OPTIMIZATION OF COMPRESSION MOULDING PROCESS PARAMETERS TO ENHANCE THE PERFORMANCE OF SOLID ROCKET NOZZLE CONVERGENT LINERS USING TAGUCHI'S ROBUST DESIGN METHODOLOGY

Dr. N. Kishore Nath

Scientist-F, Advanced Systems Laboratory, Kanchanbagh, Hyderabad
Email:- lca_droptank @yahoo.com

Abstract: *The ablative liners are used to protect the nozzle structural members from the severe thermal environment in solid rocket nozzles. The ablative liners are made with carbon phenolic prepreg flakes by compression moulding process. The objective of this work is to demonstrate the optimization of process parameters of compression moulding process to achieve better erosion resistance using Taguchi's robust design methodology. In this method four control factors Pressure applied, Charge Temperature, Tool Pre heat Temperature, Number of charges, were investigated for the compression moulding process. The presented work was to study the cogency and acceptability of Taguchi's methodology in manufacturing of ablative liners. The quality characteristic identified was erosion rate. Experiments carried out using* L'_9 *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 convergent liners are manufactured by the compression moulding process. The erosion rate is the importance characteristic 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 compression moulding process combined with statistical analysis. The robust design method was applied to the development of ablative liners for improving is performance by finding and utilizing the optimum set of compression moulding process parameters.

2. QUALITY CHARACTERISTICS AND OBJECTIVE FUNCTION

The ablative liners require minimum erosion rate for improved performance in the nozzle. This requires tight control of process parameters like Pressure applied (A), Charge Temperature (B), Tool Pre heat Temperature (C), Number of charges (D) for compression moulding processto realize convergent liners. 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 Compression Moulding 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 Pressure applied (A), Charge Temperature (B), Tool Pre heat Temperature (C), Number of charges (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	Pressure (Bar) (A)	Charge Temp (°C) (B)	Tool Preheat Temp (°C) (C)	No. of charges (D)
1	75	160	80	2
2	80	165	90	3
3	85	170	95	4

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. 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 OA $L_9(3^4)$

Experiment	Column			
No.	A	B	C	D
1	75	160	80	2
2	75	165	90	3
3	75	170	95	4
4	80	160	90	4
5	80	165	95	2
6	80	170	80	3
7	85	160	95	3
8	85	165	80	4
9	85	170	90	2

5. CONDUCTING THE EXPERIMENTS

The Compression moulding operation was carried out on Match-die moulding tool using Hydraulic press with built in platen heaters and the laminate is cured as shown in Fig. 1. The Laminate is made and the four pieces were cut from the laminate and subjected to oxy acetylene test as shown in Fig. 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. was carried out in Hydraulic press using

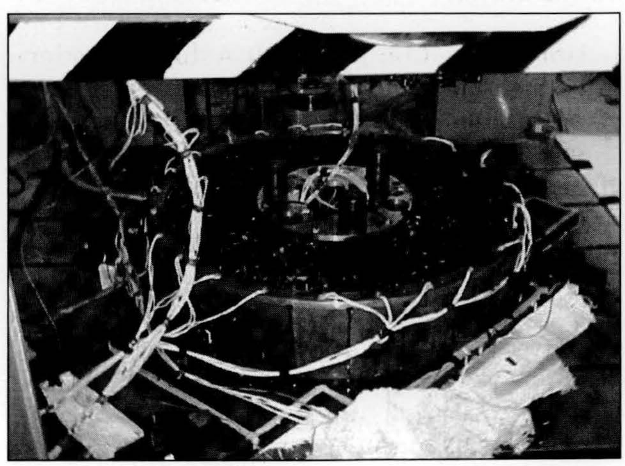

Fig 1. Compression Moulding Process

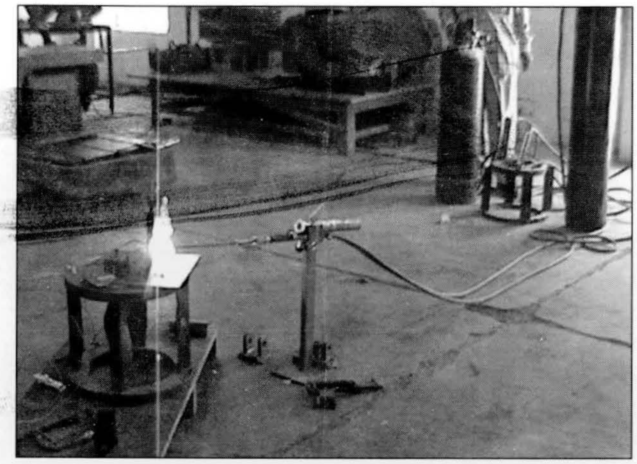

Fig 2. Oxy-Acetylene Test Set Up

match die moulding tool. 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.

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 0.305 and the overall experimental average Y is 0.2716

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 squares 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 Tool 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.

7. SELECTION OF OPTIMUM SET OF CONDITIONS

To find the optimum set of conditions, the individual level average of S/N ratio for each

Table 3: Experimental Results for Erosion Rate and S/N Ratio

Sl. No.	Erosion rate (ER i, j) j = 1, 2, 3, 4				Avg. Value	Square	S/N Ratio (η)
	1	2	3	4	yi	yi^2	$-10\log_{10} yi^2$
1	0.31	0.3	0.29	0.32	0.305	0.093025	10.3140032
2	0.28	0.26	0.27	0.28	0.2725	0.0742562	11.2926699
3	0.26	0.25	0.24	0.25	0.25	0.0625	12.0411998
4	0.22	0.24	0.23	0.24	0.2325	0.0540562	12.6715409
5	0.31	0.3	0.29	0.29	0.2975	0.0885062	10.5302606
6	0.24	0.24	0.22	0.23	0.2325	0.0540562	12.6715409
7	0.28	0.29	0.27	0.28	0.28	0.0784	11.0568394
8	0.27	0.28	0.29	0.27	0.2775	0.0770062	11.1347403
9	0.31	0.29	0.3	0.29	0.2975	0.0885062	10.5302606
					0.2716	0.6703125	11.3603395

factor is calculated and tabulated in Table 4.

Table 4: Summary of S/N Ratio

Factor	Level 1	Level 2	Level 3
Pressure Applied (A)	11.2159	**11.9577**	10.9072
Charge Temp(B)	11.3474	10.9858	**11.7476**
Tool Temp (C)	11.3734	**11.4981**	11.2094
Number of charges (D)	10.4581	11.6736	**11.9491**

The response graph having factor levels plotted on X-axis and S/N ratio on Y-axis is shown in Fig. 3. The objective is to maximize the S/N ratio, hence accordingly maximum S/N ratio values are selected. The best condition for Pressure applied factor is level 4 (80 Bar) for Charge temperature is level 3 (170°C) for Tool Temperature is level 2 (90°C) and for Number of charges is level 3 (4)

Thus the optimum conditions resulted is A2-B3-C2-D3 combination.

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 $\eta_{predicted.}$ This was calculated by summing the effects of factor levels in the optimum condition using following equation

$$\eta_{predicted.} = A2+B3+C2+D3-3Y$$

The predicted S/N ratio obtained is 13.0717

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 0.23,0.24,0.25,0.24. The average of these value is 0.24, which results in 12.396. It is found that the S/N ratio value of verification test is closer to the predicted value of 13.072. 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 0.24 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

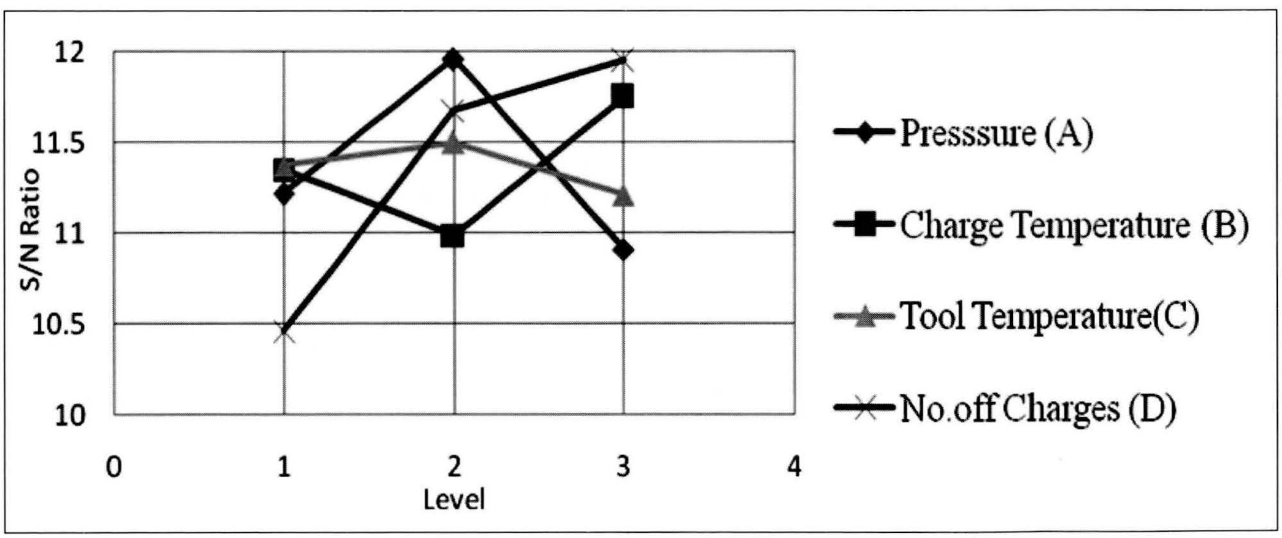

Fig 3. Response Graph of Control Factors

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 %
Pressure	0.006017	2	0.0030083	31.85294118	2.51	yes	0.00582	21.6646
Charge Temp	0.00305	2	0.001525	16.14705882	2.51	yes	0.00286	10.6361
Tool Temp	0.000417	2	0.0002083	2.205882353	2.51	no	0.00022	0.84675
No.of charges	0.014867	2	0.0074333	78.70588235	2.51	yes	0.01467	54.5642
Error	0.00255	27	9.444E-05	1			0.00330	12.2883
St	0.0269	35	0.0007686				0.0269	100
Mean	2.6569	1	2.6569					
ST	2.6838	36	0.07455					

Table 6: Analysis of Variance after Pooling

Factor	SS	DOF	MSS(Mq)	F-Ratio Data	SS'	ρ %	Pool
Pressure	0.006017	2	0.003008	29.4073	0.00581	21.6062	
Charge Temp	0.00305	2	0.001525	14.9073	0.00284	10.5777	
Tool Temp	0.000417	2	0.000208				yes
No. of charges	0.014867	2	0.007433	72.6629	0.01466	54.5058	
Error	0.00255	27	9.444E-05				yes
Pooled Error	0.002967	29	0.000102	1	0.00358	13.3102	
St	0.0269	35	0.000768		0.0269	100	
Mean	2.6569	1	2.6569				
ST	2.6838	36	0.07455				

Table 7: Optimum values and % Contribution

Process Parameter	Optimum Value	% Contribution
Pressure Applied (A)	A2 (80 Bar)	21.6646
Charge Temp (B)	B3 (170°C)	10.6361
Tool Preheat Temp (C)	C2 (90°C)	0.84675
No. of charges (D)	D3 (4)	54.5642
Error		12.2883

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 Pressure applied on the tool and Number of charges are predominant compared to charge temperature and Tool preheat temperature. This provides the importance of each factor

Table 8: Process Parameters used for Manufacturing of Laminates

Laminate No.	Pressure (Bar)	Charge Temp (°C)	Tool Preheat Temp (°C)	No. of charges
	(A)	(B)	(C)	(D)
1	75	160	80	2
2	80	165	90	3
3	85	170	95	4
4	80	170	90	4

and the factors to be observed carefully during manufacturing process.

4) Five laminates were manufactured using the values of four 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 as shown in figure. This shows that the effect of process parameters on erosion rate is considerable.

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 combinations 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 Pressure applied on the tool and Number of charges 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 has enhanced the nozzle performance.

12. REFERENCES

1. Taguchi, Genichi: Subir Chowdhury Shin Taguchi 'Robust Engineering', McGraw-Hill, 2000.
2. Phadke's, Madhav S: 'Quality Engineering Using Robust Design', Prentice Hall, Englewood Cliff, NJ, November 1989.
3. Ross, Phillip J: 'Taguchi Techniques for Quality Engineering', Tata McGraw-Hill, New Delhi-2005.
4. Bagchi, Tapan P: 'Taguchi Methods Explained: Practical Steps to Robust Design', Prentice Hall of India, New Delhi, 1993.
5. Petruccelli, Joseph D; Nandram, Balgobin; Chen, Minghui: 'Applied Statistis for Engineers and scientists', Prentice Hall, New Jersey, 1999.
6. Hall, William B: 'Standardization of the Carbon Phenolic materials and processes, vol. 1: Experimental studies', Report NASA-CR-183226, pages 180, Acc No. 89N10127, 1988.
7. Ogasawara, Toshio; Ishikawa, Takashi; Yamada, Tetsuya, Yokota, Rikio; Itoh, Masayoshi; Nogi, Shigeru: Thermal Response and Ablation characteristics of Carbon fiber Reinforces composite with Novel silicon Containing polymer MSP, 'Journal of Composite Materials', vol. 36, no. 2, page 143-157, 2002.
8. Pontarolli, Marcus Luiz: Ablative carbon phenolic composites additivated with carbon nano particles, 'Master's thesis in physics and chemistry of Aerospace Materials at the Technological Institute of Aeronautics', ITA, Sao Jose dos compos, Sao Paulo State, Brazil, 2006.
9. Patton, RD; Jr, Pittman, CU; Wang, L; Hill, JR; Day, A: Ablation, Mechanical and Thermal Properties of Vapor Grown carbon Fiber/ Phenolic Matrix Composites, 'International Journal of Composites: Part A', vol. 33, 243-251, 2002 ◘

Dr. N. Kishore Nath, joined CPDC, DRDO in 1996 working as a Scientist-F and Deputy Project Director AGNI-4 in Advanced Systems Laboratory (ASL), DRDO Hyderabad.

His research interests are Design and Development of Advanced Composite Products, flame deflector, fuel droptank, flex nozzle system, ablative liners for Aerospace Vehicles, 'Prithvi', Light Combat Aircraft TEJAS, AGNI.

He is recipient of DRDO Laboratory Scientist of the year award 2003. ISAMPE Outstanding Design and Process Development Award 2010. DRDO Award for Performance Excellence 2011. He is Fellow of Institution of Engineers India (IEI), Society for Manufacturing Engineers, Indian Society of Mechanical Engineers. He is Life member in Ae.S.I., ASI, SSI, ISTE, HEMSI, INSARMS, ISAMPE, ISCA, ICS, HMA, He has published 7 papers in International/National Journals, and presented 25 Papers in International/ National Conferences.

(E-Mail: lca_droptank@yahoo.com)