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# An Optimization of Forging Process Parameters by using Taguchi Method: An Industrial Case Study

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***Abstract***- The objective of this paper is to obtain the optimal setting of forging process parameters in order to reduce the rejection rate due to unfilling defect. Initially, the various forging defects that occur in the components during closed-die hot forging process are investigated. The investigation is done with the help of Quality Assurance department in a forging industry. During investigation, the various defects that causes high rejection rates are identified and unfilling defect which has major contribution in high rejection rate is selected for study purpose. The process parameters considered for study purpose are- billet weight, heating temperature, heating time each at three levels and required output is final job weight. To obtain the optimal process parameter combination, optimization is carried out by the Signal-to-Noise (S/N) ratio analysis of Taguchi method using L9 Orthogonal Array. An analysis of variance (ANOVA) is used to present the influence of process parameters on filling the job weight. Results obtained by Taguchi method and by ANOVA method, are compared and found that they match closely with each other. Further multiple regression equation is formulated for estimating the predicted values of job weight. The values are then evaluated by conducting confirmation experiments to verify the validity of this study. In this way, the optimum levels of process parameters can be predicted. Finally it is concluded that, in order to reduce the rejection rate due to unfilling forging defect, the best process parameter combination which is derived through this study must be followed during the production process.

***Index Terms***- Unfilling, Process Parameters, Taguchi Method, S/N ratio, ANOVA, Regression analysis.

## I. Introduction

As parts produced by forging process has superior mechanical and metallurgical properties, thus in modern times they are having wide applications in automotive industry, defense industry, marine industry and aerospace industry, agricultural machinery, off-highway and railroad equipment, valves, fittings, petrochemical applications, industrial hardware and hand tools [3]. Although forging process has special place among all the manufacturing processes, there are still high rejection rates due to forging defects. Defects ranges from those traceable to the starting materials to those caused by forging process itself or by post forging operations. In forging process, defects like unfilling, mismatch, scale pits, surface cracking, fold and lap, improper grain flow etc. are responsible for high rejection rates. In this study, unfilling forging defect is focused. Unfilling defect can be defined as some section of die cavity not completely filled by the flowing metal, or metal does not fill the recesses of the die cavity completely during the forging process. It causes due to improper design of the forging die, die wear, improper use of forging techniques, less raw material, poor heating of raw material inside the furnace, etc. It can be avoided by proper die design, using proper raw material and proper heating of billets inside the furnace to get the desired forgeability of raw material. The effect of unfilling defect is that the job dimensions cannot be filled; ultimately the required final job weight cannot be filled completely as per the requirements of company standards. Due to presence of this defect, there will be insufficient material stock on forged component for subsequent machining operations, hence the job gets rejected. In order to increase the product quality and to reduce the rejection rate due to defects, design activities need to systematically consider various designs and process related parameters and finally come out with the best parameters combination for better process performance. The quality of the closed-die forging depends on several controlling parameters such as die design parameters and process parameters. Design parameters represent the geometrical aspect of the die such as flash thickness, flash land width, fillet radii, corner radii and draft [4]. Die design also consists of die wear analysis, since die wear is also responsible for unfilling defect. Process parameters are variable related to the forging process. During the brainstorming session, it is observed that the three process parameters (billet weight, heating temperature of furnace, and heating/soaking time of raw material/billet inside the furnace) have major influence on filling the die cavity. Therefore these three process parameters are selected for trial purpose. The purpose of conducting trials is to determine the best combination of these process parameters.

Traditionally, the empirical trial-and-error method has been used to get the best parameter combination, through a series of experiments; however, this approach is tedious, expensive, and time consuming. Design of experiments (DOE) techniques like the Taguchi method can optimize the process parameters with minimum number of experimental trials. Taguchi offers a simple and systematic approach to obtain optimal setting of the process parameters. Therefore, in present study, Taguchi optimization methodology is applied.

## II. Methodology

Taguchi method was developed by Dr. Genechi Taguchi, as a researcher at the electronic control laboratory in Japan. He carried out significant research on DOE techniques in the late

1940's. He proposed that optimization of process parameters should be carried out in three-step approach- system design, parameter design, and tolerance design. System design deals with innovative research, looking for what factors and levels should be. Parameter design is used to obtain the optimum levels of process parameters to improve the performance of process/products by adjusting levels of factors. Finally, tolerance design aims to determine the control characteristics for each factor level identified in earlier studies [5]. The parameter design is the key step in Taguchi method to achieving high quality without increasing cost. The steps included in Taguchi parameter design are: selecting the proper orthogonal array (OA) according to the numbers of controllable factors (parameters); running experiments based on the OA; analyzing the data; identifying the optimum condition; and conducting confirmation trials with the optimal levels of all the parameters. To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. For three parameters each at three levels, the degrees of freedom are six. Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task [4]. A three level orthogonal array (L9 $3^3$) with nine experimental runs (total degrees of freedom = 9-1 = 8) is selected for the present study. 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. With the selection of (L9 $3^3$) orthogonal array, using three parameters and three levels for each, the numbers of experiments required are nine, which in classical combination method using full factorial experimentation would require 27 numbers of experiments to get the influencing parameters [6]. Thus, by using Taguchi method, based on orthogonal arrays, the numbers of experiments can be reduced. Taguchi method employs the S/N ratio to identify the quality characteristics applied for engineering design problems. The S/N ratio characteristics can be divided into three types: lower-the-better, larger-the-better, and nominal-the-better.

## III. INPUT DATA COLLECTION AND PROBLEM IDENTIFICATION

During the investigation that done with the help of QA department, in a forging industry, it is clear from the monthly rejection report (Table 1) for the month of December 2013, company has manufactured 14 types of gear blanks. In the total production of 12945 numbers, 787 numbers got rejected. It means the plant has a rejection rate of 6.08% in that month. This much rejection rate cannot be tolerated by the company, this lead to undergo detail study in the company about the defects that caused this much rejection rate and the remedial actions suitable for that to reduce the rejection rate. From the information of Table 1, two charts are plotted. Chart 1 shows that Part No. 2876 has maximum rejection and Chart 2 shows that 'Unfilling' defect has major contribution in rejection of part No. 2876. Therefore, Part No. 2876 is selected here for study purpose and trying to attack on unfilling defect in that product.

As per the Process Standard of company, the ranges of three process parameters (which are selected for trial purpose), for the Part No. 2876 are- Billet Weight: 6.25 Kg +/- 0.05 Kg, Heating Temperature of furnace: 1200 $^0$C +/- 50 $^0$C, and Heating/Soaking Time for billets inside the furnace: 60 min. +/- 10 min.

Table 1 : Monthly Rejection Report (Dec. 2013)

| Sr. No. | Part No. | Production Qty. (in Nos.) | Defect wise Rejected Qty. (in Nos.) | | | | | | Total Rejected Qty. (in Nos.) | Rejection (in %) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | U/F | S/P | M/M | Lap | C/R | D/M | | |
| 1 | 2682 | 1080 | 27 | 9 | 5 | 7 | 6 | 3 | 57 | 5.28 |
| 2 | 2686 | 900 | 22 | 5 | 12 | 9 | 9 | 3 | 60 | 6.67 |
| 3 | 2690 | 1100 | 10 | 18 | 3 | 10 | 0 | 2 | 43 | 3.91 |
| 4 | 2691 | 850 | 1 | 6 | 19 | 3 | 7 | 3 | 39 | 4.59 |
| 5 | 2732 | 975 | 17 | 8 | 7 | 5 | 4 | 1 | 42 | 4.31 |
| 6 | 2793 | 1000 | 20 | 4 | 12 | 9 | 10 | 0 | 55 | 5.50 |
| 7 | 2873 | 995 | 27 | 11 | 9 | 6 | 3 | 2 | 58 | 5.83 |
| 8 | 2876 | 1000 | 59 | 13 | 7 | 11 | 8 | 10 | 108 | 10.80 |
| 9 | 2877 | 790 | 32 | 8 | 5 | 3 | 2 | 4 | 54 | 6.84 |
| 10 | 2930 | 600 | 8 | 15 | 14 | 3 | 0 | 5 | 45 | 7.50 |
| 11 | 2957 | 875 | 15 | 8 | 16 | 2 | 6 | 3 | 50 | 5.71 |
| 12 | 2958 | 1000 | 24 | 4 | 9 | 13 | 8 | 1 | 59 | 5.90 |
| 13 | 3038 | 930 | 11 | 23 | 4 | 7 | 7 | 5 | 57 | 6.13 |
| 14 | 3039 | 850 | 24 | 11 | 7 | 7 | 5 | 6 | 60 | 7.06 |
| **Total** | | **12945** | **297** | **143** | **129** | **95** | **75** | **48** | **787** | **6.08** |

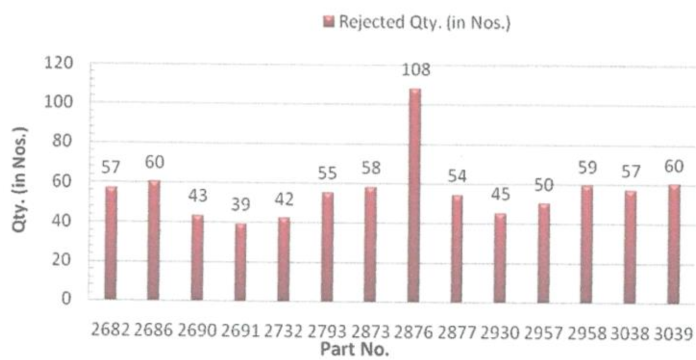


Chart 1 : Part number wise rejected Qty.

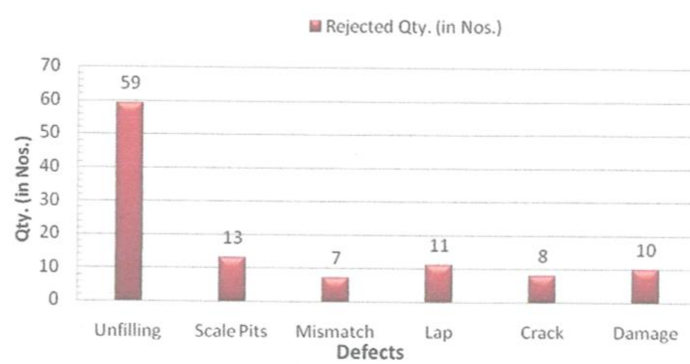


Chart 2 : Defect wise rejected Qty. for Part No. 2876

## IV. EXPERIMENTAL DETAILS

*A. Selection of Process Parameter levels and Response Factor:*

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There are three input controlling parameters selected with their three levels. Details of parameters and their levels used in this study are as shown in Table- 2. Unfilling defect is as shown in Photograph- 1 and 2. It is very difficult to predict the occurrence of this defect at a particular place on a job, but this defect directly affects the required final job weight. So, the selected response parameter/factor for this study is required final job weight. As per the Company standard, the required final job weight for Part No. 2876 is 5.50 Kg +/- 0.05 Kg.

Table 2 : Process Parameters with their Levels

| | | | | |
|---|---|---|---|---|
| A | Billet Wt. (in Kg) | 6.20 (A1) | 6.25 (A2) | 6.30 (A3) |
| B | Heating Temp. (in $^0$C) | 1150 (B1) | 1200 (B2) | 1250 (B3) |
| C | Heating Time (in min.) | 50 (C1) | 60 (C2) | 70 (C3) |

Photograph 1: Unfilling defect at front side of job

Photograph 2: Unfilling defect at back side of job

*B. Design of Experiments:*

The design of experiment is carried out by Taguchi methodology using Minitab 14 Software. In this technique the main objective is to optimize the job weight that is influenced by various process parameters. Since three controllable factors and three levels of each factor are considered L9 ($3^3$) Orthogonal Array is selected for this study. Table 3 shows the layout of experiments to be carried out according to Taguchi L9 Orthogonal Array.

*C. Experimental Set-up:*

A Series of experiments are conducted to evaluate the influence of process parameters on job weight. The trials are carried out on 2 Ton Pneumatic Hammer. Electronic weighing machine is used for weight measurement. The experiments are conducted by keeping all other parameters constant. The constant parameters are air-fuel ratio (6:1) to furnace burner, type of furnace oil (cbfs), air pressure (75 psi) to hammer, type of hammer, die wear within limit, skilled operator, etc. Photograph 3 shows hammering operation on 2-Ton hammer during experimentation and photograph 4 shows electronic weighing machine to be used for weight measurement purpose.

Table 3 : Layout of experiments

| Trial No. | Parameters Combination | | |
|---|---|---|---|
| | A | B | C |
| 1 | 6.20 | 1150 | 50 |
| 2 | 6.20 | 1200 | 60 |
| 3 | 6.20 | 1250 | 70 |
| 4 | 6.25 | 1150 | 60 |
| 5 | 6.25 | 1200 | 70 |
| 6 | 6.25 | 1250 | 50 |
| 7 | 6.30 | 1150 | 70 |
| 8 | 6.30 | 1200 | 50 |
| 9 | 6.30 | 1250 | 60 |

Photograph 3: Hammering operation

Photograph 4: Electronic weighing machine

## V. RESULTS AND DISCUSSION

### *A. S/N Ratio Analysis:*

After the conduction of trials, the results for job weight are collected and they are analyzed by means of calculating the S/N ratio. Taguchi uses the S/N ratio analysis to measure the quality characteristic deviating from the desired value. In S/N ratio, the term ‘Signal’ represents the desirable value (mean) for the output characteristic and the term ‘Noise’ represents the undesirable value for the output characteristic. In general, a better signal is obtained when the noise is smaller, so that a larger S/N ratio gives better final result. That means, the divergence of the final results becomes smaller. The S/N ratio for larger-the-better target of each experimental trial is calculated based on the following equation, and the values are listed in Table 4.

Larger-the-better characteristic

$$S/N = -10 \log (MSD)$$

Where MSD= Mean Square Deviation for the Output Characteristic.

$$MSD = (1/Y_1^2 + 1/Y_2^2 + 1/Y_3^2 + \ldots\ldots\ldots\ldots + 1/Y_n^2 ) / n$$

Where $Y_1$, $Y_2$, $Y_3$ are the responses and ‘n’ is the number of tests in a trial.

The level of a factor with the highest S/N ratio is the optimum level for responses measured. The higher the signal to noise ratio, the more favorable is the effect of input variable on the output.

Table 4: Results of Experiments

| Trial No. | Parameters Combination | | | Results | |
|---|---|---|---|---|---|
| | A | B | C | Job wt. | S/N ratio |
| 1 | 6.20 | 1150 | 50 | 5.39 | 14.6318 |
| 2 | 6.20 | 1200 | 60 | 5.37 | 14.5995 |
| 3 | 6.20 | 1250 | 70 | 5.34 | 14.5508 |
| 4 | 6.25 | 1150 | 60 | 5.44 | 14.7120 |
| 5 | 6.25 | 1200 | 70 | 5.42 | 14.6800 |
| 6 | 6.25 | 1250 | 50 | 5.41 | 14.6639 |
| 7 | 6.30 | 1150 | 70 | 5.44 | 14.7120 |
| 8 | 6.30 | 1200 | 50 | 5.48 | 14.7756 |
| 9 | 6.30 | 1250 | 60 | 5.46 | 14.7439 |

From Table 4 - It is clear that, the S/N ratio is higher for Trial No. 8, hence the optimum value levels of control factors for higher job weight, are at- billet weight (6.30 Kg), heating temperature (1200 $^0$C), and heating time (50 min.). Chart 3 shows the Trend for Results of Trials.

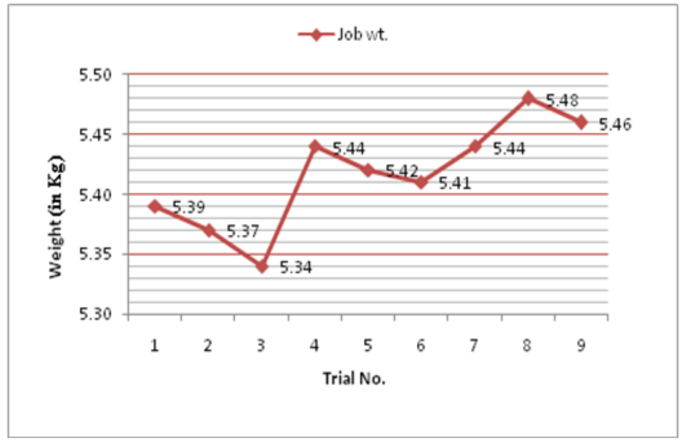


Chart 3: Trend chart for Results of Trials

Table 5: Estimated Model Coefficients for S/N ratios

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 14.6744 | 0.008126 | 1805.758 | 0.000 |
| B wt 6.20 | -0.0804 | 0.011493 | -6.992 | 0.020 |
| B wt 6.25 | 0.0109 | 0.011493 | 0.950 | 0.442 |
| Temp 1150 | 0.0109 | 0.011493 | 0.945 | 0.444 |
| Temp 1200 | 0.0106 | 0.011493 | 0.926 | 0.452 |
| Time 50 | 0.0161 | 0.011493 | 1.398 | 0.297 |
| Time 60 | 0.0107 | 0.011493 | 0.933 | 0.449 |

Table 5 shows the linear model for S/N ratios.
Summary of Model-
S = 0.02438 R-Sq = 97.1% R-Sq(adj) = 88.3%

From Table 6 and Figure 1, it is clear that, larger the ‘delta’ value, greater the significance of the control factor. It means for higher job weight, the most significant factor is billet weight (A), followed by heating time (C), and heating temperature (B).

Table 6 : Response for S/N ratios

Larger is better

| Level | B wt | Temp | Time |
|---|---|---|---|
| 1 | 14.59 | 14.69 | 14.69 |
| 2 | 14.69 | 14.69 | 14.69 |
| 3 | 14.74 | 14.66 | 14.65 |
| Delta | 0.15 | 0.03 | 0.04 |
| Rank | 1 | 3 | 2 |

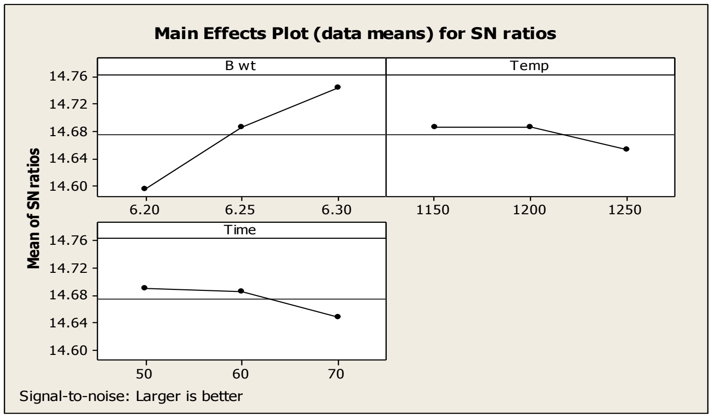


Figure 1 : Effect of process parameters on S/N Ratio

*B. Analysis of Variance (ANOVA):*

Analysis of variance is a standard statistical technique to interpret the experimental results. It is extensively used to detect differences in average performance of groups of items under investigation. It breaks down the variation in the experimental result into accountable sources and thus find the parameters whose contribution to total variation is significant. Thus analysis of variance is used to study the relative influences of multiple variables, and their significance. The purpose of ANOVA is to investigate which process parameters significantly affect the quality characteristic. The analysis of the experimental data is carried out using the software MINITAB 14 specially used for design of experiment applications.

In order to find out statistical Significance of various factors like billet weight (A), heating temperature (B), and heating time (C), and their interactions on job weight, analysis of variance (ANOVA) is performed on experimental data. Table 7 shows the results of the ANOVA for S/N ratio. The last column of the table indicates p-value for the individual control factors. The 'p-value' plays an important role in this analysis. It is known that smaller the p-value, greater the significance of the factor. Table 7 indicates that, the billet weight (p=0.034), heating time (p= 0.267), and heating temperature (p=0.363) in this order, are the most significant control factors effecting the job weight. It means, the billet weight is the most significant factor and the heating temperature has less influence on the performance output.

Table 7 : ANOVA for S/N ratios

| Source | DF | Seq SS | Adj MS | F | P |
|---|---|---|---|---|---|
| B wt | 2 | 0.034190 | 0.017095 | 28.76 | 0.034 |
| Temp | 2 | 0.002082 | 0.001041 | 1.75 | 0.363 |
| Time | 2 | 0.003271 | 0.001636 | 2.75 | 0.267 |
| Residual Error | 2 | 0.001189 | 0.000594 | | |
| Total | 8 | 0.040732 | | | |

*C. Percent contribution:*

Percent contribution to the total sum of square can be used to evaluate the importance of a change in the process parameter on these quality characteristics.
Percent contribution is calculated by the following equation:

Percent contribution (P) = (SS'A / SST) *100

Table 8 and Chart 4 shows individual % contribution of parameters under study.

Table 8: Optimum Condition and Percent Contribution

| Sr. No. | Factors | Level Description | Rank | Contribution (%) |
|---|---|---|---|---|
| 1 | A: Billet wt. | 6.30 | 1 | 83.94 |
| 2 | B: Heating Temp. | 1200 | 3 | 5.11 |
| 3 | C: Heating Time | 50 | 2 | 8.03 |

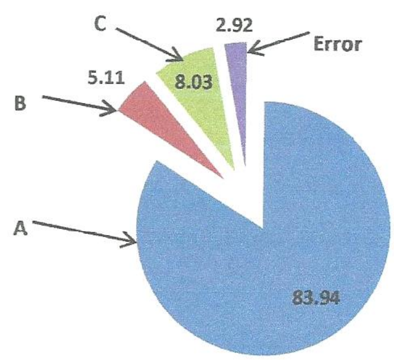


Chart 4: Percent contribution

*D. Regression Analysis:*

Regression analysis is used for explaining or modeling the relationship between a single variable Y, called the response, output or dependent variable, and one or more predictor, input, independent or explanatory variables. The mathematical model for process parameters such as billet weight, heating temperature and heating time is obtained from regression analysis using MINITAB 14 statistical software to predict the job weight. Table 9 shows the regression analysis model.

Table 9 : Regression analysis model

| Predictor | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | -0.0967 | 0.7598 | -0.13 | 0.904 |
| B wt | 0.9333 | 0.1193 | 7.83 | 0.001 |
| Temp | -0.0002000 | 0.0001193 | -1.68 | 0.154 |
| Time | -0.0013333 | 0.0005963 | -2.24 | 0.076 |

Summary of Model-
S = 0.0146059  R-Sq = 93.2%  R-Sq(adj) = 89.2%

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The regression equation is

Y = -0.0967 + 0.9333 A - 0.0002000 B - 0.0013333 C …… (1)

Where,

Y = Response i.e. Job weight (Kg)

A = Billet wt. (Kg), B = Heating Temperature ($^{0}$C), C = Heating Time (min)

If we put optimum parameters (A3B2C1) which are drawn by S/N ratio and ANOVA analyses, in equation (1), it will give the optimum value of quality characteristic which will be the maximum job weight.

$Y_{opt}$ = -0.0967 + 0.9333*A3 – 0.0002000*B2 – 0.0013333*C1

$Y_{opt}$ = -0.0967 + 0.9333*6.30 – 0.0002000*1200 – 0.0013333*50

$Y_{opt}$ = 5.4764 Kg (Predicted by Regression Equation)

In multiple linear regression analysis, $R^2$ is value of the correlation coefficient and should be between 0.8 to 1. In this study, the results obtained for final job weight are in good agreement with regression model ($R^2$>0.80). Figure 2 shows the Residual plots for job weight.


Figure 2: Residual Plots for Job weight

*E. Confirmation Experiments:*

In Order to test the predicted result, confirmation experiment has been conducted by running another three trials at the optimal settings of the process parameters, determined from the Analysis i.e. A3B2C1.

Table 10: Results for confirmation experiments

| Observation | Trial No. | | | Avg. Job wt. | S/N ratio |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | | |
| 1 | 5.49 | 5.48 | 5.49 | 5.4867 | 14.7862 |

The results for confirmation experiments are shown in Table 10, and it is observed that the average Job weight i.e. 5.4867 and S/N Ratio 14.7862, falls within predicted 80% Confidence Interval. Chart 5 shows the Trend for Results of confirmation experiments. Photograph 5 shows a defect free job produced during confirmation experiments and Photograph 6 shows the weight measurement for that job.

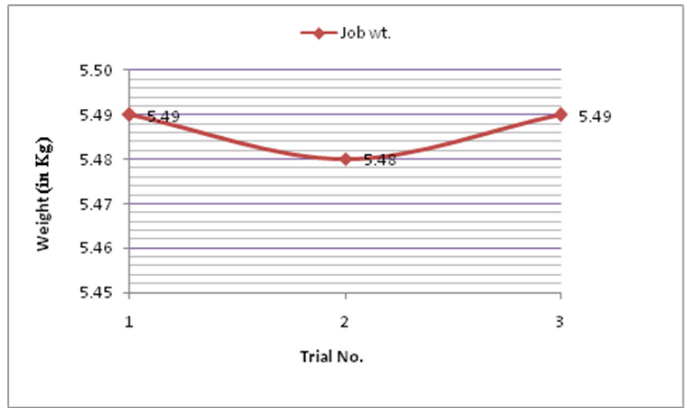


Chart 5: Trend chart for Results of confirmation experiments

Photograph 5: Defect free job

Photograph 6: Job weight = 5.49 kg

## VI. CONCLUSION

The Unfilling defect in Part No. 2876, was selected for this study. The Process parameters considered were- billet weight, heating temperature, and heating time each at three levels. To obtain the optimal setting of these parameters, the S/N ratio analysis of Taguchi method (L9 OA) is used. ANOVA is carried out for determining the influence of given input parameters from a series of experimental results by Taguchi method. The optimum job weight is calculated by Regression equation. Hence, following conclusions are drawn from the present study:

- From the S/N ratio and ANOVA analyses, it is clear that the optimal combination of process parameters is A3B2C1.

- The optimum job weight value calculated by Regression equation closely matches with the actual job weight value obtained by Trial No. 8 of Taguchi method.
- The prediction made by Taguchi parameter design technique and by Regression analysis is in good agreement with the confirmation results.
- Thus, the use of Taguchi and ANOVA methods, were effective in studying the influence of selected process parameters on job weight.
- Among three process parameters, billet weight is the most significant parameter followed by heating time and heating temperature to get the higher job weight.
- The optimal level of process parameters that must be followed during the production process in order to reduce the rejection rate due to unfilling forging defect, are:

| | |
|---|---|
| Billet weight | 6.30 Kg |
| Heating Temperature | 1200 $^0$C |
| Heating Time | 50 min. |

- The results of present study are valid within specified range of process parameters. Hence, the present study stands valid.
- As unfilling defect also causes due to die design parameters, die wear etc., significant scope exists to conduct study in this direction also to reduce the unfilling defect.
- In present study, only unfilling defect was selected. Significant scope exists to design and conduct further research and experimentation to reduce overall rejection rate due to other forging defects also.

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