Application of Taguchi Method for Process Parameters Optimization in Semi-solid Forging of A356 Al-Alloy

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Abstract— Al-alloys play an important role in achieving vehicle weight reduction and improving fuel economy in the automotive industry. Semi-solid forging (SSF) is a recent advancement in forging technology. This process involves the heating of billet to the semi-solid state in a coexisting liquid and solid phase and subsequently forging. The primary objective of this paper is to analyze the influence of the process parameters on tensile properties in the Semi-Solid Forging of A356 aluminum-alloy using Taguchi method. In Taguchi method, a three level orthogonal array has been used to determine the S/N ratio. Analysis of variance and the forging test values are used to determine the most significant process parameters affecting the tensile strength of A356 Al-alloy. The results indicate that Forging temperature and deformation percent are the influential parameters to create appreciable improvement in the mechanical properties of the Semi-Solid Forged components.

Keywords- Semi-solid Forging, Taguchi Method, Process Parameters, ANOVA

I. INTRODUCTION

Semi-solid forging (SSF) is a recent advancement in forging technology. This process involves the heating of billet to the semi-solid state in a coexisting liquid and solid phase and subsequently forging. It is a mushy state metal forming process that produces near net-shape parts in a single step. In semi-solid forging, it is necessary to control the forming variables accurately in order to make near net shape products. Generally, the defects of products may occur due to liquid segregation that can be caused by deformation, strain rate, and condition of friction. The liquid segregation is to be predicted by flow analysis.

A356 Al-alloys play an important role in achieving vehicle weight reduction and improving fuel economy in the automotive industry. A rise in consumption of Al alloys in car and lightweight truck market has been observed in last two decades. Semi-solid processing is one of the methods of producing spheroidal morphology of the phases and a good materials processing method to traditional casting and forging [Sirong et al. (2006)]. The advantages of semi-solid processing of alloys have longer die life, minimization of hot tearing tendency and modification of dendritic structure into globular structure, improvement in mechanical properties etc [Fan (2002) and Kirkwood (1994)]. Semi-solid metal processing may be used to make the components of complex shape with higher in quality than die castings and lower in cost than forgings. Semi-solid forging is a mushy state metal forming process that produces near net-shape parts in a single step. It reduces production costs, increase productivity and competitiveness and enhances fluidity of the materials [Sang-Yong et al. (2001) and Yoon et al. (1999)]. Muammer Koc et.al [1996] used finite element simulations to predict the deformation behavior and the load requirement of semi-solid forging of A356 aluminum alloy.

The proper setting up of process parameters before the SSF was crucial to obtain better hardness of the components. Taguchi method is applied in this work to find out the optimum settings for each process parameter and parameter combination at which SSF components are to be produced to achieve higher hardness. The hardness values predicted with the optimum settings are then evaluated by means of confirmation experiments to verify the validity of this study.

II. EXPERIMENTAL DESIGN WITH TAGUCHI METHOD

The main purpose of this paper is to establish the significant factors that influence the metal flow of A356 Al-alloy during the SSF process. This can be determined through a series of experiments. However, such experiments will be expensive and time-consuming. Design of experiment (DOE) techniques like the Taguchi method, the response surface methodology, etc. can optimize process parameters with minimum experimental runs. Enormous amount of research has been conducted for determining optimal process parameters of various manufacturing processes [Ho et al. (2004); Alauddin et al. (1997) and Dhavlikar et al. (2003)].
The SSF process parameters namely, Forging Temperature, percent reduction and die preheating temperature each at three

levels is considered in this work and the details are presented in Table 1. Selection of an appropriate orthogonal array based on the chosen process parameters is the prime aim in the Taguchi method. The total degrees of freedom for three parameters in each of three levels are six. Then, a three level orthogonal array (L_9 3^4) with nine experimental runs [degrees of freedom = 9−1 = 8] is selected for the present research. Orthogonal array (OA) is nothing but the shortest possible matrix of combinations in which all the parameters are varied at the same time and their effect and performance interactions are studied simultaneously.

An array's name indicates the number of rows and columns it has, and also the number of levels in each of the columns. Thus, the array (L_9 3^4) has nine rows and four columns of three levels. With the selection of (L_9 3^4) orthogonal array, using four parameters and three levels for each, the number of experiments required can be drastically reduced to nine, which in classical combination method using full factorial experimentation would require 3^3 = 27 number of experiments to capture the influencing parameters. The SSF process parameters namely Forging Temperature (A), percent reduction (B) and die preheating temperature (C) are assigned to the first, second and third columns of (L_9 3^4) array, respectively.

Table 1: Process Parameters with Levels

Process Parameters	Level 1	Level 2	Level 3
A: Forging Temperature (^{0}C)	540	560	580
B: Percent Reduction (%)	0.4	0.6	0.8
C: Die Temperature (^{0}C)	150	200	250

III. CONDUCT OF EXPERIMENT AND DATA COLLECTION

A356 aluminum alloy, popular in industrial products, is used for the investigation of mechanical properties. The solidus temperature of A356 alloy is 557^{o}C and liquidus temperature is 614^{o}C. The plate type conventional casting sample was cut into dimensions 100 X 60 X 40 mm^3. as shown in Figure 1a and Figure 1b. The next step in Taguchi method is to conduct the experiments. A 150 tons capacity hydraulic Press is employed for the application of pressure. The experimental setup is shown in Figure 2a. These samples were heated in a resistance-heating furnace at temperature ranges between 540^{o}C to 580^{o}C for 45 minutes of soaking time. Before forging the die setup of the Hydraulic Press was pre-heated to the temperature ranges between 150^{o}C to 250 ^{0}C as per Taguchi design of experiments. Forging is performed with the help of Hydraulic press with different reduction in the thickness of the each sample as per Taguchi design data sheet of (L_9 3^4) OA for each trial condition and they are shown in Figure 2b. Then the forged samples were cooled in atmosphere for 2 hours. Test specimens carved out of these samples**. T**ensile test were carried out at crosshead having speed of 1mm/min using HOUNDFIELD testing machine at room temperature of ≈ 300K. The tensile curves were analyzed to evaluate ultimate tensile strength (UTS) and percent elongation. The fracture surfaces were examined under scanning electron microscope (SEM). Samples from Semi-Solid Forged at different temperature, different deformation specimens were prepared following standard dimensions as given in Figure 3. The values along with the average response values of tensile strength are shown in Table 2.

Figure 1: (a) As cast A356 Al-alloy

Figure 1: (b) Sample of A356 for Semi-Solid Forging

Figure 2: (a) Hydraulic Press

Figure 2: (b) Semi-solid Forged Samples

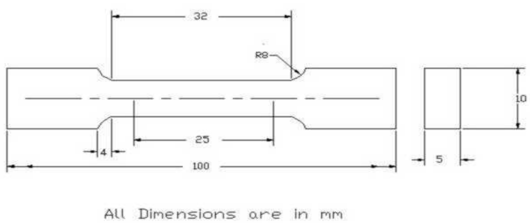


Figure 3 Flat tensile Test Specimen

IV. RESULTS AND DISCUSSION

After the collection of data, they are analyzed by means of calculating S/N ratio. The S/N ratio is simply a quality indicator by which the effect of changing a particular process parameter on the performance of the process or product is evaluated. In general, a better signal is obtained when the noise is smaller, so that a larger S/N ratio yields better final results. That means, the divergence of the final results becomes smaller. The S/N ratio for larger-is-better target of each experimental run is calculated based on the following equation, and the values are listed in Table 2.

$$\frac{S}{N} = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

Where n is the number of measurements in a trial (here n=3) and y_i is the i^{th} response for each noise repetition

The equation for tensile strength and the S/N ratio can be formulated as

$Y= a_1 + a_2 A + a_3B + a_4C + a_{11}AB + a_{12}AC + a_{13}BC.$

The constants were calculated and the final equations are-

Y_{mean}=199.347 – 18.779A + 18.534B – 9.902C + 5.806AB – 1.204AC + 3.446BC.

$Y_{S/N}$= 45.9494 – 0.8543A + 0.8129B – 0.4818C + 0.2711AB – 0.0924AC + 0.1645BC

Table 2: Results of (L9) Orthogonal Array Experiments

Expt. No	Process Parameter Assignment			Tensile Strength (M Pa)	S/N Ratio
	A	B	C		
1	540	0.4	150	160.91	44.1317
2	540	0.6	200	185.43	45.3636
3	540	0.8	250	195.36	45.8167
4	560	0.4	200	224.37	47.0193
5	560	0.6	250	212.89	46.5631
6	560	0.8	150	216.38	46.7043
7	580	0.4	250	183.06	45.2519
8	580	0.6	150	217.13	46.7344
9	580	0.8	200	198.58	45.9587

ANOVA computation is performed for evaluating the significance of the process parameters over tensile strength. Table 3 and Table 4 show the average effect response for raw data and S/N ratio. From Table 5 it is observed that forging temperature is the most significant factor for the response tensile strength. Table 6 it is observed that forging temperature is the most significant factor for the response tensile strength and S/N ratio.

Table 3: Average Effect Response for Raw Data

Levels	A: Forging Temp.	B: % Reduction	C: Die Temp.
1	180.6	189.4	198.1
2	217.9	205.2	202.8
3	199.6	203.4	197.1
Maximum - Minimum	37.3	15.7	5.7
Rank	1	2	3

Table 4: Average Effect Response for S/N Ratio

Levels	A: Forging Temp.	B: % Reduction	C: Die Temp.
1	45.1	45.47	45.86
2	46.76	46.22	46.11
3	45.98	46.16	45.88
Maximum - Minimum	1.66	0.75	0.26
Rank	1	2	3

Table 5: Computation of ANOVA

Source of Variation	DOF	SS	MS	F Ratio	P Value
A: Forging Temp.	2	2088.70	1044.35	2.68	0.272
B: % Reduction	2	445.33	222.67	0.57	0.636
C: Die Temp.	2	55.10	27.55	0.07	0.934
Error	2	779.63	389.81		
Total	8	3368.76			

DOF: Degree of Freedom; SS: Sum of Squares; MS: Mean of Squares

A. Response Graph

The response graphs exhibit a pictorial view of variation of each parameter and describe what the effect on the system performance would be, when a parameter shifts from one level to another. Figure 4 shows response for tensile strength for all the parameters. Figure 5 shows response for S/N ratio, as an example, level two for percent reduction (B_2 = 60%) has the highest S/N ratio value, which indicates that the SSF performance at such level produces minimum variation of the response tensile strength. The three dimensional representation of the response surface for tensile strength illustrates the importance of the input process parameters as shown in Figure 6.

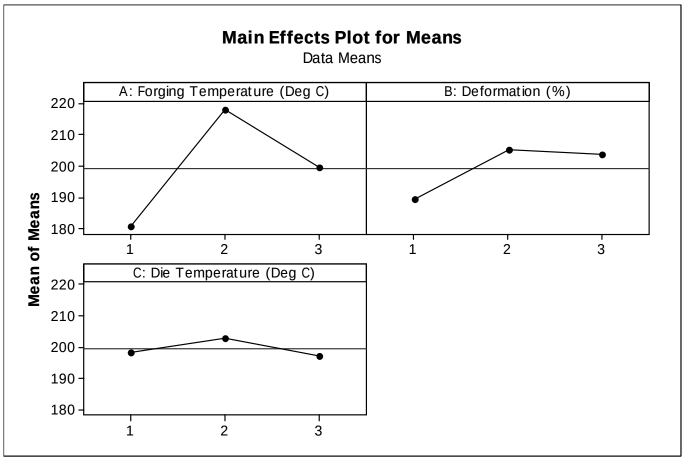


Figure 4 Main Effect Plot for Tensile Strength

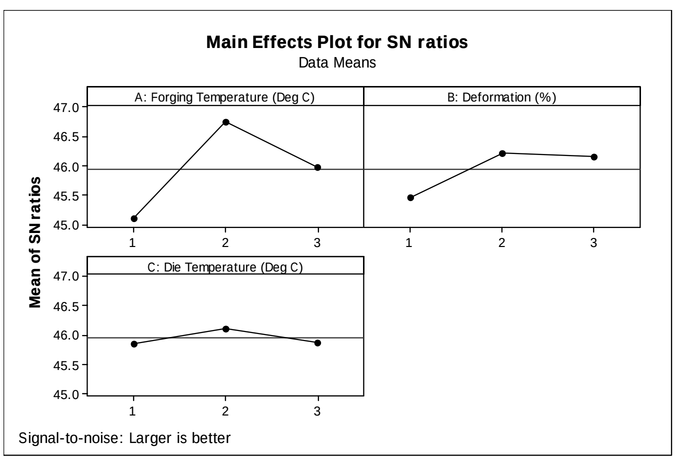
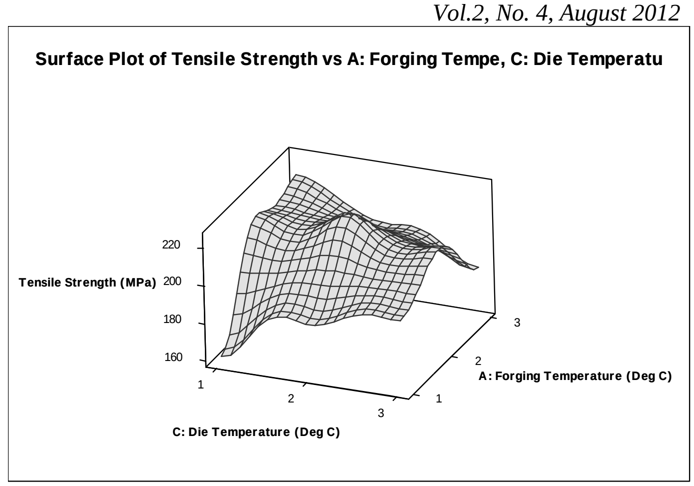
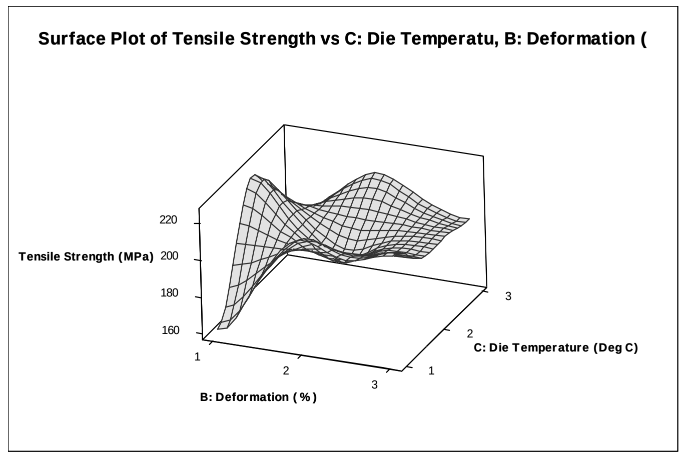


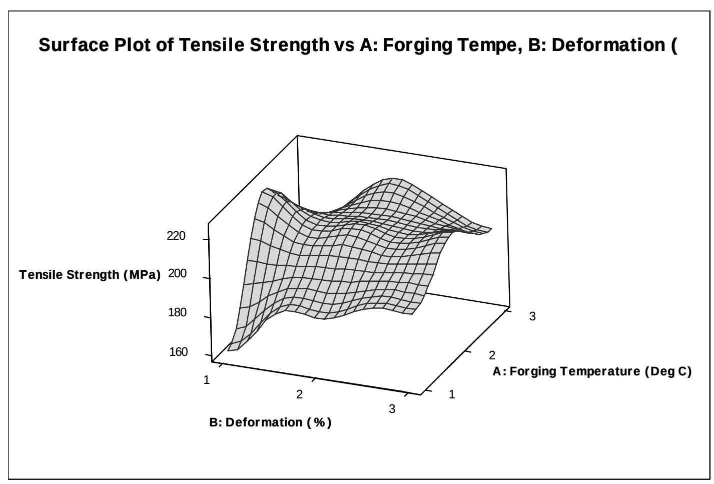
Figure 5 Mean S/N Ratio Plot for Tensile Strength



(a)



(b)

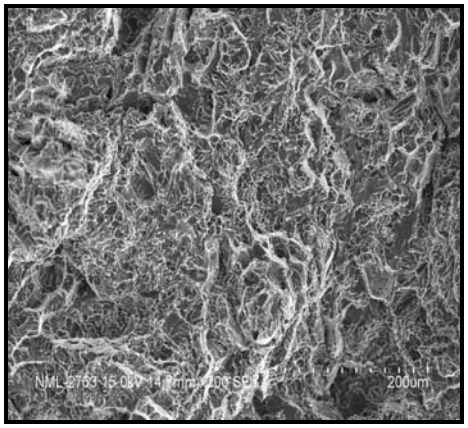


(c)

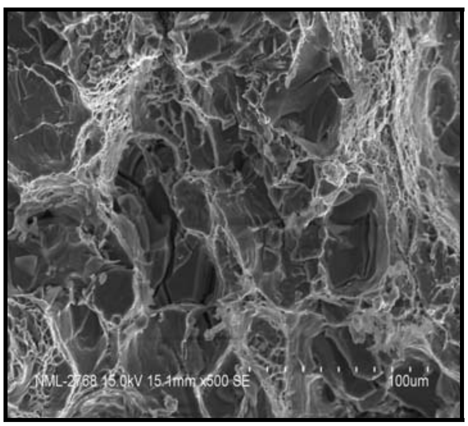
Figure 6 Three Dimensional Surface Plots for the Response Tensile Strength

B. Scanning Electron Microscopy

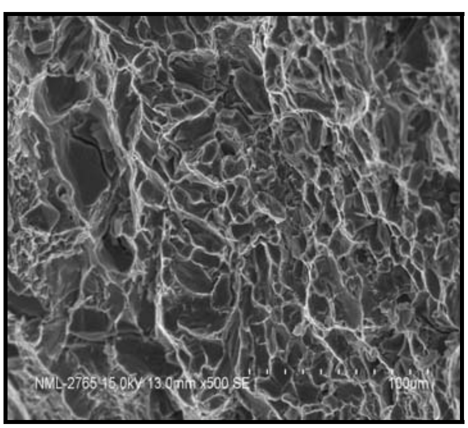
The SEM examination of as cast and semi-solid forged tensile specimen at different process parameters is shown in Figure 7.



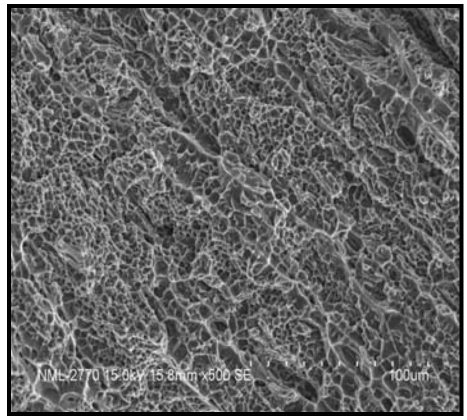
(A)



(B)



(C)



(D)

Figure 7: SEM Microscopy for (A) As Cast of A356; (B) Forging at 540°C 80% Deformation; (C) Forging at 560°C 40% Deformation; (D) Forging at 580°C 60% Deformation

Figure 7 shows the SEM microscopy of the fractured tensile samples for conventional and Semi-Solid Forged samples, respectively. From the figures the fracture mechanism is quite clear. The tensile fracture paths tended to follow the primary α-phase boundaries. The shearing of primary α-phase is observed in the conventional cast samples. From the fractographic view it is evident that the tensile fracture occurred by dimpled rupture with the void initiation at the eutectic Si particles for both products. Figures 7 (B), (C) and (D) give the SEM microscopy of the fracture surfaces of Semi-Solid Forged samples. The Semi-Solid Forged samples show the mixed mode of ductile and brittle fracture. Figures 6 (B), (C) and (D) give the SEM microscopy of the fracture surfaces of semi-solid forged at 540^0C, 560^0C and 580^0C samples. The fractographs show completely ductile fracture. Finer and more dimples were observed with increasing deformation percentage and with increasing forging temperature.

V. CONCLUSION

The optimum level of process parameter to obtain maximum hardness of SSF components of A356 aluminium alloy are A2, B2, C2 (forging temperature of 560 ^{0}C, percent reduction of 60% and die preheating temperature of 200 ^{0}C). From the response graph for tensile strength and S/N ratio, and ANOVA Table, it reveals that the forging temperature is a major contributing factor towards the improvement of tensile strength of A356 Al-alloy. As the pressure is applied during SSF, it forced the metal to accommodate closely to the die surface**,** thereby paving the way for the components to exhibit improved mechanical properties. During this research, only three factors namely forging temperature, percent reduction and die preheating temperature were considered. Significant scope exists to design and conduct further experiments for determining the exhaustive combination of factors and levels by including parameters like forging pressure, strain rate and time of applying pressure. These findings would enable the production of SSF components with higher degrees of tensile strength and mechanical properties.

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