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OPTIMIZATION OF TAPE WINDING PROCESS PARAMETERS TO ENHANCE THE PERFORMANCE OF SOLID ROCKET NOZZLE DIVERGENT LINERS USING TAGUCHI'S ROBUST DESIGN METHODOLOGY

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ABSTRACT

The ablative liners are used to protect the nozzle structural members from the severe thermal environment in solid rocket nozzles. The ablative divergent liners are made with carbon phenolic prepregs by tape winding process. The objective of this work is to demonstrate the optimization of process parameters of tape winding process to achieve better erosion resistance using Taguchi's robust design methodology. In this method four control factors machine speed, roller pressure, tape tension, tape temperature, were investigated for the tape winding process. The presented work was to study the cogency and acceptability of Taguchi's methodology in manufacturing of ablative divergent liners. The quality characteristic identified was erosion rate.

Experiments carried out using L'_{16} Orthogonal array with four different levels of control factors. The test results were analyzed using smaller the better criteria for S/N ratio in order to optimize the process. The experimental results were analyzed conformed and successfully used to achieve the minimum erosion rate of the ablative liners. The enhancement in performance of the ablative liners were observed by carrying out the oxy acetylene tests. The influence of erosion rate on the performance of ablative liners was verified by ground firing test.

Keywords: *Ablative Liners, Carbon Fabric, Phenolic Resin, Prepreg, Erosion Rate, Taguchi's Robust Design Methodology, Orthogonal Array.*

1. Introduction

The performance of ablative liners is influenced by the erosion rate. The divergent liners are manufactured by the tape winding process. The erosion rate is the importance charactersitic of ablative liners.

Robust design is an engineering methodology for improving productivity during design and development so that high quality products can be produced at low cost Robust design is based on the principle of optimization, which uses a mathematical tool called orthogonal Array to study a large number of decision variables with a small number of experiments.

It also uses a new measure of quality called Signal-to Noise (S/N) Ratio to predict the quality. The fundamental principal of robust design is to improve the quality of a product by minimizing the effects of causes of variations without eliminating the causes. This is achieved by optimizing the product and process designs to make the performance insensitive to the various causes of variations [1].

Taguchi's quality improvement technique was utilized for efficient characterization of tape winding process combined with statistical analysis. The robust design method was applied to the development of ablative liners for improving its performance by finding and utilizing the optimum set of tape winding process parameters.

Level Number	Machine Speed rpm (A)	Tape Tension Kg (B)	Roller Pressure Bar (C)	Tape Temperature °C (D)
1	0.5	2	10	80
2	1	4	12	85
3	1.5	6	15	90

2. Quality Characteristics and Objective Function

The ablative liners require minimum erosion rate for improved performance in the nozzle. This

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requires tight control of process parameters like machine speed, tape tension, pressure applied on the mandrel and tape temperature during tape winding of divergent liners of nozzle. Hence the quality characteristic chosen for this is erosion rate. There are three types of quality characteristics in Taguchi methodology namely smaller-the better, larger-the-better, and nominal-the-best. Since the requirement is to reduce the erosion rate to improve the performance of ablative liners in solid rocket nozzle, the objective function selected and implemented is smaller-the-better [2].

S/N ratio (η) = -10 x log $_{10}$ (mean squares of erosion rate)

3. Control Factors and their Levels

A total of four tape winding parameters with four levels were chosen as the control factors such that the levels are sufficiently far apart so that they cover wide range. The four control factors selected are Machine speed (A), Tape tension (B), Pressure applied(C), Tape temperature(D) as they can potentially affect the erosion rate of ablative liners. The uncontrolled noise factors considered in this study as per attributes of Taguchi's parameter design is erosion rate measurement on different laminates [3]. The control factors and their alternative levels are listed in Table 1.

Table 1. Control Factors and Levels

Level Number	Machine Speed rpm (A)	Tape Tension Kg (B)	Roller Pressure Bar (C)	Tape Temperature °C (D)
1	0.5	2	10	80
2	1	4	12	85
3	1.5	6	15	90

4. Selection of Orthogonal Array(OA)

The four control factors with three levels will give 9 degrees of freedom of factor which require a minimum number of thirteen experiments to be conducted. The nearest OA fulfilling this condition is chosen as $L_9(3^4)$ from the 18 basic types of standard orthogonal arrays and it can accommodate a maximum four number of control factors each at three levels with 9 number of experiments. Here the requirement is to accommodate four control factors at three levels. Each experiment had four data collection a total of 36 data values were collected. The layout of $L_9(3^4)$ Orthogonal Array and factor assignment is given in Table 2.

Table 2. Experimental design using standard L_9 (3^4) OA

Exp	Columns			
No.	A	B	C	D
1	0.5	2	10	80
2	0.5	4	12	85
3	0.5	6	15	90
4	1	2	12	90
5	1	4	15	80
6	1	6	10	85
7	1.5	2	15	85
8	1.5	4	10	90
9	1.5	6	12	80

5. Conducting the Experiments

The Tape Winding of divergent liner experiment was conducted on tape winding machine. Experiments were carried out using carbon phenolic prerpeg tape by winding on mandrel as shown in Figure1.

The tape winding operation was carried out on mandrel using tape winding machine and the component is cured in autoclave. The divergent liner sample is made and the four pieces were cut from the liner and subjected to oxy acetylene test as shown in Figure 2. and the erosion rate is reported.

The experimental set-up having a provision of variations in the process parameters as given in Table 2. The erosion rate was measured using oxy- acetylene torch test.

Four samples from the laminate was taken for erosion rate measurement and S/N ratio computed for each of the 9 trials are tabulated in Table 3.

Fig. 1 Tape winding of Divergent Liner

Table 3. Experimental results for Erosion rate and S/N Ratio

Exp No.	Erosion rate (ER i,j) j=1,2,3,4				Average Value	Square	S/N Ratio (ŋ)
	1	2	3	4	y_i	y_i^2	$-10 \log_{10} (y_i^2)$
1	0.31	0.32	0.31	0.33	0.3175	0.10080625	9.96512541
2	0.29	0.28	0.27	0.29	0.2825	0.07980625	10.979631
3	0.25	0.26	0.25	0.27	0.2575	0.06630625	11.7844553
4	0.29	0.31	0.3	0.32	0.305	0.093025	10.3140032
5	0.25	0.26	0.27	0.26	0.26	0.0676	11.700533
6	0.3	0.29	0.3	0.31	0.3	0.09	10.4575749
7	0.28	0.27	0.28	0.27	0.275	0.075625	11.2133461
8	0.31	0.29	0.3	0.29	0.2975	0.08850625	10.5302606
9	0.27	0.24	0.25	0.26	0.255	0.065025	11.8691964
					0.2833	0.7267	10.9793473

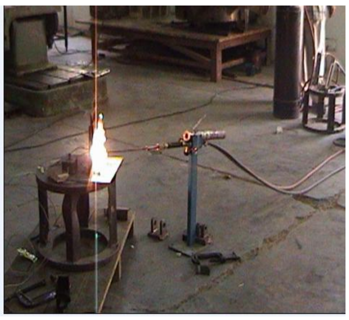

Fig. 2 Oxy-Aceytene test set up

6. Construction of Analysis of Variance

The process parameters that are significantly affecting the quality characteristic erosion rate are determined by using analysis of variance (ANOVA) [4]. The average of the first experiment yi is 0.3175 and the overall experimental average Y is 0.2833

The F-ratio is calculated by dividing the mean sum of squares by the error sum of squares. The F-ratio from the table for combination $F_{0.1, 2, 27}$ is 2.51 for all factors [5]. Comparing the value of F-ratio, the calculated F_C is greater than the tabulated F_T value ($F_{calculated} > F_{0.1, 2, 27}$). This concludes that the factors selected are significant for the process. The percent contribution of the various sources were estimated by calculating pure sum of squared and divided by the total sum of squares.

The analysis of variance only shows if the factors are significant or not, but in engineering sense it is not useful. In order to avoid over estimation, it is recommended that use of only half of the number of factors should be considered. So out of the total number of factors two are pooled for better understanding of the results. In this one column called pool and one row called pooled error are introduced in the analysis of variance table. Initially poling starts with the least variance factor, in this case, that is error. So move values of error rows into pooled error row. Next pooling of lowest mean variance factor i.e Tape temperature had to be pooled, The results of the calculations are used to draw the analysis of variance along with pooling of error and ANOVA after pooling is shown in the Table.5 and Table.6 respectively.

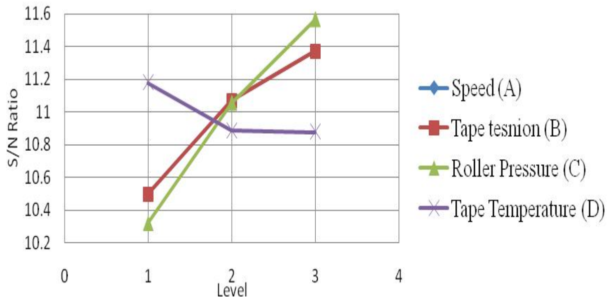

Fig. 3 Response graph of control factors

7. Selection of Optimum set of Conditions

To find the optimum set of conditions, the individual level average of S/N ratios for each factor is calculated and tabulated in Table 4.

Table. 4 Summary of S/N Ratio

Factor	Level 1	Level 2	Level 3
Machine Speed (A)	**10.9097**	**10.824**	**11.2042**
Tape Tension(B)	10.4974	11.0701	11.3704
Roller Pressure (C)	10.3176	11.0542	11.5661
Tape Temp. (D)	11.1782	10.8835	10.8762

The response graph having factor levels plotted on X-axis and S/N ratio on Y-axis is shown in Figure 3. The objective is to maximize the S/N ratio; hence accordingly maximum S/N ratio values are selected. The best condition for Machine Speed factor is level 3 (1.5 rpm) for Tape Tension is level 3 (6 Kg), for Roller Pressure is level 3 (15 Bar) and for Tape Temperature is level 1 (80^{o}C)

Thus the optimum conditions resulted is A3-B3-C3-D1 combination.

Table 5. Analysis of variance with pooling of error

Factor	SS	DOF	MSS(Mq)	F-Ratio Data	F-Ratio Table	$F_{data}> F_{table}$	SS'	ρ %
Speed	0.0011	2	0.000525	5.451923077	2.51	yes	0.000857	04.4196
Tension	0.005	2	0.0025083	26.04807692	2.51	yes	0.004824	24.8663
Pressure	0.0101	2	0.0050583	52.52884615	2.51	yes	0.009924	51.1550
Temperature	0.0006	2	0.0003083	3.201923077	2.51	yes	0.000424	02.1859
Error	0.0026	27	9.63E-05	1			0.003370	17.3730
St	0.0194	35	0.0005543				0.0194	100
Mean	2.89	1	2.89					
ST	2.9094	36	0.0808167					

Table 6. Analysis of variance after pooling

Factor	SS	DOF	MSS(Mq)	F-Ratio Data	SS'	ρ %	Pool
Speed	0.0011	2	0.00052	4.73316	0.00082	4.26887	
Tension	0.005	2	0.00250	22.6139	0.00479	24.7156	
Pressure	0.0101	2	0.00505	45.6036	0.00989	51.0042	
Temperature	0.0006	2	0.00030				Yes
Error	0.0026	27	9.63E-05				Yes
Pooled Error	0.0032	29	0.00011	1	0.00388	20.0112	
St	0.0194	35	0.00055		0.0194	100	
Mean	2.89	1	2.89				
ST	2.9094	36	0.0808				

8. Prediction of process average for optimum condition

The optimum condition determined from the orthogonal array experiment was used to predict the anticipated process average ŋ predicted. This was calculated by summing the effects of factor levels in the optimum condition using following equation

$$ŋ_{\text{predicted.}} = A3+B3+C3+D1-3Y$$

The predicted S/N ratio obtained is 12.381

9. Performing Verification Experiment

Verification test was carried out with optimum set of conditions to conform the predicted results. In this final step the laminate is manufactured with optimum set of conditions. The erosion rate at four different locations were recorded 0.26, 0.28,0.25,0.23. The average of these value is 0.2525, which results in 11.95. It is found that the S/N ratio value of verification test is closer to the predicted value of 12.381. As the conformation and projected improvements matched, suggested optimum conditions can be adopted.

10. Results and Discussions

1) Taguchi's Robust Design Methodology has been successfully implemented to identify the optimum settings for process parameters in order to minimize erosion rate of nozzle ablative liners for its performance enhancement. After analysis of data from the robust design experiments, the optimum process parameters found were validated by conducting conformation test, which concluded that the results were within the acceptable limits of the predicted value and can be implemented in the real time applications. This also reduced the erosion rate to 0.2525 which is better than the initial value 0.28 and improved S/N ratio from 10.99 to 11.95

2) This experimental work required 9 experiments for effective implementation of Taguchi's robust design methodology compared to 81 experiments by conventional method which in turn reduced the development time as well as the experimental cost.

3) The optimum values of process parameters and their percentage of contributions towards erosion rate is shown in Table 7. From the tabulated value it is observed that the influence of Tape tension and Roller pressure are predominant compared to machine speed and tape temperature. This provides the importance of each factor and the factors to be observed carefully during manufacturing process.

Table 7. Optimum values and % Contribution

Process Parameter	**Optimum Value**	**% Contribution**
Machine Speed (A)	A3 (1.5 rpm)	04.4196
Tape Tension (B)	B3 (6 Kg)	24.8663
Roller Pressure (C)	C3 (15 Bar)	51.1550
Tape Temp. (D)	D1 (80^{o}C)	02.1859
Error		17.3730

4) Four laminates were manufactured using the values of three experiments from OA table and one using the optimum process values resulted from experiment as given in Table 8. The laminates were tested in oxy acetylene torch test for erosion rate measurement. The laminate manufactured with the optimum conditions yielded good results compared to the other four laminates. This shows that the effect of process parameters on erosion rate is considerable.

Table 8.Process parameters used for manufacturing of Laminates

Laminate No.	**Machine Speed (A) rpm**	**Tape Tension (B) kg**	**Roller Pressure (C) bar**	**Tape Temp (D) ^{o}C**
1	0.5	2	10	80
2	1	4	12	85
3	1.5	6	15	90
4	1.5	6	15	80

5) By using the optimum process parameters the nozzle divergent liners are manufactured and the nozzle is assembled to solid rocket motor and subjected to ground firing test. The erosion rate measured after the ground firing test measured are 0.25 and 0.26 in two consecutive tests, which are in very close agreement with the predictions.

11. Conclusions

The objective of this work which is to find out the optimum set of control factors for the manufacturing of nozzle ablative liners using Taguchi's Robust Design Methodology is fully met. This combination was successfully tested for its validity. Using ANOVA, the individual factor effects were also found out and pooling of the less significant factors concluded that the effect of Tape Tension and Roller Pressure are more on the quality characteristic. With this optimum set of control factors reduced the erosion rate on the nozzle ablative lines. The Improved nozzle ablative liners have enhanced the nozzle performance.

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