Design Parameter Optimization to Enhance Strength of Adhesively Bonded Single Lap Joint using Taguchi Methodology

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Abstract— Taguchi Method is a statistical approach to optimize the process parameters and improve the quality of components that are manufactured. The orthogonal array, signal-to-noise ratio and analysis of variance are employed to study the performance characteristics of single lap joint. Thus the objective of this work is to obtain optimal values of joining process parameters such as surface texture pattern type, adhesive thickness, adherent overlap length, concentration of surface textures for each adhesive material separately for optimizing shear stress values of the joint under same loading conditions. Since here four factors at three levels i.e. 34 experiments were taken. Average Signal to Noise Ratio (SNR) for each factor at different level is determined. Analysis of variance (ANOVA) is performed for percentage of contribution of different factor. The factor that has much influence on response variable is identified through the percentage of contribution. The factor, which has more percentage of contribution, is the significant factor.

Key words: Lap Joint, S/N Ratio, Taguchi, ANOVA

I. INTRODUCTION

Dr. Taguchi started to develop new methods to optimize the process of engineering experimentation. He developed techniques which are now known as the Taguchi methods. Taguchi believed that the better way to improve quality was to design and build it into the product. Quality has been traditionally defined as "conformance to specifications" or "fitness for use". These quality definitions focus only on conformance and the consequent scrap and rework cost. Roy[34] discussed the Taguchi approach to quality which focuses on designing quality into the design stage. By addressing quality issues at the design stage, this methodology reduces development lead times and quality costs. The Taguchi method of off-line quality control encompasses all stage of product/process development however the key element for achieving high quality and low cost is parameter design. Through parameter design optimal levels of process parameters can be determined. Taguchi method is used where number of factors and levels are large, to minimize the number of experiments and to find the improving optimum solution.

Several authors have worked on adhesive bonded joints and their strength optimization, Lucas F.M. Da silva et al.[1] has studied that the influence of the macroscopic state of the substrate surface on the strength of adhesive joints. D.M.Gleich et al.[2] has studied, the effect of bond-line thickness on strength of joint. E.F. Karachalios et al. [3] has studied, Single lap joints in many different geometric and material configurations were analysed using finite element analysis and tested in tension.

II. STEPS OF TAGUCHI METHOD FOR SINGLE LAP JOINT DESIGN

A. Problem Definition

The effect of various factors on strength of adhesively bonded joint is identified and it is found that the best combination of parameter can lead to strength improvisation of adhesively bonded joint.

B. Identification of Noise Factors

Noise factors are those parameters which are either uncontrollable or are too expensive to control. Noise factors include variations in environmental operating conditions.

C. Selection of Process Parameter and Their Levels

After going through extensive studies on the adhesive joint and the parameters which affect the strength of joint following parameters are chosen:

1) Overlap length (mm)
2) Surface texture
3) Number of punches per unit width
4) Adhesive thickness(mm)

As this research work is limited to two type of adhesive material, the Taguchi technique is studied for both the type separately.

Factor	Designation	Level		
		Level 1	Level 2	Level 3
Overlap length (mm)	A	20	25	30
Surface texture	B	Cross rectangle (+)	Rectangle (-)	Cone
Number of punches per unit width	C	3	4	5
Adhesive thickness(mm)	D	2	2.5	3

Table 1: Process parameters with their levels

D. Selection of Orthogonal Array

For four process parameters with three levels of each, standard orthogonal array available is L9.

Trial number/ test number	A	B	C	D
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	2	1	2	3
5.	2	2	3	1
6.	2	3	1	2
7.	3	1	3	2
8.	3	2	1	3

9.	3	3	2	1

Table 2: L9 Orthogonal Array

E. Numerical Analysis to Find Result of Nine Combination of L9 Orthogonal Array

An UTM is chosen to test the specimen experimentally but to avoid cost of manufacturing and testing here in this work numerical analysis using computer software (ANSYS 16) is use to analyze the effect of design factors on strength of joint. After the numerical analysis the best combination is to be selected from Taguchi and ANOVA analysis. As per Standard orthogonal array nine trials were taken for each adhesive and results of nine tabulated as below.

Trial number/ test number	A	B	C	D	Shear stress (MPa)
1.	20	Cross rectangle	3	2	17.84
2.	20	Rectangle	4	2.5	19.26
3.	20	Cone	5	3	20.39
4.	25	Cross rectangle	4	3	21.54
5.	25	Rectangle	5	2	17.21
6.	25	Cone	3	2.5	20.08
7.	30	Cross rectangle	5	2.5	19.62
8.	30	Rectangle	3	3	21.14
9.	30	Cone	4	2	18.31

Table 3: Summarizing the data of nine trials for araldite 2015

Trial number/ test number	A	B	C	D	Shear stress (MPa)
1.	20	Cross rectangle	3	2	19.48
2.	20	Rectangle	4	2.5	22.62
3.	20	Cone	5	3	23.93
4.	25	Cross rectangle	4	3	24.45
5.	25	Rectangle	5	2	20.28
6.	25	Cone	3	2.5	24.43
7.	30	Cross rectangle	5	2.5	24.51
8.	30	Rectangle	3	3	23.96
9.	30	Cone	4	2	21.18

Table 4: Summarizing the data of nine trials for Loctite E-30HV

Since adhesively bonded joint failed in shear, the shear stress is taken as comparison parameter. Above two tables summarizes the results for araldite 2015 and Loctite E 30 HV respectively.

F. S/N Calculation

After the experiments have been conducted, the optimal test parameter configuration within the experiment design must be determined. To analyze the results, the Taguchi method uses a statistical measure of performance called signal to noise (S/N) ratio borrowed from electrical control theory. The S/N ratio developed by Dr. Taguchi is a performance measure to choose control levels that best cope with noise. The S/N ratio takes both the mean and the variability into account. In its simplest form, the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The S/N equation depends on the criterion for the quality characteristic to be optimized. While there are many different possible S/N ratios, three of them are considered standard and are generally applicable in the situations; Biggest-Is-best quality characteristic (strength, yield), Smallest-is-best quality characteristic (contamination, stresses), and Nominal-is-best quality characteristic (dimension).

As an evaluation tool for determining the robustness of the design, 'signal to noise' ratio (SNR) is the most important component of the factor Taguchi method, the term 'signal' represents the desirable target and 'noise' represents the undesirable value. Since in case of adhesive joints, strength of joint is evaluated according to shear stress developed. The smallest is better quality characteristic is chosen in SNR calculation. Factor level is calculated using the following formula.

$$\frac{S}{N_L} = -10\log_{10}\left[\sum(y^2)/n\right]$$

$$\frac{S}{N_L} = -10\log_{10}\left[\sum\frac{(17.84^2 + 19.26^2 + 20.39^2)}{3}\right]$$

$$\frac{S}{N_L} = -25.64$$

Where,
S/N is the average SNR
'n' is the number of experiment conducted at level 'i'
'y' is the shear stress

A robust system will have a low SNR. SNR should be as small as possible for higher values of improved strength. Following table shows the average SNR for each at the signal level and factors respectively.

Level	Overlap length	Surface Texture	Number of punches per unit width	Adhesive Thickness
1	-25.64	-25.64	-25.60	-26.14
2	-25.54	-25.45	-25.47	-25.79
3	-26.14	-26.24	-26.25	-25.39
Delta	0.6	0.79	0.78	0.75
Rank	4	1	2	3

Table 5: Average SNR values and Ranking of parameter for Araldite 2015

Factor	SNR	Level	Optimum Value of Factors
A	-26.14	3	30
B	-26.24	3	CONE
C	-26.25	3	5
D	-26.14	1	2

Table 6: Design optimum values of factors for Araldite 2015

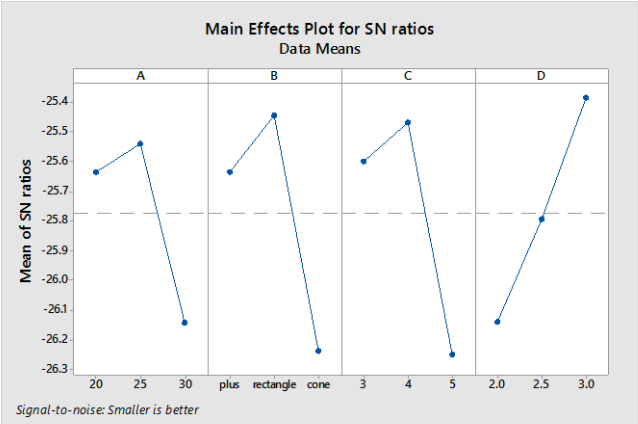

Fig. 1: Graph of SN value vs. Level for Araldite 2015

Level	Overlap length	Surface Texture	Number of punches per unit width	Adhesive Thickness
1	-26.88	-27.02	-27.05	-27.55
2	-26.81	-27.03	-26.58	-26.71
3	-27.72	-27.37	-27.78	-27.15
Delta	0.91	0.35	1.20	0.85
Rank	2	4	1	3

Δ =max-min=(-27.37)-(27.02)=0.35

Table 7: Average SNR values and Ranking of parameter for Loctite E 30 HV

FACTOR	SNR	LEVEL	OPTIMUM VALUE
A	-27.72	3	30
B	-27.37	3	CONE
C	-27.78	3	5
D	-27.55	1	2

Table 8: Design optimum values of factors for Loctite E 30 HV

Fig. 2: Graph of SN value vs. Level for Loctite E 30 HV

III. ANOVA ANALYSIS

ANOVA (Analysis of variance) is a statistical analysis tool that can be applied in conjunction with Taguchi method to experimental situations and may be used with any set of data that has some structure. ANOVA (Analysis of Variance) was developed by Sir Ronald Fisher in the 1930s as a way to interpret the results from agricultural experiments. It is not a complicated method and has a lot of mathematical beauty associated with it and is a statistically based, objective decision-making tool for detecting any differences in average performance of groups of items tested. The decision, rather than using pure judgment, takes variation into account. In statistics, analysis of variance is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are all equal. The discussion of ANOVA will start with a very simple case, no-way ANOVA, and build up to more comprehensive situations such as three-way ANOVA. ANOVA can also be applied to experimental situations utilizing orthogonal arrays, although this analysis method can be used with any set of data that has some structure. The experimental designs and subsequent analyses are intimately tied to one another. In the experimental two-way ANOVA there are two controlled parameters in the experimental situation. In two way ANOVA total variation may be decomposed into: variation due to factor A, Variation due to factor B, variation due to the interaction of factors A and B and variation due to error. After calculating the total variation from the above, number of degrees of freedom are calculated.

Analysis of variance (ANOVA) is an analytical method to square the dispersion of specific numbers. The factor that has much influence on response variable is identified through the percentage of contribution. The factor, which has more percentage of contribution, is the significant factor.

Procedure of ANOVA ANALYSIS is described as.

1) Set degrees of freedom (DOF) for each parameter.

DOF = number of levels of parameter ‘i’-1.

Total D.O.F = N-1 = 3-1 = 2

Calculation of mean square for each factor

$$MS = \frac{SS}{DOF}$$

Calculation of % contribution (P)

$$\text{Percentage contribution (\%P)} = \frac{\text{Sum of square}}{\text{Total sum of square}} = \frac{SS_A}{SSTO} \times 100$$

All the above steps in ANOVA analysis are to be done using Minitab software to minimize the computational time. After following above steps ANOVA Analysis table were obtained. Following table and graph shows the result for both araldite 2015 and Loctite E30 HV adhesive.

Factor	DF	SS	MS	F-Value	% Contribution
A	2	3.372	1.686	0.64	17.63
B	2	7.167	3.583	1.8	37.46
C	2	4.484	2.242	0.92	23.44
D	2	4.108	2.054	0.82	21.47
Total	8	19.131			100

Table 9: ANOVA analysis for Araldite 2015

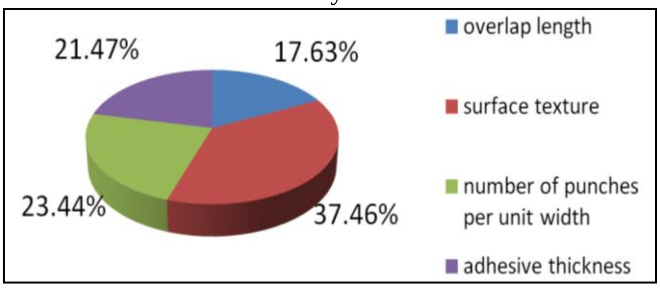

Fig. 3: Percentage contribution of each factor in strength of joint for Araldite 2015

Factor	DF	SS	MS	F-Value	% Contribution
A	2	6.807	3.403	0.79	20.75
B	2	14.24	7.122	2.3	43.41
C	2	10.23	5.114	1.36	31.17
D	2	1.533	0.7667	0.15	4.67
Total	8	32.812			100

Table 10: ANOVA analysis for Loctite E 30 HV

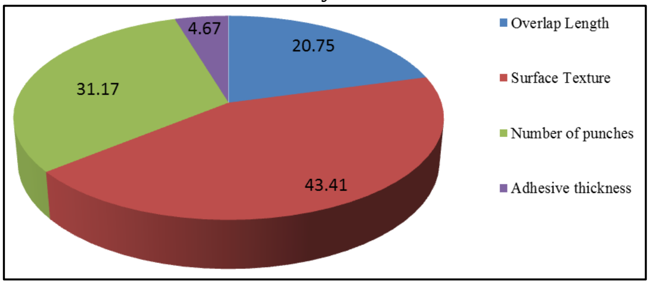

Fig. 4: Percentage contribution of each factor in strength of joint for Loctite E 30 HV

IV. Conclusion

This paper illustrates the application of the parameter design (Taguchi method) in the optimization of single lap joint design. The following conclusions can be drawn based on the above experimental results of this study:

1) Taguchi's Method of parameter design can be performed with lesser number of experimentations as compared to that of full factorial analysis and yields similar results.
2) It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for optimizing the process parameters
3) The optimized joining process parameter of adhesively bonded lap joint for adhesive Araldite 2015 and Loctite E 30 HV by Taguchi method are

Factor	Optimum Value of Factors
A Overlap length(mm)	30
B Surface texture	CONE
C Number of punches per unit width	5
D Adhesive thickness(mm)	2

4) From the ANOVA analysis the Percentage contribution of each factors in strength of joint for Araldite 2015 and Loctite E 30 HV are

Factor	% Contribution	% Contribution
A Overlap length(mm)	17.63	20.75
B Surface texture	37.46	43.41
C Number of punches per unit width	23.44	31.17
D Adhesive thickness(mm)	21.47	4.67

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