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OPTIMIZATION OF HYDROFORMING PROCESS FOR MANUFACTURING OF STAINLESS STEEL CORRUGATED FLEXIBLE HOSE PIPE USING THE TAGUCHI METHOD

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ABSTRACT

This paper presents a study in which the Taguchi method, a powerful tool to design and process optimization for quality, is used to determine the optimal parameters of hydroforming process that is used to produce stainless steel corrugated flexible hose pipes. An orthogonal array, the signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) are employed to investigate the process parameters in order to achieve optimum performance of the hose pipe. Through this study, not only can the optimal parameters of hydroforming process be obtained, but also the main parameters of the process that affect the performance of the hose pipe can be found. Experimental results are provided to confirm the effectiveness of this approach. From the results, it is found that the process parameters, i.e. water pressure and sensor distance significantly affect the outer diameter and pitch of the hose pipe respectively.

Keywords: Taguch method; Optimization; Hydroforming process; Flexible hose pipe; Stainless steel

1. INTRODUCTION

Hydroforming is an important process in the manufacturing of stainless steel (SS) flexible corrugated hose pipes. A special version of this process i.e. tube hydroforming has attracted the increasing attention of the automotive industry worldwide [1]. Hydroforming of corrugations is based on the principle of bulging of SS tube and subsequently forming the annular convolutions on it with the help of water pressure. Plain SS tube is fed on the Hydraulic corrugating forming machine to form the corrugations. The tube is inserted in the mandrel mounted longitudinally to the axis of the machine. The hydroforming process starts with clamping the tube in the hydraulically operated pipe holder clamping device. Water pressure is applied on the tube through the holes present on the periphery of the mandrel. The intensifier develops the water pressure which is controlled by means of pressure switches. Due to the applied water pressure the portion of the tube above the periphery of the mandrel gets bulged. The bulged shape is then compressed by the moving die plates. The movement of the die plates is controlled by the sensors as per the required pitch of the convolution. Thus each convolution is formed and one cycle is completed. The process is repeated until convolution is formed on the entire length of the pipe. It is due to these convolutions that the pipe becomes flexible. It should be noted that the movements of hydraulic cylinders, dies, plates, and intensifier are made possible with the help of photosensors and proximity switches provided on the hydroforming machine. These sensors are mounted on the machine at appropriate locations and the pitch is controlled by the sensor .All signals are fed to programmable logic controller (PLC) mounted in the panel. PLC is preprogrammed and converts signals into commands, actuate various relays and contactors to operate various hydraulic control valves mounted on power pack. These hydraulic valves such as direction control valves, flow control valves, pressure control valves, operate various hydraulic cylinders to form the stainless steel corrugated flexible hoses. Outer diameter (OD) and pitch (p) are the two important parameters that determine quality of the stainless steel flexible hose pipes since the burst pressure of the hose pipe depends on these parameters. Hence it is of utmost importance to correctly select the hydroforming process parameters in order to get the desired outer diameter and the pitch of the corrugated hose pipe. In this paper an attempt has been made to optimize hydroforming process parameters for manufacturing of stainless steel corrugated flexible hose pipe using the Taguchi method. The effect of three process parameters, i.e. water pressure, hydraulic oil pressure and sensor distance on the outer diameter as well as pitch of the corrugated flexible hose pipe is investigated. Based on Taguchi design of experiment [2-4] trials have been carried out in order to determine the optimum process parameters. In the following, the Taguchi method is introduced first. The experimental details of using the Taguchi method to determine and analyze the optimal process parameters are described next. The optimal process parameters with regard to performance index such as outer diameter and pitch are considered. Finally, the paper concludes with a summary of this study.

2. THE TAGUCHI METHOD

The Taguchi method is a powerful tool for the design of high quality systems. It provides a simple, efficient and systemic approach to optimize designs for performance, quality and cost. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to source variation. In recent years, the rapid growth of interest in the Taguchi method had led to numerous applications of the method in a world-wide range of industries and nations [5]. The technique has been widely used for product design and process optimization [6-11]. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only and thus, it results in significant cost and time saving. A desired number of experiments as suggested by the orthogonal array are performed and the experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to determine which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

3. OPTIMIZATION OF HYDROFORMING PROCESS PARAMETERS

3.1 Selection of process parameters and their levels

The experiments were carried out on a hydroforming SPM machine (make: India) with a power pack and electrical panel. The feasible space for the process parameters was defined by varying the water pressure in the range 80 – 100 kg/cm^2, the hydraulic oil pressure in the range 25 – 35 kg/cm^2, and the sensor distance in the range 3 –
5 mm. Three levels of each process parameter, based on the experience of the experts, were selected as shown in Table 1.

Table 1: Process parameters and their levels

Symbol	Process parameter	Unit	Level -1	Level - 2	Level - 3
A	Water pressure	Kg/cm^2	80	90	100
B	Hydraulic oil pressure	Kg/cm^2	25	30	35
C	Sensor distance	mm	3	4	5

3.2 Process performance measure

The performance of the hydroforming process was measured in terms of outer diameter and pitch of the corrugated hose pipe for the reason mentioned earlier. The outer diameter was measured with the help of a digital vernier caliper. The pitch, in mm, was measured by simply counting the number of convolution present on one meter length of the pipe and subsequently dividing 1000 by this number.

4 DESIGNS AND ANALYSIS OF THE PROCESS PARAMETERS

In the following section, the use of an orthogonal array to reduce the number of experiments for design optimization of the process parameters is presented. Results of the experiments are studied using the S/N ratio and ANOVA analyses. Based on the results of these analyses, optimal settings of the process parameters for outer diameter and pitch are obtained and verified.

4.1 Orthogonal array experiment

In order to select an appropriate orthogonal array for the 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. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with the interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the process parameters is neglected. Therefore, there are six degrees of freedom owing to there being three process parameters in the hydroforming operation.

Once the required degrees of freedom are known, the next step is to select an appropriate orthogonal array to serve the specific purpose. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L_9 orthogonal array with four columns and nine rows was used. This array has eight degrees of freedom and it can handle three-level design parameters. Each process parameter is assigned to a column, nine process-parameter combinations being available. Therefore, only nine experiments are required to study the entire parameter space using the L_9 orthogonal array. The experimental layout for the three process parameters using the L_9 orthogonal array is shown in Table 2. Since the L_9 orthogonal array has four columns, one column of the array is left empty for the error of experiments: orthogonality is not lost by letting one column of the array remain empty.

4.2 Analysis of the S/N ratio

In the Taguchi method, the term "signal" represents the desirable value (mean) for the output characteristic and the term "noise" represents the undesirable value (S.D.) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the S.D. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio η is defined as:

$$\eta = -10 \log (\text{M.S.D.}) \qquad (1)$$

where M.S.D. is the mean-square deviation for the output characteristic.As mentioned earlier, there are three categories of quality characteristics, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the better. To obtain optimal hydro- forming performance, the-higher-the-better quality characteristic for outer diameter of the hose pipe should be taken. The mean-square deviation (M.S.D.) for the-higher-the-better quality characteristic can be expressed as:

$$\text{M.S.D.} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{d_i^2} \qquad (2)$$

where m is the number of tests and d_i is the value of outer diameter for the i th test. Table 3 shows the experimental results for the outer diameter and the corresponding S/N ratio using Eqs. (1) and (2). It should be noted that the outer diameter shown in this table is the mean of three outer diameters, measured at three different positions, of a one meter long hose pipe produced by following the experimental plan shown in Table 2. Since the experimental design is orthogonal, it is then possible to separate out the effect of each process parameter at different levels. For example, the mean S/N ratio for the water pressure at levels 1, 2 and 3 can be calculated by averaging the S/N ratio for the experiments 1 – 3, 4 – 6, and 7 – 9, respectively. The mean S/N ratio for each level of the other process parameters can be computed in a similar manner. The mean S/N ratio for each level of the process parameters is summarized and called the S/N response table for outer diameter (Table 4). Figure 1 shows the S/N response graph for the output characteristic (outer diameter). As shown in Eqs. (1) and (2), the greater the S/N ratio, the smaller is the variance of the output characteristic around the desired (the-higher-the-better) value. However, the relative importance amongst the process parameters for outer diameter still needs to be known so that optimal combination of the process parameters and their levels can be determined more accurately. This will be discussed in the next section using the analysis of variance. On the other hand, the-lower-the-better quality characteristics for pitch should be taken for obtaining optimal process performance. The M.S.D. for the-lower-the-better quality characteristic can be expressed as:

$$\text{M.S.D.} = \frac{1}{m}\sum_{i=1}^{m} p_i^2 \qquad (3)$$

where p_i is the value of pitch for the i th test. Table 5 shows the experimental results for pitch and the corresponding S/N ratio using Eqs. (1) and (3). It should be noted that the pitch shown in this table is the mean of three pitches, measured at three different positions, of a one meter long hose pipe produced by following the experimental plan shown in Table 2. The S/N response table and S/N response graph for pitch are shown in Table 6 and Figure 2. Regardless of the-lower-the-better quality characteristic, the greater S/N ratio corresponds to the smaller variance of the output characteristic around the desired value (Eqs. (1)–(3)).

4.3 Analysis of variance

The purpose of the analysis of variance (ANOVA) is to investigate which process parameters significantly affect the quality characteristic. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SS_T from the mean S/N ratio η_m is calculated as:

$$SS_T = \sum_{i=1}^{n}(\eta_i - \eta_m)^2 \qquad (4)$$

where n is number of experiments in the orthogonal array, η_i is the S/N ratio for the i th experiment. The total sum of squared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each process parameter and the sum of squared error SS_e.

The percentage contribution *p* by each of the process parameter in the total sum of squared deviations SS_T is a ratio of the sum of squared deviations SS_d due to each process parameter to the total sum of squared deviations $SS_{T.}$

Table 2: Experimental layout using L_9 orthogonal array

Experiment number	Process parameter level		
	A	B	C
	Water pressure	Hydraulic oil pressure	Sensor distance
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

Table 5: Experimental result for pitch and corresponding S/N ratio

Experiment number	Water pressure (kg/cm^2)	Hydraulic oil pressure (kg/cm^2)	Sensor distance (mm)	Pitch (mm)	S/N ratio (dB)
1	80	25	3	4.53	-13.12
2	80	30	4	4.62	-13.29
3	80	35	5	3.83	-11.66
4	90	25	5	3.83	-11.66
5	90	30	3	4.32	-12.70
6	90	35	4	4.74	-13.51
7	100	25	4	4.62	-13.29
8	100	30	5	3.83	-11.66
9	100	35	3	4.52	-13.10

Table 6: S/N Response table for pitch

Symbol	Process parameter	Mean S/N ratio (dB)			
		Level-1	Level-2	Level-3	Max-min
A	Water pressure	-12.69	-12.62	-12.68	-0.07
B	Hydraulic oil pressure	-12.69	-12.55	-12.75	-0.020
C	Sensor distance	-12.97	-13.36	-11.66	-1.70

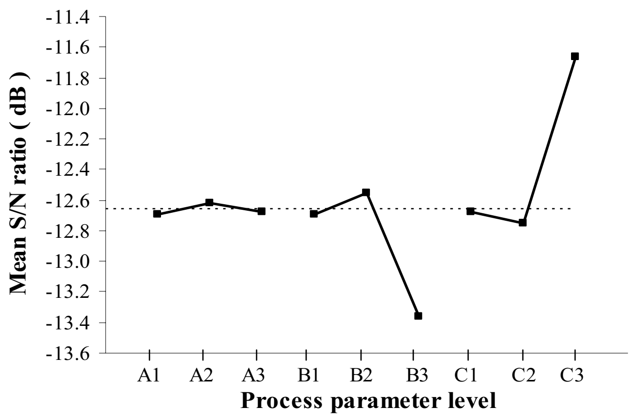

Figure 2: S/N Ratio

Statistically, there is a tool called *F* test to see which process parameters have significant effect on the quality characteristic. For performing the *F* test, the mean of squared deviations SS_m due to each process parameter needs to be calculated. The mean of squared deviations SS_m is equal to the sum of squared deviations SS_d divided by the number of degrees of freedom associated with the process parameter. Then, the *F* value for each process parameter is simply the ratio of the mean of squared deviations SS_m to the mean of squared error SS_e. Usually, when $F > 4$, it means that the change of the process parameter has significant effect on the quality characteristic [6]. Table 7 shows the results of ANOVA for the outer diameter. It can be seen from this table that the water pressure is the highly significant process parameter affecting the outer diameter of the hose pipe. Therefore, based on the S/N and ANOVA analyses, the optimal process parameters are the water pressure at level 3, the hydraulic oil pressure at level 3, and the sensor distance at level 2. However, the most significant process parameter contributing maximum to the quality characteristic i.e. outer diameter is water pressure (97.67%). Table 8 shows the results of ANOVA for pitch of the hose. It can be observed from this table that the sensor distance is the highly significant parameter affecting the pitch of the convolutions of the hose pipe with a maximum percentage contribution of 97.65%. The optimal process parameters for pitch are the water pressure at level 2, the hydraulic oil pressure at level 2, and the sensor distance at level 3.

4.4 Confirmation tests

Once the optimal level of the process parameters has been selected, the final step is to predict and verify the quality characteristic using the optimum level of the parameters. The estimated S/N ratio $\hat{\eta}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o} (\overline{\eta}_i - \eta_m) \quad (5)$$

where η_m is the total mean S/N ratio, $\overline{\eta}_i$ is the mean S/N ratio at the optimal level, and *o* is the number of the main design parameters that affect the quality characteristic. The estimated S/N ratio using the optimal process parameters for the outer diameter as well as pitch can then be obtained and the corresponding outer diameter and pitch can also be calculated by using Eqs. (1), (2) and (3). Table 9and 10 shows the comparison of the predicted outer diameter with the actual outer diameter and pitch using the optimal process parameters, where a predicted outer diameter consistent with the actual outer diameter is noted. Thus, the experiment results confirm the prior design and analysis for optimizing the process parameters

Table 7: Results of analysis of variance (ANOVA) for outer diameter

Symbol	Process parameter	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)	P-Value
A	Water pressure	2	0.5958	0.2979	152.76	97.67	0.0065
B	Hydraulic oil Pressure	2	0.0052	0.0026	1.33	0.85	0.4292
C	Sensor Distance	2	0.0051	0.0026	1.3076	0.84	0.4334
Error		2	0.0039	0.0019	-	0.64	-
Total		8	0.61	-	-	100	-

Table 8: Results of analysis of variance (ANOVA) for pitch of the hose

Symbol	Process parameter	Degree of freedom	Sum of squares	Mean square	F	Contribution (%)	P-Value
A	Water pressure	2	0.0147	0.0074	0.54	0.30	0.6494
B	Hydraulic oil pressure	2	0.0734	0.0367	2.72	1.49	0.2688
C	Sensor distance	2	4.7849	2.3924	177.21	97.65	0.0056
Error		2	0.027	0.0135	-	0.56	-
Total		8	4.90	-	-	100	-

Table 9: Results of the confirmation experiment for outer diameter

	Optimal cutting parameters	
	Prediction	Experiment
Level	A3B3C2	A3B3C2
Outer diameter (mm)	36.45	36
S/N ratio (dB)	31.24	31.07

Table 10: Results of the confirmation experiment for pitch

	Optimal cutting parameters	
	Prediction	Experiment
Level	A2B2C3	A2B2C3
Pitch (mm)	3.76	4.25
S/N ratio (dB)	-11.51	-13.34

5. CONCLUSIONS

The application of the Taguchi method for optimizing the parameters of hydroforming process for manufacturing of stainless steel corrugated flexible hose pipe has been presented in this paper. As shown in this study, the Taguchi method provides a systematic and efficient methodology for the optimization of the process parameters with far less effort than would be required for most optimization techniques. On the basis of the results obtained the following can be concluded:

- The optimum combination of the parameters and their levels for obtaining maximum outer diameter is A3B3C2 i.e. water pressure at 100 kg/cm^2, hydraulic oil pressure at 35 kg cm^2 and sensor distance at 4 mm.
- The percentage contribution of the water pressure is maximum i.e. 97.67% for obtaining the maximum outer diameter.
- The optimum combination of the parameters and their levels for obtaining minimum pitch is A2B2C3 i.e. water pressure at 90 kg/cm^2, hydraulic oil pressure at 30 kg cm^2 and sensor distance at 5 mm.
- The percentage contribution of the sensor distance is maximum i.e. 97.65% for getting minimum pitch of the hose.

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