Parametric optimization of hot forging process: a six sigma based approach

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Abstract: One of the major concerns for industries in the modern world is to focus efforts on producing high quality products with minimal costs. Various quality improvement philosophies have emerged in recent times, Six Sigma being one of the most practical and efficient techniques for quality improvement of processes. In this work, Six Sigma based DMAIC (Define, Measure, Analyze, Improve, Control) approach is used to enhance productivity and quality performance, and to make the hot forging process robust to quality variations. Finite element method has been employed for the simulation of hot forging of the connecting rod. The influence of design and process parameters is investigated for the response 'forging die load'. Analysis of various critical parameters and the interaction among them has been carried out with the help of Taguchi's method of experimental design. To further optimize the response and make the analysis more precise and robust, response surface methodology has been incorporated. Parameters have been optimized, leading to the accomplishment of a minimized forging die load which is verified using a confirmation experiment. Confirmatory results reveal the potential of the DMAIC approach of Six Sigma in optimizing the process parameters successfully and thereby present significant applicability in the industry.

1 Introduction

Forging is a traditional metal working technology that has been used by humans for several centuries. On the basis of temperature of the work-piece, forging is classified as cold, warm or hot forging. In hot forging, the metal work-piece or billet is heated at high temperatures to improve ductility and then it is plastically deformed using localized compressive forces imparted by hammers or presses. The work-piece deforms plastically to fill the cavity in the die which is designed according to the shape of the desired product. [1]

In internal combustion engines, a connecting rod connects the piston to the crankshaft. The connecting rod acts as a link and converts the reciprocating motion of the piston into the rotary motion of the crankshaft. Connecting rods are manufactured in developing countries like India, through the conventional hot closed die forging that involves flash formation. Typically, a cylindrical work piece or billet is heated and deformed plastically in various stages to yield a connecting rod. These stages include blocking, finishing and trimming operations. The work piece takes the final shape of connecting rod in the finishing operation, which is the last stage of forming before the trimming operation. [2]

Hot forging process is advantageous over other manufacturing processes like casting or machining, as forged products offer higher strength than cast or machined products. This is because the internal grain structure of the forged part varies continuously as it deforms with the work piece during forging. Process design for hot forging usually follows a bottom up approach, with repeated iterations to study and improve the process. Thus, cutting costs and reducing the time consumed becomes a challenging task. Hence there is a need to study the process parameters involved in hot forging operation, and to optimize them. [3]

Six-Sigma has been hailed as one of the most viable techniques in research in the recent times. Many researchers have employed six-sigma based techniques to study and improve a wide variety of industrial processes [4]. It is an analytically rigorous continuous improvement process. Over the years, Six Sigma has become an effective management philosophy and has served as a model for the industry to follow. [5] This work focuses on the implementation of Six Sigma philosophy to optimize the conventional hot closed die forging process. A widely used technique to implement Six Sigma is the DMAIC approach (Define, Measure, Analyze, Improve and Control) (Koning and Mast, 2004) [6]. Using this approach, a lot of research has been done to improve various process outcomes which drastically improve quality, reduces costs and time consumed. Figure 1 illustrates the general flow of Six Sigma based DMAIC approach.

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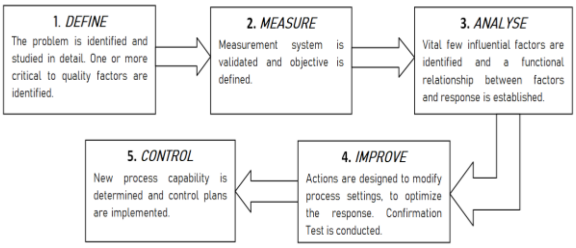

Fig. 1: General flow of DMAIC approach.

In this work, we have studied hot closed-die forging through the DMAIC approach of Six-Sigma and organized our work as per the steps involved in the DMAIC approach. Taguchi's method of experimental design has been employed to study the relationship of various design and process parameters with the response variable. Computer based simulation has helped us to conduct trials in a time and cost effective manner. DEFORM 3D, a Finite Element Method (FEM) based software package has been used to run simulations. Statistical analysis has been used to establish a functional relationship between the response and factors of the experiment. A regression equation is built to generate response surface plots. Using the Response Surface Methodology (RSM), the factors of the experiment are further fine tuned in the optimum range. The predictions of RSM are finally confirmed through experimental simulation. Rest of the paper has been structured as per the steps involved in the DMAIC approach.

2. Define (Hot Closed Die Forging)

In this phase of the DMAIC implementation, the chief task is identifying influential parameters and describing the whole process of hot forging operation.

Die's performance significantly influences the quality of the product. Moreover, die life directly influences process cost. With an improper die, the product shall not be formed properly, thereby making die design a crucial stage in the process. In this work, the focus is on minimizing the die load developed during hot closed die forging of automobile connecting rods. With minimized die load, damage and wear are reduced and the die life improves. Since the product quality is influenced by die life and performance, optimizing die performance improves process economy and quality. Several factors have been found to influence die performance in the literature. These factors can be broadly divided into two groups – the Design parameters and the Process parameters. Design parameters include Flash Thickness (F_t), Flash Width (F_w), Corner Radius (R_c), and Fillet Radius (R_f). These factors describe the geometry of the die. The second group of factors, called the process parameters include Billet Temperature (T_b), Die Temperature (T_d) and Friction Coefficient (μ). [7][8]

Flash is formed during the forging operation of connecting rods. Flash is a scrap material and depending upon the complexity of the part, it can exceed even half the total volume of the formed metal. Flash formed during hot forging cools faster due to greater surface area and thus sticks to the die, acting as a pressure release valve for the almost incompressible metal. It restricts the outward flow of metal and ensures deeper die filling of the work-piece. Since the flash is a scrap material, it is later punched and removed from the formed product as waste product in the trimming operation. Thus the amount of flash produced also influences process cost and needs to be optimized.

Corner radius and fillet radius are also important parameters to be considered in die design as revealed in the literature. A sharp corner or fillet poses a risk of cracking or lapping, thereby increasing die wear, and hampering the die life and performance. A smooth corner also ensures better flow of metal. With improper metal flow, die filling is inadequate and quality of the product is compromised. This also increases the die load. Corner and fillet radius affect the grain flow. Sharp corners weaken both the dies and formed part. Thus they need to be optimized for least cracking and wear of the die. [9]

Forging temperature is directly related to the workability of metal. Workability of the metal generally increases with temperature. Higher temperature ensures better die filling by improving the metal flow. This also reduces die load which reduces the risk of die wear. If the dies are too hot, the amount of heat transfer between the dies and the billet will reduce. Cooler dies will allow more rapid heat transfer and cool the surface layers of the work-piece considerably. Flash formation, which is directly related to product quality, is essentially formed by quicker cooling than the rest of the work piece.

The material of die and the lubricant are selected based on these limitations. Friction between the dies and work-piece affects the die load while forging, and hence the die life. Proper lubrication affects the coefficient of friction and thus the die load. [10, 11]

It has been revealed in the previous works that a deteriorating die performs poorly and thus product quality is compromised. A low die load during the forging operation improves die life. It can be seen that the die life and hence the product quality can be considerably improved with the optimization of design and process parameters for a lowest die load in forging operation. Die can fail prematurely if the die load in the forging operation exceeds the strength of die material. Low die load causes minimal damage to the dies, enhances die life and performance and hence the product quality and process economy.

3. Measure

Researchers in metal forming industries have conducted extensive research in this area to attain the optimization of hot forging variables. Srivastava et al. [12] have studied the effect of billet temperature and coefficient of friction on forging die load and strain rate. It was observed that the forging die load increased with increasing friction coefficient and decreased with an increasing billet temperature. Desai et al. [13] studied the design parameters of gear forging using Finite Element Method and Design of Experiments (DOE). It was observed that several parameters influenced the quality of forged gear. These included shear friction factor, punch velocity, aspect ratio and die temperature. Friction and die temperature has been studied in this work.

Ab-Kadir et al. [14] studied the effect of corner radius and friction while optimizing the cold forging die design. It was observed that a sharp corner (less corner radius) would introduce a high stress concentration, worsening the die performance and life. Die load required was observed to increase with larger values of friction coefficient. With a smaller value of the friction coefficient, the work-piece deformed almost uniformly. Higher friction increases wear and deteriorates the die life. With an increase in the flash thickness, the required die load was seen to decrease. Thus, the most favourable flash thickness has to be designed based on the press capacity, die life, and the number of products in order to minimize the total cost.

As discussed, it is found that there are 7 influencing parameters also known as control factors, for the underlying hot forging operation. These are the four design parameters: Flash thickness (F_t), Flash width (F_w), Corner Radius (R_c), and Fillet Radius (R_f) and three process parameters: Billet Temperature (T_b), Die temperature (T_d), Friction Coefficient (μ). These seven control factors have been identified as the major influencing parameters. The material of the connecting rod is AISI–1045[1650-2200F (900-1200C)], whose properties are given in Table 1.

Table 1 Material properties

Properties	**Conditions**	
		Temperature
Density	7.7-8.03 (x1000 Kg/m^3)	298
Poisson's Ratio	0.27-0.30	298
Elastic Modulus	190-210 Gpa	298
Tensile Strength	44.6 Mpa	
Yield Strength	472.3 Mpa	
Elongation	22 %	
Hardness	217 HB	
Izod Impact Strength	51.1 J	
Thermal Conductivity	44.5 W/m-K	

Figure 2 shows the cause and effect diagram drawn from the observed process conditions. **Figure 3** shows the 3D rendering of upper and lower dies. **Figure 4** shows the design of the product.

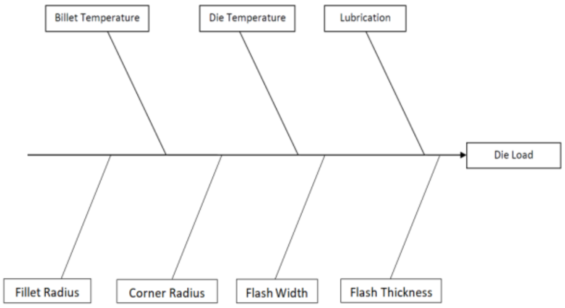

Fig. 2: Cause and effect diagram for process parameters and die load

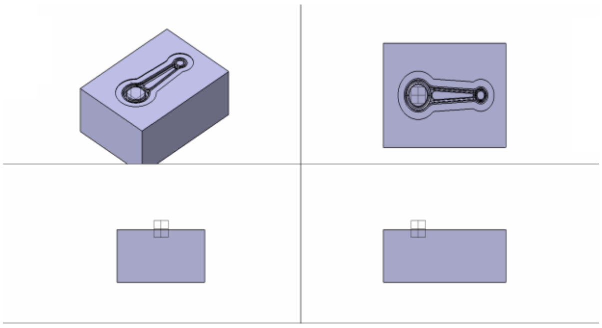

Fig. 3: 3D image of the die

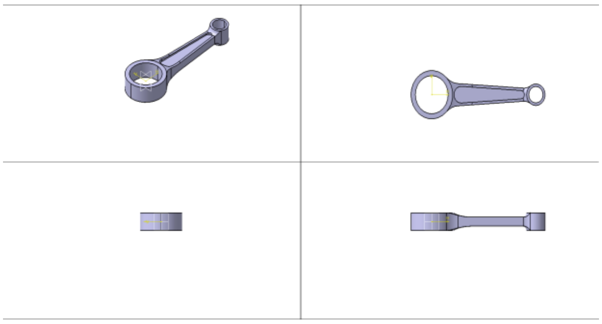

Fig. 4: Connecting Rod Design

4. Analyze

In this stage of the DMAIC approach, the main task is validating a functional relationship between the control parameters and the response parameter, thereby identifying the critical parameters that significantly influence the response variable. Taguchi's method of experimental design is a practical methodology for this purpose. It allows studying the process with minimum number of experimental trials. Thus it greatly helps in saving time and cost. Analysis of Taguchi's experimental design reveals the functional relationship between the input and output variables (Ghani et al., 2004).[15] Taguchi's experimental method is utilized to design the parameter settings for experimental trials, to identify the relative influence of each parameter considered in the study. [16]

4.1 Selection of Orthogonal Array

An orthogonal array is used in the Taguchi's method. The orthogonal array (OA) is a form of general fractional factorial design. It contains a representative set of all possible combinations of experimental conditions. Using the Taguchi method, all levels of all factors are considered equally. A balanced comparison of levels of the critical parameters is achieved. This significantly reduces the total number of experimental trials. [17]For simulation purposes, the component drawing of a three-dimensional solid model of connecting rod (Fig. 4) and top and bottom die (Fig. 3) are done using CATIA V5. Finally, RSM is adopted to determine the optimum settings of design and process parameters and thereby optimize the response.

More than 2 levels of design and process parameters helps in studying the non-linear relationship between the factors and the response parameter. Thus, the design and process parameters each at three levels are considered important for the present study. The operating conditions under which experimental trials are conducted are given in Table 2. These levels have been selected after an ample literature survey. For example, Newberger and Mockel[3] have studied optimum flash thickness and flash width previously.

Product weight computed from CATIA V5 is nearly 340 g. Friction Coefficient has been chosen from inbuilt values of DEFORM 3D based upon the nature of lubrication (whether in one die, or on both dies or neither) in hot closed die forging. In hot forging, when both the dies are lubricated, the value of coefficient of friction is assigned as 0.3 for the considered material and conditions. For lubrication of neither die, the value of coefficient of friction is assigned as 0.7. And for lubrication of only one of the dies, the value of coefficient of friction is taken as 0.5. Dies are assumed as rigid bodies in the simulation software.

Table 2: Factors and their levels

Factors	**Symbol**	**Level**			**Unit**
		1	2	3	
Flash Thickness	A	1	1.5	2	mm
Flash Width	B	4	6	8	mm
Corner Radius	C	1.5	2	2.5	mm
Fillet Radius	D	3	4	5	mm
Billet Temperature	E	900	1050	1200	ºC
Die Temperature	F	200	250	300	ºC
Friction Coefficient	G	0.3	0.5	0.7	--

The total degree of freedom (DOF) for seven factors each at three levels is 14. Signal to noise or S/N is a measure used in studies which is used to compare the levels of a desired signal to the level of background noise. The S/N ratio is treated as the quality characteristics evaluation index. Least variation and optimal design is obtained through analyzing the S/N ratio since stability of quality is dependent on it. Depending on the objective, there are three types of S/N ratio: the lower the better, the higher-the-better and the nominal-the-better. In present work, since the die load is of the characteristic – smaller the better, the type of S/N ratio used is expressed as follows,

$$\text{S/N} = -10 \log_{10} \frac{\sum y_i^2}{n} \qquad \ldots(1)$$

Where, n = number of experiments and y_i = die load. Data analysis is made using MINITAB 15 at a 95% confidence interval. [18]

Table 3: Process Parameters and Taguchi L$_{27}$ Orthogonal Array with S/N Ratio Value

S No.	**Flash Thickness**	**Flash Width**	**Corner Radius**	**Fillet Radius**	**Billet Temp.**	**Die Temp.**	**Friction Coefficient**	**Maximum Die Load**	**S/N Ratio**
1.	1	1	1	1	1	1	1	9.19	-19.266
2.	1	1	1	1	2	2	2	9.25	-19.322
3.	1	1	1	1	3	3	3	7.08	-17.000
4.	1	2	2	2	1	1	1	13.10	-22.345
5.	1	2	2	2	2	2	2	11.90	-21.510
6.	1	2	2	2	3	3	3	9.68	-19.717
7.	1	3	3	3	1	1	1	10.70	-20.587
8.	1	3	3	3	2	2	2	9.23	-19.304
9.	1	3	3	3	3	3	3	7.07	-16.988
10.	2	1	2	3	1	2	3	7.01	-16.914
11.	2	1	2	3	2	3	1	3.40	-10.629
12.	2	1	2	3	3	1	2	2.62	-8.3660
13.	2	2	3	1	1	2	3	6.47	-16.218
14.	2	2	3	1	2	3	1	3.39	-10.604
15.	2	2	3	1	3	1	2	2.40	-7.6042
16.	2	3	1	2	1	2	3	7.77	-17.808
17.	2	3	1	2	2	3	1	3.92	-11.865
18.	2	3	1	2	3	1	2	2.96	-9.4258
19.	3	1	3	2	1	3	2	3.94	-11.909
20.	3	1	3	2	2	1	3	2.78	-8.8809

21.	3	1	3	2	3	2	1	1.35	-2.6067
22.	3	2	1	3	1	3	2	4.74	-13.515
23.	3	2	1	3	2	1	3	3.57	-11.053
24.	3	2	1	3	3	2	1	1.65	-4.3497
25.	3	3	2	1	1	3	2	4.58	-13.217
26.	3	3	2	1	2	1	3	3.31	-10.397
27.	3	3	2	1	3	2	1	1.61	-4.1365

Table 4: Response Table for S/N Ratio for each parameter level

Level	**Flash Thickness**	**Flash Width**	**Corner Radius**	**Fillet Radius**	**Billet Temperature**	**Die Temperature**	**Friction Coefficient**
1	-19.56	-12.766	-13.734	-13.085	-16.865	-13.103	-11.821
2	-12.16	-14.102	-14.137	-14.008	-13.73	-13.575	-13.797
3	-8.896	-13.748	-12.745	-13.523	-10.022	-13.939	-14.998
Delta	10.664	1.336	1.392	0.923	6.843	0.836	3.176

Table 5: Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Flash Thickness	2	220.297	110.149	1111.18	2.4E-14
Flash Width	2	5.899	2.949	29.75	2.23E-05
Corner Radius	2	5.762	2.881	29.06	2.51E-05
Fillet Radius	2	6.099	3.049	30.76	1.89E-05
Billet Temperature	2	53.773	26.887	271.23	1.03E-10
Die Temperature	2	4.101	2.05	20.68	0.000129
Friction Coefficient	2	2.298	1.149	11.59	0.001576
Error	12	1.19	0.099		
Total	26	299.418			

4.2 Experimental Procedure

The DEFORM™-3D V6.1 software package was used for the simulation and analysis of this work. Some assumptions have been made in this work, such as the plastic material model for billet and the rigid material model for die has been assumed. The velocity of the moving ram is kept constant at 1 mm/s. The strain rate at the initial deformation is equal to 1 s^{-1}. All the simulations started with 48000 tetrahedral elements of mesh. Table 3 shows the design of experiment using Taguchi L27 orthogonal array with S/N ratio data. Figure 5 shows the S/N ratio plots for forging die load (F_L). [19]

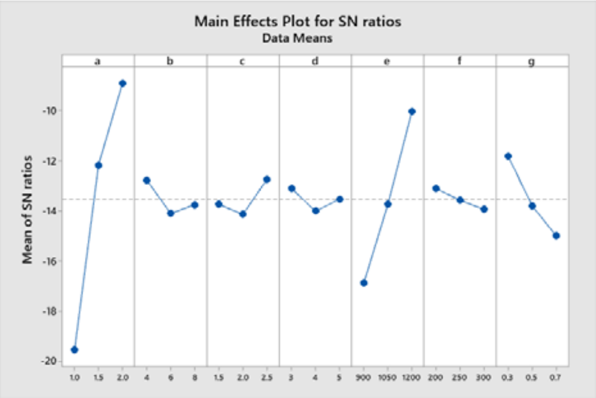

Fig. 5: Main effect plot of S/N ratio for forging load

From Table 4, it is observed that significant factors and their optimum levels are different for different responses. The results obtained from the Taguchi's experimental design can further be improved by using RSM or the response surface methodology (Box and Draper 1987) [20]. Hence, the response surface methodology is employed in this work to make the analysis more precise.

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4.3 Analysis of Variance (*ANOVA*)

An ANOVA was performed to find the relative influence of the control parameters. In Table 5, DF stands for the degrees of freedom, Adj SS stands for the adjusted sum of squares, Adj MS stands for adjusted mean squares, F-value refers to the variance ratio and the P-value refers to the probability value. The F ratio is used to determine whether an effect is insignificant or not. Adj SS alone is not used to determine whether an effect is significant. The degree of freedom (DOF) is also an important measure, i.e. an effect's mean square (MS) also predicts if an effect is significant. The effect is weaker for smaller values of adj MS. Contrasting the results by using Adj SS and Adj MS to select the weak effects, Shiau (1989) [21] established that MS was the better measure to group the insignificant effects. Table 5 shows that the flash thickness and billet temperature are the most important contributing parameters affecting the forging die load under a 95% confidence level.

The analysis clearly shows the relevance of all factors taken into consideration in influencing the response, with Flash Thickness and Billet Temperature being the most influential respectively. The optimum parameter combination for forging die load (F_L) is shown in Table 6.

Table 6: Optimum Setting of Parameter

Factor	**Level**	**Value**
Flash Thickness (F_T)	3	2.0 mm
Flash Width (F_W)	1	4 mm
Fillet Radius (R_F)	3	2.5 mm
Corner Radius (R_C)	1	3 mm
Billet Temperature (T_B)	3	1200 ^{0}C
Die Temperature (T_D)	3	300 ^{0}C
Friction Coefficient (μ)	1	0.3

5. Improve

In the Improve phase of DMAIC, the results obtained from the analysis of the Taguchi's experimental design are further optimized. To optimize the settings of critical parameters, response surface methodology (RSM) has been employed to establish a robust regression model and find the optimum set of parameters.

5.1 Response Surface Methodology

A lot of researchers have used this methodology to tackle several problems in the recent years. Tiwari et. al [22] have used response surface methodology in the improve phase (of DMAIC) to optimize hot radial forging variables. It is a sequential method for a series of regression model fits to the output variables (Shang et al., 2004). [23]

Implementing the response surface methodology starts with a linear regression model:

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots \beta_k x_k \qquad \ldots (2)$$

A low order (linear) polynomial is selected to approximate the true function in some regions of the independent variable (Shang et al., 2004)[23]. Thereafter, a higher-order (quadratic or higher) polynomial is employed to search for the general vicinity of the optimum region. In this work, the second-order model was directly employed to further augment the optimization process. This significantly saved analysis time. A typical fitted second-order model is of the form

$$\hat{y} = \sum_{i=1}^{k} \widehat{\beta_i}\, x_i + \sum_{i=1}^{k} \widehat{\beta_{ii}}\, x_i{}^2 + \sum_{i=1}^{k} \sum_{j}^{k} \widehat{\beta_{ij}}\, x_i x_j \qquad \ldots (3)$$

Where 'k' is the number of factors, 'x_i' represents the process parameter, and 'β_i' is the regression coefficient. In matrix format, the second-order model can be expressed as

$$y = \widehat{\beta_0} + x'b + b'Bx \qquad \ldots (4)$$

Where,

$$b = \begin{pmatrix} \widehat{\beta_1} \\ \widehat{\beta_2} \\ \cdot\cdot \\ \cdot\cdot \\ \widehat{\beta_k} \end{pmatrix} \text{ and } x = \begin{pmatrix} x_1 \\ x_2 \\ \cdot\cdot \\ \cdot\cdot \\ x_k \end{pmatrix} \qquad \ldots (5)$$

While 'B' can be expressed as

$$B = \begin{pmatrix} \hat{\beta}_{11} & \frac{\hat{\beta}_{12}}{2} \ldots\ldots \hat{\beta}_{1k}/2 \\ \vdots & \hat{\beta}_{22} \ldots\ldots \hat{\beta}_{2k}/2 \\ \vdots & \vdots \\ symm \ldots\ldots\ldots\ldots & \hat{\beta}_{kk} \end{pmatrix} \qquad \ldots (6)$$

Least square estimate method is used to construe estimated regression coefficients given as:

$$b = \begin{pmatrix} \widehat{\beta_1} \\ \widehat{\beta_2} \\ \cdot\cdot \\ \cdot\cdot \\ \widehat{\beta_k} \\ \cdot\cdot \\ \cdot\cdot \\ \widehat{\beta_{kk}} \end{pmatrix} = (X'X)^{-}X'y \qquad \ldots (7)$$

Where x is the process parameters and can be represented as

$$X = \begin{pmatrix} 1 & x_{11} & x_{21} \dots & x_{k1} \\ 1 & x_{12} & x_{22} \dots & x_{k2} \\ 1 & \dots \dots \dots & \dots \dots & \dots \\ 1 & x_{1n} & x_{2n} \dots & x_{kn} \end{pmatrix} \quad \dots (8)$$

And y is the response which is expressed as

$$y = \begin{pmatrix} y_1 \\ y_2 \\ \cdot\cdot \\ \cdot\cdot \\ y_k \end{pmatrix} \quad \dots (9)$$

On comparing the partial derivatives of the regression equation to zero, the optimum levels of process parameters can be found.

$$\frac{\partial \hat{y}}{\partial x_1} = \begin{pmatrix} \frac{\partial \hat{y}}{\partial x_1} \\ \frac{\partial \hat{y}}{\partial x_2} \\ \vdots \\ \frac{\partial \hat{y}}{\partial x_k} \end{pmatrix} = \frac{\partial}{\partial x_1}(\widehat{\beta_0} + x'b + x'Bx) = b + 2Bx = 0 \quad \dots (10)$$

The point $x_0 = (x_{10}, x_{20}, \dots, x_{k0})$ is called the stationary point and is expressed as:

$$x_0 = -\frac{1}{2} B^{-1} b \quad \dots (11)$$

In this work, 27 experimental trials were conducted as shown earlier. Based on the analysis of these trials, the significant contribution of the seven process parameters was analyzed using the *F*-value as shown in Table 7. ANOVA analysis also illustrates that the linear effect and square effect of each parameter and two-way interactions (among flash width and billet temperature) should be taken into account. Hence, the second-order model is considered to develop the regression equation between the input variables and the response i.e. die load. Table 8 depicts the X matrix. The coding is as x_1 for factor A, x_2 for B, x_3 for C, x_4 for D, x_5 for E, x_6 for F and x_7 for factor G.

Table 7: ANOVA for Regression Model Fit

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	19	299.081	99.89%	299.081	15.7411	327.68	1.63E-08
x_1	1	197.806	66.06%	36.818	36.8182	766.44	2.06E-08
x_2	1	1.14	0.38%	3.539	3.5387	73.66	5.8E-05
x_3	1	0.436	0.15%	2.596	2.596	54.04	0.000156
x_4	1	0.408	0.14%	4.099	4.0986	85.32	3.6E-05
x_5	1	53.665	17.92%	0.059	0.0591	1.23	0.30394
x_6	1	0.445	0.15%	1.958	1.9578	40.76	0.000373
x_7:1	2	2.298	0.77%	2.298	1.1488	23.91	0.000744
x_1*x_1	1	22.491	7.51%	22.491	22.4912	468.19	1.14E-07
x_2*x_2	1	4.759	1.59%	4.759	4.7585	99.06	2.21E-05
x_3*x_3	1	5.327	1.78%	5.327	5.3267	110.88	1.52E-05
x_4*x_4	1	5.691	1.90%	5.691	5.6908	118.46	1.22E-05
x_5*x_5	1	0.108	0.04%	0.108	0.1085	2.26	0.176659
x_6*x_6	1	3.656	1.22%	3.656	3.6556	76.1	5.22E-05
x_2*x_5	1	0.449	0.15%	0.481	0.4805	10	0.015869
x_2*x_6	1	0.126	0.04%	0.01	0.0098	0.2	0.66517
x_3*x_5	1	0.012	0.00%	0.016	0.0157	0.33	0.58565
x_3*x_6	1	0.013	0.00%	0.076	0.0761	1.58	0.248654
x_4*x_5	1	0.253	0.08%	0.253	0.2533	5.27	0.055277
Error	7	0.336	0.11%	0.336	0.048		
Total	26	299.418	100.00%				

By implementing the least square method, the regression coefficients can be found and the regression equation is built up as:

$$\text{Die Load} = -16.19 - 29.86\,x_1 + 3.585\,x_2 + 14.12\,x_3 + 9.70\,x_4 - 0.01094\,x_5 + 0.1398\,x_6 + 7.744\,x_1^2 - 0.2226\,x_2^2 - 3.769\,x_3^2 - 0.9739\,x_4^2 + 0.000006\,x_5^2 - 0.000312\,x_6^2 - 0.000861\,x_2{*}x_5 \quad \dots (12)$$

Since the interaction factor $X_2 \times X_6$ ($B\times F$) or $X_3 \times X_5$ ($C\times E$), $X_3 \times X_6$ ($C\times F$), and $X_4 \times X_5$ ($D\times E$) are not significant as compared with $X_2 \times X_5$ or ($B\times E$), this interaction has not been included in the regression equation, to simplify the analysis. The ANOVA result for G_2 and G_3, i.e. for the friction co-efficient values of 0.5 and 0.7, reveals that both are insignificant in building the regression equation. Hence the value of friction coefficient (μ) is taken at 0.3, i.e. both the dies to be lubricated. Thus for $\mu = 0.3$, the above regression equation (12) has been built and is further analyzed. The surface plot of Die Load vs. Flash Thickness and Die Temperature and its contour plot generated in Minitab 15 are shown below in figure 6 and figure 7.

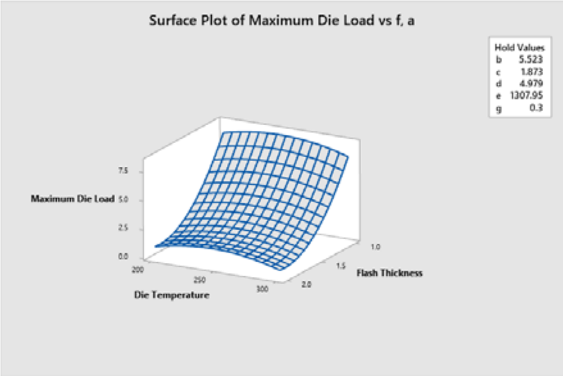

Figure 6: Surface Plot of Maximum Die Load vs. Flash Thickness and Die Temperature

Table 8: X matrix used to obtain coefficients of the regression equation

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_1^2	x_2^2	x_3^2	x_4^2	x_5^2	x_6^2	x_7^2	x_1*x_5
1	1	4	1.5	3	900	200	0.3	1	16	2.25	9	810000	40000	0.09	900
1	1	4	1.5	3	1050	250	0.5	1	16	2.25	9	1102500	62500	0.25	1050
1	1	4	1.5	3	1200	300	0.7	1	16	2.25	9	1440000	90000	0.49	1200
1	1	6	2	4	900	200	0.3	1	36	4	16	810000	40000	0.09	900
1	1	6	2	4	1050	250	0.5	1	36	4	16	1102500	62500	0.25	1050
1	1	6	2	4	1200	300	0.7	1	36	4	16	1440000	90000	0.49	1200
1	1	8	2.5	5	900	200	0.3	1	64	6.25	25	810000	40000	0.09	900
1	1	8	2.5	5	1050	250	0.5	1	64	6.25	25	1102500	62500	0.25	1050
1	1	8	2.5	5	1200	300	0.7	1	64	6.25	25	1440000	90000	0.49	1200
1	1.5	4	2	5	900	250	0.7	2.25	16	4	25	810000	62500	0.49	1350
1	1.5	4	2	5	1050	300	0.3	2.25	16	4	25	1102500	90000	0.09	1575
1	1.5	4	2	5	1200	200	0.5	2.25	16	4	25	1440000	40000	0.25	1800
1	1.5	6	2.5	3	900	250	0.7	2.25	36	6.25	9	810000	62500	0.49	1350
1	1.5	6	2.5	3	1050	300	0.3	2.25	36	6.25	9	1102500	90000	0.09	1575
1	1.5	6	2.5	3	1200	200	0.5	2.25	36	6.25	9	1440000	40000	0.25	1800
1	1.5	8	1.5	4	900	250	0.7	2.25	64	2.25	16	810000	62500	0.49	1350
1	1.5	8	1.5	4	1050	300	0.3	2.25	64	2.25	16	1102500	90000	0.09	1575
1	1.5	8	1.5	4	1200	200	0.5	2.25	64	2.25	16	1440000	40000	0.25	1800
1	2	4	2.5	4	900	300	0.5	4	16	6.25	16	810000	90000	0.25	1800
1	2	4	2.5	4	1050	200	0.7	4	16	6.25	16	1102500	40000	0.49	2100
1	2	4	2.5	4	1200	250	0.3	4	16	6.25	16	1440000	62500	0.09	2400
1	2	6	1.5	5	900	300	0.5	4	36	2.25	25	810000	90000	0.25	1800
1	2	6	1.5	5	1050	200	0.7	4	36	2.25	25	1102500	40000	0.49	2100
1	2	6	1.5	5	1200	250	0.3	4	36	2.25	25	1440000	62500	0.09	2400
1	2	8	2	3	900	300	0.5	4	64	4	9	810000	90000	0.25	1800
1	2	8	2	3	1050	200	0.7	4	64	4	9	1102500	40000	0.49	2100
1	2	8	2	3	1200	250	0.3	4	64	4	9	1440000	62500	0.09	2400

Figure 7: Surface Plot of Maximum Die Load vs. Flash Thickness and Die Temperature

6. Control

Control, which is the final phase of the DMAIC approach, is a crucial stage of Six Sigma implementation. The entire work done is updated and preserved. Recording the data in the optimization process is crucial, as the lack of continuous improvement impedes six sigma efforts. With appropriate documentation, the process is constantly monitored and the documentation is maintained and updated at regular periods. Statistical quality control tools like control charts assist the monitoring of the process and alert personnel if the process has gone out of control at a point of time. [22]

Table 9: Improved Operating Parameters after analyzing Taguchi's Experimental Design

Factor	Level	Value
Flash Thickness (F_T)	3	2.0 mm
Flash Width (F_W)	1	4 mm
Fillet Radius (R_F)	3	2.5 mm
Corner Radius (R_C)	1	3 mm
Billet Temperature (T_B)	3	1200 ^{0}C
Die Temperature (T_D)	3	300 ^{0}C
Friction Coefficient (μ)	1	0.3

Table 10: Revised Operating Parameters after employing RSM

Factor	Value
Flash Thickness (F_T)	1.928 mm
Flash Width (F_W)	5.523 mm
Fillet Radius (R_F)	1.873 mm
Corner Radius (R_C)	4.979 mm
Billet Temperature (T_B)	1307.95 ^{0}C
Die Temperature (T_D)	224.04 ^{0}C
Friction Coefficient (μ)	0.3

7. Analysis of Results

Table 7 shows the results obtained from the taguchi design and provides an insight into the process parameters affecting the forging process. The ANOVA reveals that the flash thickness is one of the most crucial and influential parameter; the billet temperature is the second most significant parameter; the interaction effect between flash thickness and billet temperature is also quite significant and must be considered in the die design stage of production. Response surface methodology was employed to optimize the set of parameters to attain a minimum die load. Table 10 gives the optimum conditions found by RSM for the hot forging of the connecting rod. The optimum parameter values were then applied to the process and confirmation experiments were done to check the results.

7.1 Confirmation Experiments

A confirmation test was conducted through computer based simulation with the obtained optimal combination of parameters at appropriate levels. Thus the quality characteristic – die load, for hot forging of connecting rod was assessed. The conformation simulation was done at levels predicted by the Taguchi method and RSM. The optimum levels for forging die load based on Taguchi's experiment are F_t3, F_w1, R_c3, R_f1, T_b3, T_d3, and μ1. The response values obtained from the confirmation experiment is a die load of 1.29 MN as shown in figure 8. The response values obtained from the confirmation experiment is a die load of 0.68 MN as shown in figure 9. The forging die load shows a reduced value from 1.29 MN to 0.68 MN respectively. The corresponding improvement was 47.3%.

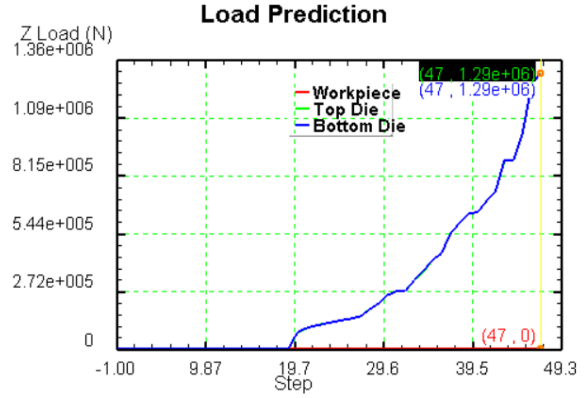

Figure 8: Graph Showing Die Load vs. Step for the combination of parameters optimized by Taguchi's Design

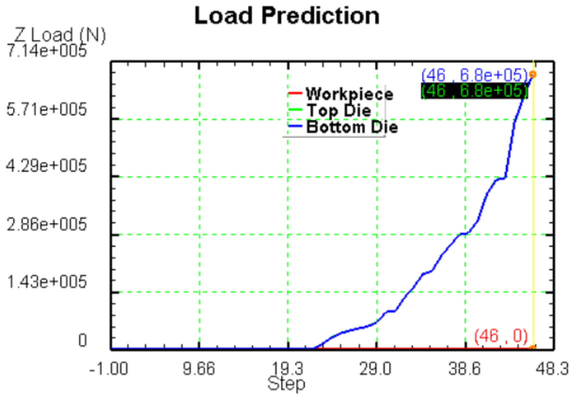

Figure 9: Graph Showing Die Load vs. Step for the combination of parameters optimized by RSM

Proper die filling has been observed with the obtained optimum settings of the parameters. The presence of cracks or deformities was not observed in the confirmation simulation.

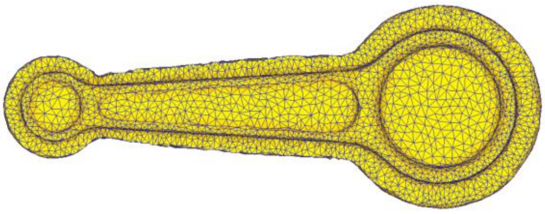

Figure 10: Top view of connecting rod with mesh elements showing a lack of rough edges demonstrating proper die filling of the work-piece in the confirmation experiment

8. CONCLUSION

In this work, the conventional hot closed die forging of connecting rod involving flash formation has been studied using the Six Sigma based DMAIC approach. FEM based simulation software package, DEFORM ™ 3D V6.1 was used to simulate the hot forging process and study the effect of design and process parameters on the forging die load. Taguchi method as well as Response Surface Methodology (RSM) was employed to optimize the parameters for a minimum forging die load (F_L). The confirmation test value for the forging die load is 1.29 MN. After performing ANOVA on the experimental results, four parameters namely flash thickness, billet temperature, friction coefficient, and corner radii were found to be the most significant parameters affecting the forging die load under a 95% confidence level. The conformation test value for forging die load, 1.29 MN obtained from Taguchi's method is further improved from results obtained by response surface method. RSM has been employed successfully to obtain the minimized die load of 0.68 MN for the optimum setting of parameters. Future scope of work may involve extensive experimentation which may help to analyze the parameters in the real time working environment. Other techniques for analysis and parameter optimization maybe adopted. More parameters maybe included in future works. Same parameters with different and/or more levels maybe incorporated. Apart from the die load, other response parameters maybe included in studies involving die life.

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