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A grey-based Taguchi method to optimize hot forging process

Md. Israr Equbal[a]* , Randhir kumar[b],Mohammad Shamim[c], R.K. Ohdar[d]

[a]*Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi -834003, India*
[b]*Department of Production Engineering, B.I.T. Mesra, Deoghar Campus-814142, India*
[c]*Department of Manufacturing Engineering, National Institute of Foundry and Forge Technology, Ranchi-834003, India*
[d]*Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi-834003, India*

Abstract

In this study, Three dimensional finite element analysis has been carried out using FEM based DEFORM^{TM} 3D software on hot forging of spring saddle. The influence of design parameter viz. flash thickness and process parameters viz. billet temperature, die temperature and friction coefficient along with their interactions are investigated for the responses forging load and billet temperature loss during hot forging operation using Taguchi's L27 orthogonal array. Analysis of variance (ANOVA) is employed to determine significant parameters. It has been observed that optimal factor settings for each performance characteristic are different. Flash thickness and Billet temperature and interaction of flash with billet temperature are observed as the most significant parameters affecting the responses. In order to minimize two responses simultaneously, Grey Taguchi method is adopted and optimum factor levels have been reported. Optimization of the process parameters simultaneously leading to a low billet temperature loss along with a low forging load and it is also verified through a confirmation experiment for validation of these results. Confirmatory results prove the potential of Taguchi design of experiments, ANOVA analysis and Grey Taguchi method in Multi-objective optimization of process parameters.

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Keywords: Hot Forging; Finite Element Analysis; Taguchi Method; Grey Taguchi Method

1. Introduction

Forging is oldest metal processing technology known for producing parts of superior mechanical properties with minimum waste. In it metals or their alloys are plastically deformed to the desired shape by a compressive force

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* Corresponding author. Tel.: + 91 9771838144 ; fax: +916512290860.
E-mail address: israr_equbal@yahoo.co.in

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applied with the help of a pair of dies, which are the main tools for getting the desired shape and geometry of the work piece. Forging process generally includes sequential deformation steps, which gradually bring the workpiece to the desired final shape. Forging is a cost-effective way to produce net-shape or near-net-shape components. Forged parts are used in high performance, high strength and high reliability applications where tension, stress, load and the human safety are critical considerations. They are also employed in a wide range of demanding environments, including highly corrosive and extreme temperatures and pressures. Various parameters such as complexity of the part, friction between dies and work piece, type of press, die and work piece temperature, material of work piece govern the forging process. Forging process is said to be successful if die cavity is completely filled and stress in the work piece is less than ultimate stress corresponding to the work piece material, with minimum force.

Large amount of research in the area of forging process and parameters optimization have been done by researchers. Few of them Santos et al. (2001) optimize the die design by taking into consideration shape and size of the initial billet and predict the forces needed as well as the defect occurrences. Saniee and Hosseini (2006) studied the effects of flash allowance and bar size on the die filling and required load. The tests were carried out with Plasticine as the model material. They found that the die filling for the component with horizontal axis of symmetry was more sensitive to the sizes of the billet and greater the flash allowance, the larger was the forming load and energy.Gangopadhyay et al. (2011)uses three-dimensional finite element analysis DEFORM 3D software on multistage hot forming of railway wheels involving the processes of upsetting, forging, and punching of wheels. This study shows that design, optimization, and analysis of process perturbations for multi-stage railway wheel manufacturing process can be done efficiently in three-dimensional finite element simulations instead of conventional time and cost intensive trials. Satish et al. (2007)uses FEM-based computer simulation to optimize the design parameters and input billet cross-section for front axle beam. By carrying out multiple number of forging experiments during simulation trials, input billet size has been optimized. Srivastava et al. (2004)studied the effect of billet temperature, die velocity and coefficient of friction on forging load and strain rate by using FEM based FORGE2^R. These works reveal the performance of the die and hence product quality is heavily dependent on various parameters which can be broadly divided into two groups that are design parameter and process parameter. Design parameters such as flash thickness, flash width, corner radius, fillet radius etc represent the geometrical aspect of the die and are important for die modeling stage. Whereas process parameters like billet temperature, die temperature, friction coefficient, die velocity, strain rate etc are related to the forging process condition. During the die design and process planning stage it is necessary to estimate proper values of these parameters to avoid unexpected die failure and inadequate die filling. Most of the researchers consider these design and process variables separately and did not study their combine influence on process performance. To fill this gap present work concentrate on the study of effect of above mention design and process parameters along with their interaction on the forging load (F_L) and Billet temperature loss (dT). Spring saddle of an automobile is taken as an example product and Taguchi experimental method is utilized to design the parameter combinations so as to identify the relative influence of each parameter on the studied responses. As the real-time forging is time consuming and costly therefore FEM based DEFORM^{TM} 3D software is used for simulating forging process. For simulation purpose 3D (three-dimensional) solid model of spring saddle and its bottom and top die (Fig. 1) are modelled in CATIA V5 software. The material of spring saddle is AISI 1035 alloy steel, whereas Tool Steel DIN 1.2714 die steel is used as die material and their properties are given in Table 1.

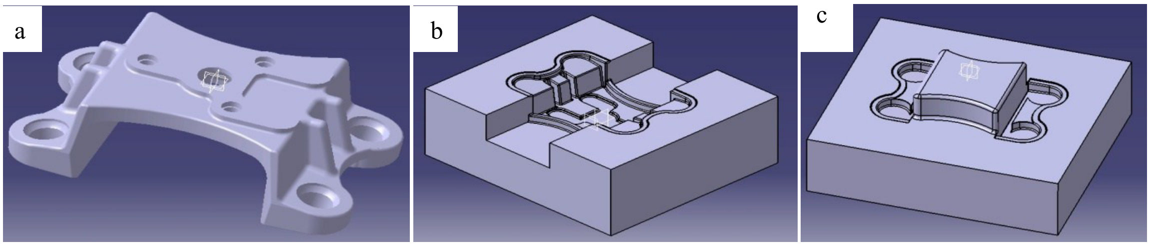

Fig. 1. 3D CAD model of (a) connecting rod; (b) Bottom Die; (c) Top Die

Table 1. Material Properties

Property	Component	Die	Units
Density	7.7-8.03	7.86	(x1000 kg/m^3)
Poisson'sRatio	0.27-0.3	0.27-0.3	
Elastic modulus	190-210	190-210	GPa
Tensile strength	485	655	MPa
Yield strength	415	380	MPa
Hardness	143	93	HB

Optimization of multiple performance characteristics is much more complicated than single performance characteristics. Conventional Taguchi method can effectively establish optimal parameter settings for single performance characteristic. When multiple performance characteristics with conflicting goals are considered, the approach becomes unsuitable. Recently, some researchers have used genetic algorithm, data envelopment analysis, desirability function approach etc. for multi response optimization in various fields of engineering. Grey based Taguchi method is a new method forwarded by Deng Ju-long from China to solve multi response optimization problems. Deng first proposed grey relational analysis in 1982 to fulfill the crucial mathematical criteria for dealing with poor, incomplete and uncertain systems. In recent years grey relational analysis becomes a powerful tool to analyze the processes with multiple performance characteristics. A.K. Sood et al. (2010) studied the effect of process parameters on multiple performance characteristics of FDM build part by using Taguchi method with gray relational analysis. K. Jangra et al. (2011)optimizes the material removal rate (MRR) and surface roughness simultaneously for WEDM of WC-Co composite by the use of Grey relational analysis. Tarang et al. (2002) utilized the grey-based Taguchi method to optimize the process parameters of submerged arc welding in hardfacing, considering multiple weld qualities. Huang et al. (2003)successfully optimized the machining parameters in wire EDM using the grey relational analysis along with Taguchi method. Based on the above survey we can conclude that the grey relational analysis is a better approach for optimization of multi response characteristics in different fields. Therefore, grey relational analysis is utilized in this study, for multiple- optimization of the hot forging of spring saddle.

2. Experimental work

For the present experimental work the four process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behaviour of output parameters of study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 2. Flash is an important parameter for amount of waste material, die filling, forging load, cost, and so on and its influence seems to be more than any other parameter. Hence, interaction of other parameters with flash is also considered. The impact of four parameters each at three level and two interactions are studied using L27 (3^9) orthogonal array design.

Table 2. Factors and their levels

Factors	Symbol	Level			Unit
		1	2	3	
Flash thickness	A	2	3	4	mm
Billet Temperature	B	900	1050	1200	^{0}C
Friction Co-efficient	C	0.3	0.4	0.5	--
Die temperature	D	200	250	300	^{0}C

Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. The most important stage in this method lies in the selection of control factors. An exhaustive literature review reveals that the die life and quality of the forged part are largely influenced by flash thickness, billet temperature, die temperature and friction coefficient. These parameters each at three levels and their interactions are considered for the present study. The FEM simulations were conducted to study the effect of process parameters over the output response characteristics namely forging load and billet temperature loss.

As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degrees of freedom (DOF). This gives a total of 8 DOF for four process parameters selected in this work. For three process parameters, flash thickness, billet temperature and friction coefficient, taking two parameters at a time we have three possible interactions (AxB, AxC and BxC) out of which two interactions AxB and AxC have been included in the present study. As a two factor interaction consists of two process parameters and the degree of freedom of interaction will be equal to the product of DOF of the interacting factors. Thus each interaction e.g. AxB will have (3-1) x (3-1) = 4 DOF. This gives total DOF of 8 for two interactions AxB and AxC. Thus we have a total of 16 DOF for the factors as well as the interactions considered for the present experiments. The nearest three level orthogonal array available satisfying the criterion of selecting the OA is L27 having 26 DOF as explained in Ross (1988). For each trial in the L27 array, the levels of the process parameters are indicated in Table 3.

Table 3. Taguchi's L27 standard orthogonal array

Exp. No.	Flash thickness	Billet temperature	Friction coefficient	Die temperature	S/N Ratio Forging load(x10^6)	S/N Ratio Billet Temperature Difference (^{0}C)
1	2	900	0.3	200	-14.9327	-39.9127
2	2	900	0.4	250	-15.6638	-40.3407
3	2	900	0.5	300	-15.0870	-33.6248
4	2	1050	0.3	250	-13.3863	-43.3463
5	2	1050	0.4	300	-14.3534	-42.6067
6	2	1050	0.5	200	-15.1175	-43.7504
7	2	1200	0.3	300	-13.3863	-47.3471
8	2	1200	0.4	200	-14.1854	-47.8890
9	2	1200	0.5	250	-14.2866	-46.7691
10	3	900	0.3	200	-15.1327	-39.9127
11	3	900	0.4	250	-14.5995	-39.3697
12	3	900	0.5	300	-15.2686	-38.3816
13	3	1050	0.3	250	-9.9937	-41.1381
14	3	1050	0.4	300	-10.1571	-40.6685
15	3	1050	0.5	200	-10.9061	-40.7485
16	3	1200	0.3	300	-12.0629	-46.2351
17	3	1200	0.4	200	-12.5473	-45.1536
18	3	1200	0.5	250	-12.7698	-46.0206
19	4	900	0.3	200	-13.8745	-37.7298
20	4	900	0.4	250	-14.5182	-37.6163
21	4	900	0.5	300	-14.0830	-35.2686
22	4	1050	0.3	250	-13.6609	-44.5062
23	4	1050	0.4	300	-13.2740	-42.0761
24	4	1050	0.5	200	-14.3033	-43.1672
25	4	1200	0.3	300	-11.3170	-45.3434
26	4	1200	0.4	200	-11.9099	-44.8110
27	4	1200	0.5	250	-10.3439	-44.5062

In Taguchi method the least variation and the optimal parameters are obtained by mean of the S/N ratio. The higher the S/N ratio, the more stable the achievable quality. Depending on the required objective characteristics, there are three types of S/N ratio: the lower-the better, the higher-the-better and the nominal-the-best. To reduce overloading that can cause unexpected die failure and inadequate die filling forging load need to be minimized. During hot forging heat transfer from the billet to the die reduces the hardness of the die surface, which leads to the plastic deformation of the die and ultimately reduces the die life; hence the billet temperature loss needs to be minimized. For this S/N ratio with a lower -the-better characteristic given by Equation 1 is used for forging load (F_L) and billet temperature loss (dT).

$$S/N = \log_{10}(1/n)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}}(1)$$

Where n= number of replications and y_{ij}= observed response value

Where i = 1,2..........n; j = 1,2...k.

The actual FEM-based analysis is carried out using DEFORM^{TM} 3D v 6.1. Table 4 shows operations parameters assigned to complete the simulation.

Table 4.Operation parameters assigned to complete the simulation

Problem Type	Closed die hot forging
Forging Equipment	Mechanical press
Press capacity	2500 Ton
No. of elements	45000
Mesh type	Tetrahedral
Die displacement	0.5 mm
Simulation mode	Isothermal
Simulation step	100
Step increment	2
Primary die	Top die
Environment Temperature	20^0C

3. Determination of optimal process parameters using Grey taguchi method

This method provides approaches for analysis and abstract modelling of systems for which the information is limited, incomplete and characterized by random uncertainty. It combines the entire considered performance characteristic (objectives) into a single value that can be used as the single characteristic in optimization problems. To apply this method, input attributes (performance characteristic or objective function) need to be normalized. This process is called grey relational generation (GRG).

3.1. Grey relational analysis

Grey data processing must be performed before calculating the grey correlation coefficients. In this study, a linear normalization of the experimental results (S/N ratios) for effective strain rate and forging load were performed in the range of 0 and 1, which is also called the grey relational generating. y_{ij} is normalized as Z_{ij} ($0 \leq Zij \leq 1$) by the following formula to avoid the effect of adopting different units and to reduce the variability. A linear data pre-processing method for the S/N ratio can be expressed as follows,

$$Z_{ij} = \frac{y_{ij} - min(y_{ij,} i = 1,2, \ldots\ldots n)}{max(y_{ij,} i = 1,2, \ldots\ldots n) - min(y_{ij,} i = 1,2, \ldots\ldots n)} \qquad (2)$$

The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized experimental results. The grey relational coefficient can be expressed as,

$$\gamma\,(\,(k), yi\,(k)\,) = \frac{\Delta\, min + \xi\Delta max}{\Delta oj(k) + \xi\Delta max} \qquad (3)$$

Where; $Z_{ij}$is the sequence after the data processing, j = 1,2...n; k = 1,2...m, n is the number of experimental data items and m is the number of responses. $y_o(k)$ is the reference sequence ($y_o(k) = 1$, k = 1,2...m); $y_j(k)$ is the specific comparison sequence.

$\Delta_{oj} = \left\|y_o(k) - y_j(k)\right\|$ = The absolute value of the difference between $y_o(k) and y_j$(k).

$\Delta\, min = \underset{\forall j\varepsilon}{min}\,\underset{\forall k}{min} \|\, y_{o\,(k)} - y_j\,(k)\|$ is the smallest value of $y_j(k)$

$\Delta max = \underset{\forall j\varepsilon\forall k}{max\ max} \|\, y_{o\,(k)} - y_j\,(k)\|$ is the largest value of $y_j(k)$

Where ξ is the distinguishing coefficient, which is defined in the range $0 \leq \xi \leq 1$. The forging parameters are equally weighted in this study, and therefore ζ is 0.5 as explained in Deng (1989). The grey relational grade is determined by averaging the grey relational coefficient corresponding to each performance characteristic. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade. The grey relational grade can be expressed as,

$$\overline{\gamma_j} = \frac{1}{K}\sum_{i=1}^{m}\gamma_{ij} \quad (4)$$

Where $\overline{\gamma_j}$ is the grey relational grade for the jth experiment and k is the number of performance characteristics. This approach converts a multiple response process optimization problem into a single response optimization situation with the objective function of an overall grey relational grade. Table 5 shows the grey relation coefficient and grey relational grade for each experiment using the L27 orthogonal array. The higher grey relational grade reveals that the corresponding experimental result is closer to the ideally normalized value. The higher the value of the grey relational grade, the closer the corresponding factor combination is, to the optimal. A higher grey relational grade implies better product quality; therefore, on the basis of the grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined.

4. Analysis of results

Simulations are run as per Taguchi experiment plan and respective values of forging load and billet temperature loss for each simulation run is converted into their respective S/N ratios as per equation 1 and are given in Table 3. Data analysis is made using MINITAB R14 software at 95% of confidence. Main effect plots and interaction plots are used to determine the optimum factor levels for each response and results are shown in Fig. 2 and Fig. 3. Relative influence of each factor is determined by analysis of variance method (ANOVA) and results are presented in Table 6. ANOVA results show that flash thickness, billet temperature and interaction between flash thickness and billet temperature are significant for F_L whereas billet temperature and interaction between flash thickness and billet temperature are significant for dT. 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.

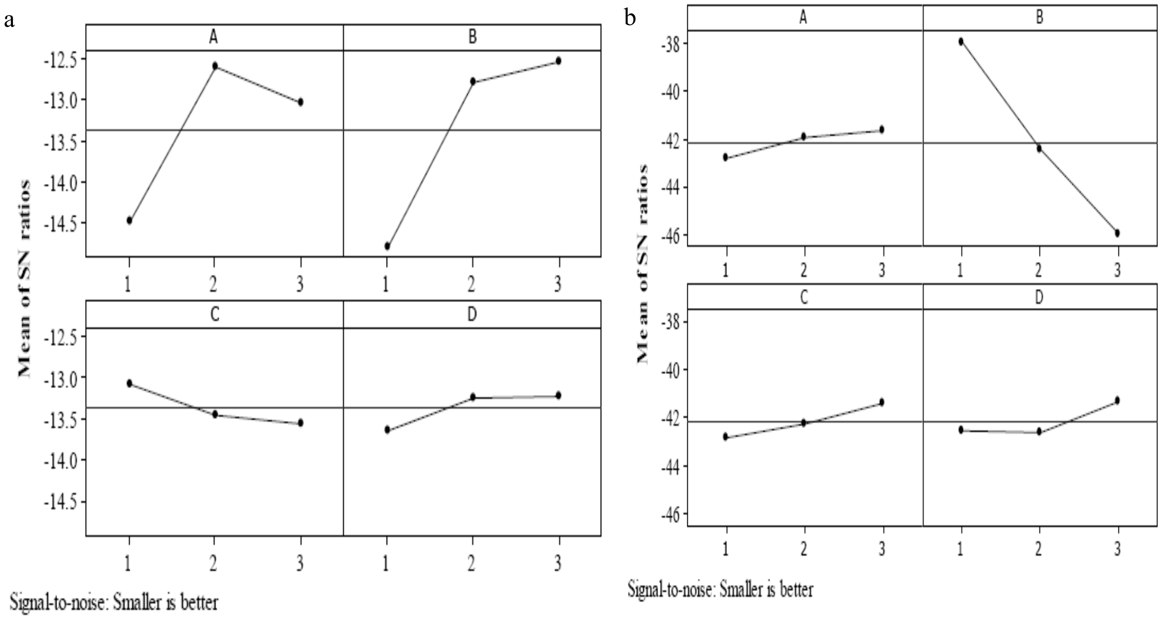

Fig. 2. Main effect plot of S/N ratio (a) Response is forging load; (b) Response is billet temperature loss

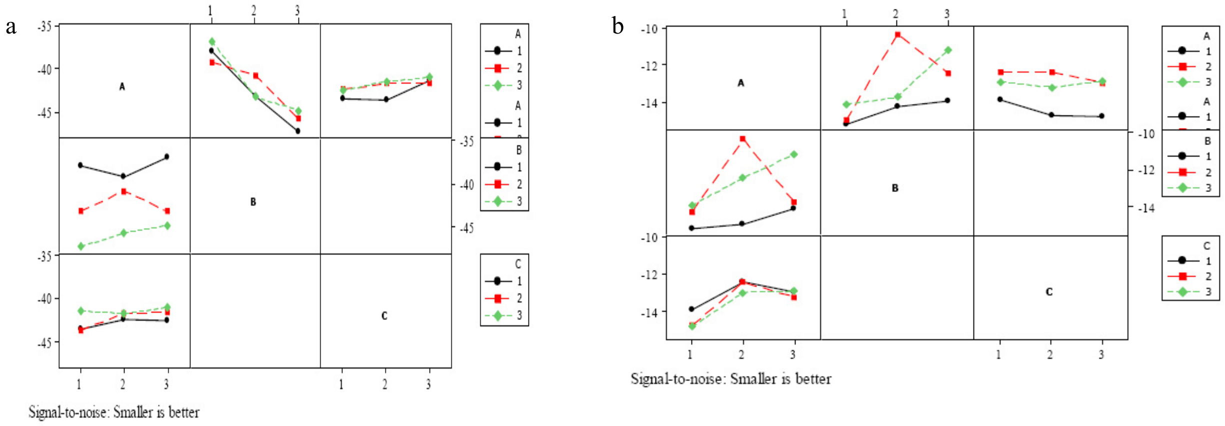

Fig. 3. Interactions plot of S/N ratio (a) Response is forging load; (b) Response is billet temperature loss

Table 5. Optimum factor level for each response

		Forging load		Billet temp. loss	
Factors	Symbol	Level	Value	Level	Value
Flash thickness	A	2	3 mm	3	1 mm
Billet temperature	B	3	1200^0 C	1	1050^0 C
Friction coefficient	C	1	0.3	3	0.7
Die temperature	D	3	400^0 C	3	200^0 C

Table 6. ANOVATable

		Forging load				Billet temp. loss			
Factor	DOF	SS	V	F	P	SS	V	F	p
A	2	17.5727	8.78635	48.50	0.000	6.729	3.3645	2.39	0.142
B	2	27.5525	13.77625	76.05	0.000	288.469	144.2345	102.29	0.000
C	2	1.2009	0.60045	3.31	0.079	9.939	4.9695	3.52	0.069
D	2	1.0747	0.53735	2.97	0.097	10.317	5.1585	3.66	0.064
A*B	4	23.0834	11.5417	31.86	0.000	22.178	11.089	3.93	0.036
A*C	4	1.1932	0.5966	1.65	0.238	4.388	2.194	0.78	0.564
Error	10	1.8115	0.90575			14.101	7.0505		
Total	26	73.4888				356.121			
		R^2=97.53% R^2(adjusted)=93.59%				R^2= 96.04% R^2(adjusted)= 89.71%			
DOF=degree of freedom, SS=sum of square, V=variance, F=F-value, p=p-value									

5. Multi response optimization

As indicated in Table 5, factor levels for both the responses are different and different factors are significant for both the responses (Table 6). In real industrial requirement, forging operation has to be performed at the same level of design and process variables. For this purpose, it is necessary to find out the level of various factors that will simultaneously minimize the forging load and billet temperature loss during forging. To achieve this goal, both the responses are converted into single response that is grey relational grade. S/N ratio of both the responses is taken as input for grey relational generation. As S/N ratio is always maximized irrespective of the quality characteristic of response Eq. (2) is used for this purpose. Grey relational coefficient is calculated by using Eq. (3) and distinguishing coefficient value is taken as 0.5. Finally, grey relational coefficients are combined to form grey relational grade by considering equal weight for both the responses. The entire results of grey relational grade calculations are summarized in Table 7.

Table 7. Results of Grey Taguchi calculation

Grey relational generation			Grey relation coefficient		Grey relation grade
Exp. No.	Forging load	Billet Temp. Loss	Forging load	Billet Temp. Loss	
1	0.128939	0.559185	0.822313	0.90923	0.865772
2	0	0.529182	0.801239	0.903648	0.852443
3	0.101729	1	0.817774	1	0.908887
4	0.401662	0.318467	0.870755	0.866291	0.868523
5	0.231103	0.370323	0.839815	0.875194	0.857505
6	0.096345	0.29014	0.816881	0.861503	0.839192
7	0.401662	0.037991	0.870755	0.821108	0.845932
8	0.260735	0	0.845031	0.815348	0.83019
9	0.242887	0.078511	0.841882	0.827342	0.834612
10	0.093659	0.559185	0.816437	0.90923	0.862834
11	0.187704	0.597255	0.83229	0.916414	0.874352
12	0.069702	0.666526	0.812495	0.929781	0.871138
13	1	0.473278	1	0.893426	0.946713
14	0.971186	0.506201	0.992903	0.899417	0.94616
15	0.839084	0.500589	0.961614	0.89839	0.930002
16	0.635073	0.115951	0.916988	0.833187	0.875088
17	0.549637	0.191771	0.899507	0.84528	0.872393
18	0.510401	0.130988	0.8917	0.922875	0.907287
19	0.31556	0.712217	0.854856	0.938814	0.896835
20	0.202034	0.720177	0.83476	0.940405	0.887582
21	0.278793	0.884765	0.848242	0.974566	0.911404
22	0.353231	0.237156	0.86174	0.852688	0.857214
23	0.421471	0.407521	0.874497	0.881695	0.878096
24	0.239933	0.331023	0.841363	0.86843	0.854896
25	0.76663	0.178461	0.945276	0.843132	0.894204
26	0.662051	0.215788	0.92265	0.849184	0.885917
27	0.938241	0.237156	0.984911	0.852688	0.9188

Optimum parameter levels for maximizing grey relational grade is obtained from main effect plot (Fig. 4). The levels for flash thickness, billet temperature, friction coefficient and die temperatureare 2, 2, 3 and 3 respectively whereas the significant factors determined using ANOVA (Table 8) are flash thickness and interaction between flash thickness and billet temperature.

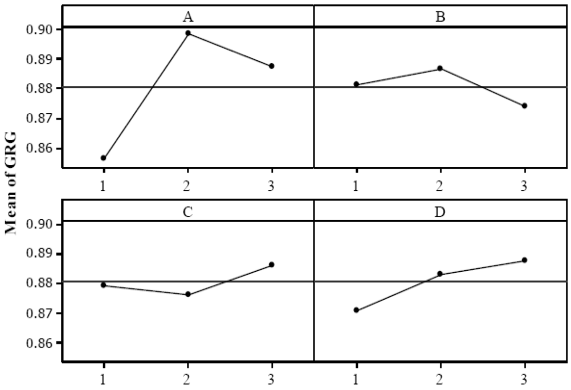

Fig.4. Main effect plot for grey relational grade (GRG) (Larger is better)

Table8. ANOVA for GRG

Factor	DOF	SS	V	F	p
A	2	0.0087515	0.00438	18.09	0.000
B	2	0.0007277	0.00036	1.50	0.268
C	2	0.0004881	0.00024	1.01	0.399
D	2	0.0013436	0.00067	2.78	0.110
A*B	4	0.0125803	0.00629	13.01	0.001
A*C	4	0.0002664	0.00013	0.28	0.887
Error	10	0.0024183	0.00121		
Total	26	0.0265759			
	R^2= 90.90% R^2(adjusted)= 76.34%				
DOF=degree of freedom, SS=sum of square, V=variance, F=F-value, p=p-value					

6. Confirmation experiment

The optimum parameter level for forging load and billet temperature loss on the basis of main effect plots illustrated in Fig. 2 are A_2, B_3, C_1, D_3 and A_3, B_1, C_3 andD_3 respectively. The confirmation test at the optimal parameter setting was conducted to evaluate the quality characteristics for Hot forging of spring saddle. For confirmation purpose dies are designed at the optimal parameter setting respectively for forging load and billet temperature loss as given in Table 7. The process is simulated in DEFORM^{TM} 3D software keeping all the operation parameter of simulation fixed as given in Table 4.

The response values obtained from the confirmation experiment are Forging load = 3.02x10^6 N and billet temp. loss = 148^{0}C as shown in Figure 5(a) and (b). The optimal level on the basis of Grey taguchi method is A_2, B_2, C_3 and D_3, as shown in Fig. 4 and the response values obtained from the confirmation experiment are Forging Load = 3.22x10^6 N and billet temperature loss= 159^{0}Cas shown in Figure 6 (a) and (b).

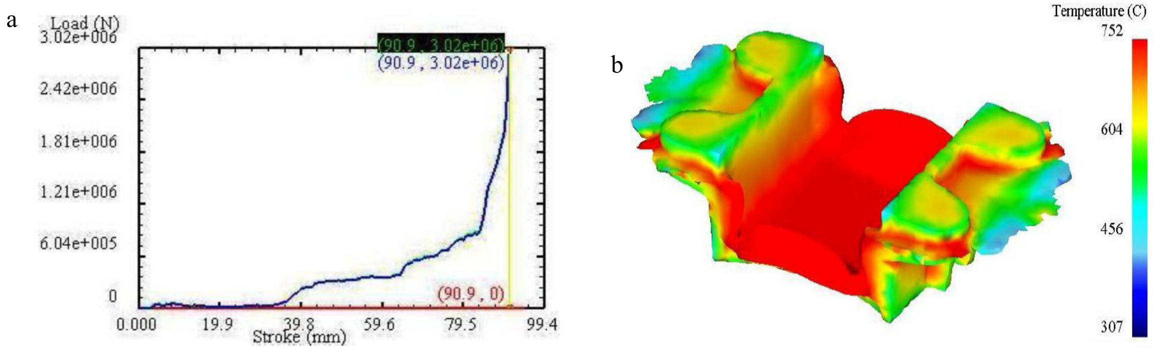

Fig.5. (a) Load-Stroke curve; (b) Temperature distribution for Taguchi Design

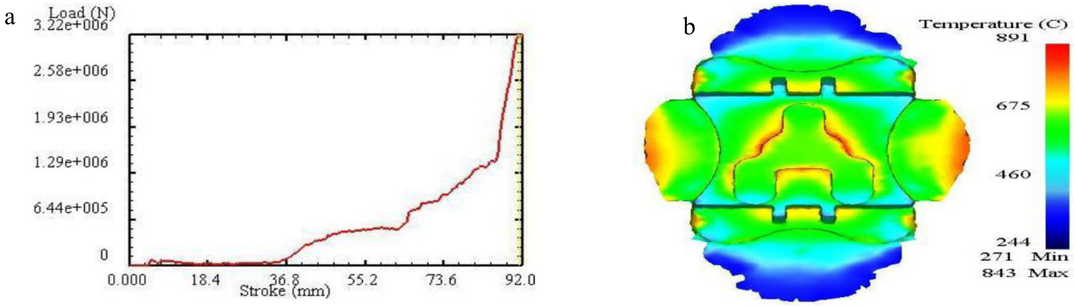

Fig.6. (a) Load-Stroke curve; (b) Temperature distribution for Grey Taguchi Design

7. Conclusion

In the present work, Hot Closed Die Forging of spring saddle has been studied. DEFORM ^{TM} 3D FEM based simulation software is used to examine the effect of design and process parameters on forging load and billet temperature loss. Grey relational analysis (GRA), along with Taguchi method were employed to optimize the forging load and billet temperature loss simultaneously. Based on the results and discussions, the following conclusions are made:

- DEFORM^{TM} 3D is found to be an effective tool to investigate the effect of design and process parameters on effective strain rate and forging load.
- Using Taguchi method, forging load and billet temperature loss are optimized individually. Two different optimal settings of process parameters are found for forging load and billet temperature loss. Using ANOVA on experimental results, parameters namely flash thickness, billet temperature and interaction between flash thickness and billet temperature are found to be the most significant parameters affecting the forging load. For billet temperature loss, billet temperature and interaction between flash thickness and billet temperature are significant.
- Grey Taguchi method is adopted to determine the optimum parameter level setting to optimize both performance characteristics simultaneously. ANOVA for grey relational grade reveals the flash thickness and interaction between flash thickness and billet temperatureaffecting the grey relational grade for forging load and billet temperature loss simultaneously.

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