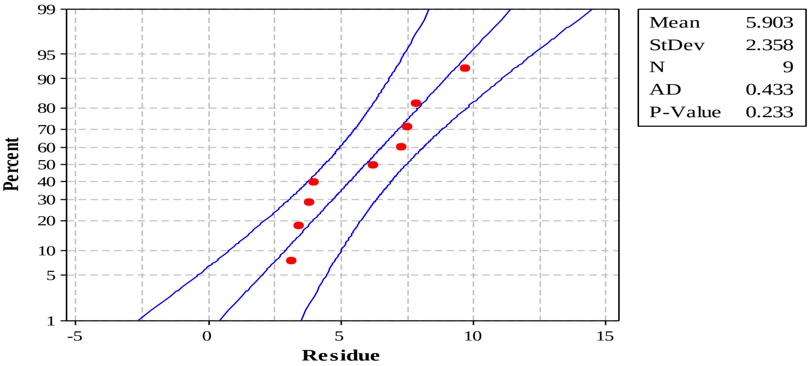

Figure 7: Normal probability plot of residue at 95% of confidence

IX. CONFIRMATION EXPERIMENT

For confirmation purpose process is simulated at optimum factor level setting keeping all the simulation parameter fixed as given in Table 5. Fig. 8 shows the optimal forging load value of $2.13x10^6$ N. At this load the complete die filling is achieved with maximum yield (Fig. 9). On comparing the simulation results with Taguchi predictive model which is $2.17 x10^6$ small error of 1.84 % indicate the Taguchi experimental plan has proceeded in a smooth manner.

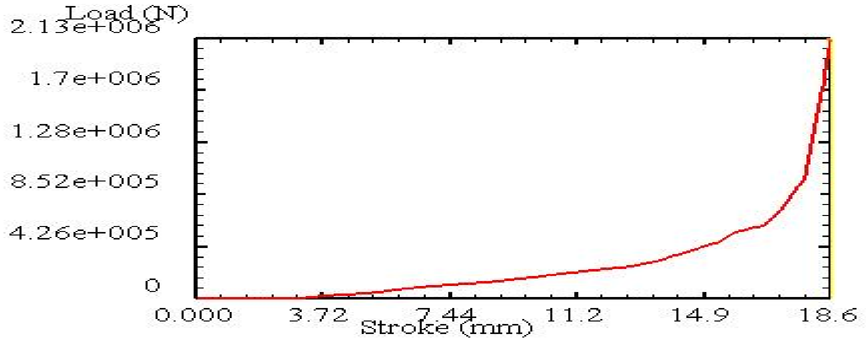

Figure 8: Load vs. stroke curve showing minimum forging load

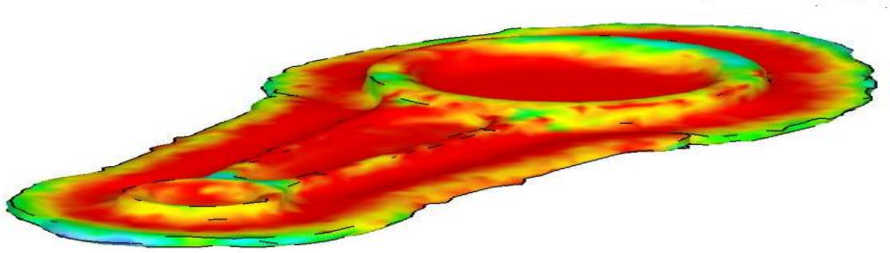

Figure 9: Complete die filling with maximum forging yield and without any defect

X. CONCLUSION

FEM-based computer simulation has been used to optimize the design parameters viz. flash thickness, flash width, corner radius and fillet radius on perform shape of connecting rod.Using Taguchi method, design parameters were optimized individually for forging load. In order to study the significance of the parameters in effecting the quality characteristics of interest i.e. forging load ANOVA has been performed. The conformation experiment was conducted by taking the optimized value (output of Taguchi's experiment) and was simulated once again. The results shows that at optimum factor level setting complete die filling is achieved with minimum forging load. It is found that optimization can be achieved quickly and efficiently through the use of simulation software. Modeling provides more information about the process i.e. load requirement and metal flow at different stages of the process. These techniques are also cheaper than performing tryouts with actual dies and equipments.

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