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An Investigation on Strength of Lap Joints Using Different Adhesives and Surface Texture Patterns

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ABSTRACT

Adhesively bonded joints are increasingly being used in aerospace and automotive industries. The use of adhesive bonding rather than mechanical fasteners offers the potential for reduced weight and cost. Since the joint strength is influenced by many factors such as the type of adhesive, the type of adherent, the overlap length, roughness of adherent surface and the bond line thickness, therefore, there is scope to improve the joint strength. The main objective of this work is to study the influence of the macroscopic state of the adherent surface on the strength of adhesive joints. To study the same, different types of texture are drawn on the adherent surface in CAD software. In addition to the surface texture the influence of the thickness of adhesive on the strength of single lap joints has been studied using FEA software for several adhesives. To analyse the effect of each parameter on the strength of adhesive joint a Taguchi method is applied. All the models of single lap joints will be drawn using CAD software and analysis is done in Ansys 16.0. The results coming out from numerical analysis are compared with the computerized UTM test taken under static loading.

Keywords : Adhesive bonding, FEA, overlap length, surface texture, adhesive thickness.

I. INTRODUCTION

Materials can be joined by using a variety of methods. About 60 years ago, the principle joining techniques were by mechanical fastenings (screws, rivets, bolts, etc.) or by welding, soldering and brazing. All of these methods had their own advantages and disadvantages. During the Second World War, a series of novel adhesives, developed by Dr. Norman de Bruyne at the company which became to be known as Ciba, was used for structurally bonding aircraft, such as, the de Havilland Mosquito. Since that time, enormous advances have been made in adhesive bonding technology.

Several authors have worked on adhesive bonded joints and their strength optimization, Lucas F.M. Da silva et al.[11] has studied that the influence of the macroscopic state of the substrate surface on the strength of adhesive joints. D.M.Gleich et al.[15] has studied, the effect of bond-line thickness on strength of joint. E.F. Karachalios et al. [16] has studied, Single lap joints in many different geometric and material configurations were analysed using finite element analysis and tested in tension.

In existing design of adhesive joint, two substrate objects (e.g. plates) are bonded using direct adhesive on overlap area, so that actual contact area is same as that of geometrical area and it is found from the previous research that the strength of adhesive joint directly affected by the overlap area. Hence, because of the same, the strength of adhesive joints is not fully utilized. The new research is developed in this paper by making the micro-texture pattern on substrate overlap area which lead to increased adhesion area and in addition to this other parameters are also selected so that strength of adhesive joint will improve.

II. Design of Adhesive Bonded joint

The design is mainly focused on the selection of adherent material, dimension of adhesive joint, type of adhesive material and selection of different surface texture patterns.

A. Substrate Material

The material used for the substrates was AA6082-T6 aluminum. This choice is made because; the aluminum due to its low weight and good mechanical properties is increasingly used material in aerospace and automotive industries which are among those that use adhesive techniques.

B. Adhesive Material

There are a wide variety of adhesives available with different properties that are adequate for different situations. The adhesives used for single or double lap joint of aluminum having higher strength and life and are largely used out of different types of adhesives, those are tested here and the properties of the same are as follows.

TABLE 1: MECHANICAL PROPERTIES OF ARALDITE 2015 ADHESIVE

Shear Modulus (MPa)	564
Shear strength (MPa)	17.9
Poisson's ratio	0.38
Temperature resist (^oC)	356
Shore hardness	43.9
Mixing ratio	1:1

TABLE 2: MECHANICAL PROPERTIES OF LOCTITE E-30HV ADHESIVE

Shear Modulus (MPa)	638
Shear strength (MPa)	12.6
Poisson's ratio	0.39
Temperature resist (^oC)	250
Shore hardness	85
Mixing ratio	2:1

C. Single lap joint

A wide variety of joint configurations are possible when bonding structures. The single-lap and double-lap configurations are the most commonly found in practice and are applicable for joining relatively thin adherents. Since the single-lap joint is generally the simplest and cheapest of all joints to manufacture due to its simple design and easy assembly, it was chosen for the test according to the ISO 4587 standard for the determination of tensile lap shear strength of rigid-to-rigid bonded assemblies. The joint configuration which is going to be used throughout this dissertation is as shown in figure.

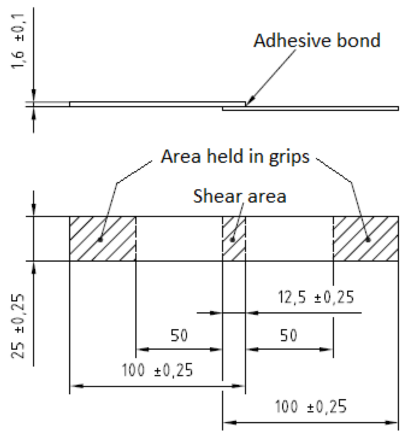
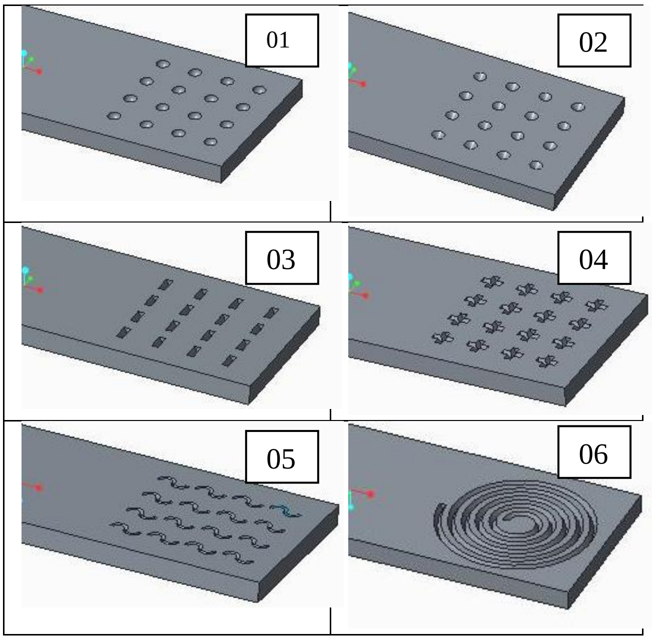


Figure 1: Joint configuration

D. CAD modal of different surface textures

The surface pattern chosen in this work are based on their manufacturing possibilities. The basic dimensions of the substrate plate are taken as per ISO 4587. All the CAD models are made in Creo parametric 2.0 and they are as shown below:



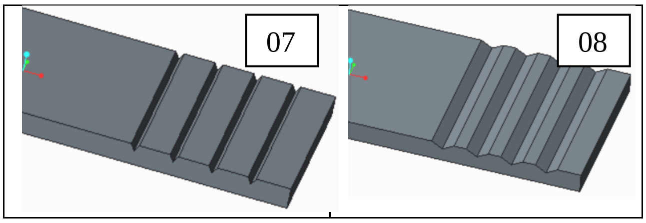


Figure 2: Surface textures 1) cup 2) cone 3) rectangle 4) cross rectangle 5) s-curve 6) spin 7) 30 deg horizontal milling 8) 60 deg horizontal milling.

III. Numerical analysis of effect of various parameter on strength of adhesive joint

The numerical analysis is divided into two parts: first part of analysis is used to select type of surface textures which influence the most and the second part will be carried out as per Taguchi orthogonal array which gave the result of effect of each parameter on joint strength.
While doing analysis on any type of assemblies it is essential to define a contact between each pair of component. There are variety of contact connections available in Ansys workbench structural module like frictional contact, bonded contact, frictionless contact etc. In this paper bonded contact is defined in between both the pair of adhesive and adherent plates.

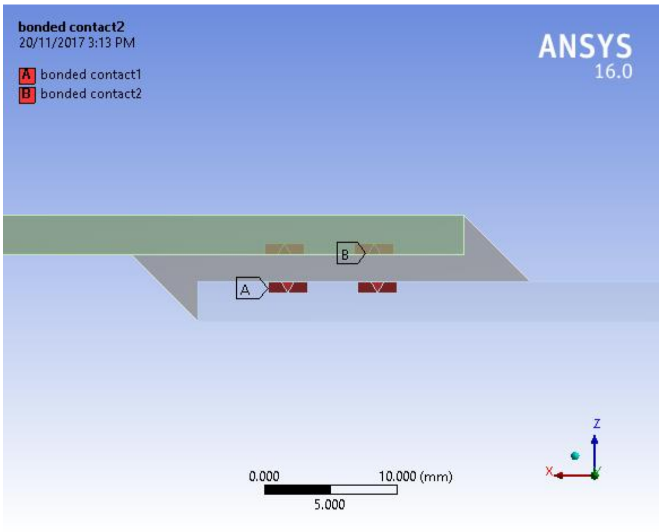


Figure 3: Contact between joint

Meshing:

Meshing is done using Hexagonal mesh with number of elements approximately of 3k and number of nodes of 4.5 k. The element size is 0.5 mm. This mesh is used as it is fine and gives least number of elements with good results. So the calculation time is reduced.

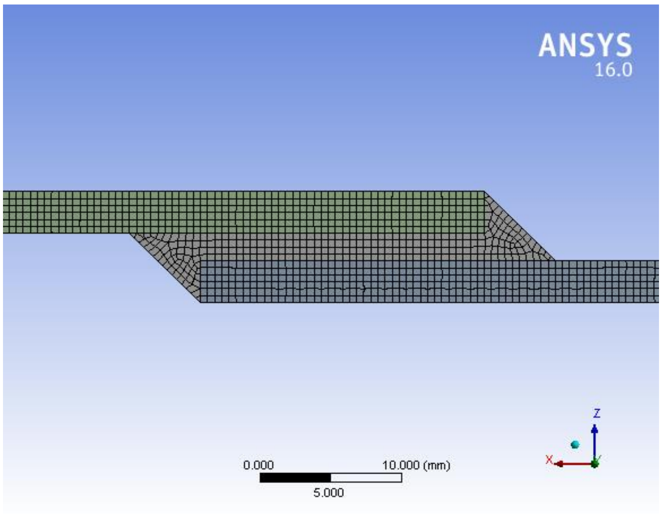


Figure 4: Meshing of adhesive joint

Boundary condition:

In this work two types of boundary constraints are apply the first one is the fixed support which is applied to the lower adherent plate and a load of 500 N which is applied to the upper adherent plate as shown in figure.

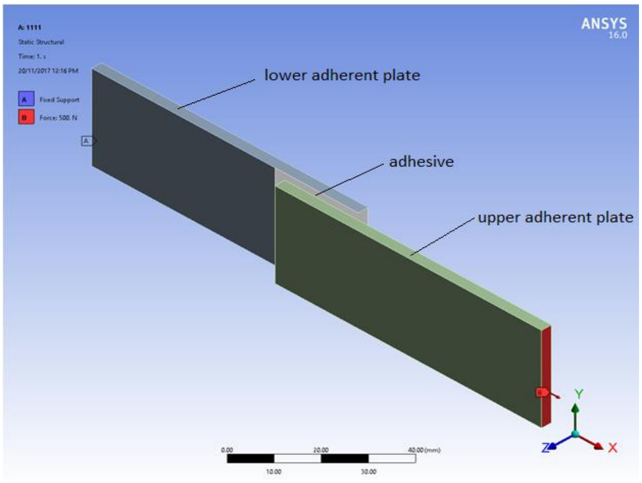


Figure 5: Boundary conditions

Analysis result:

Here a total deformation is selected for comparison of effect of surface texture on strength of adhesive joint. Following figure shows the result of total deformation of the all the combination of adhesive joint.

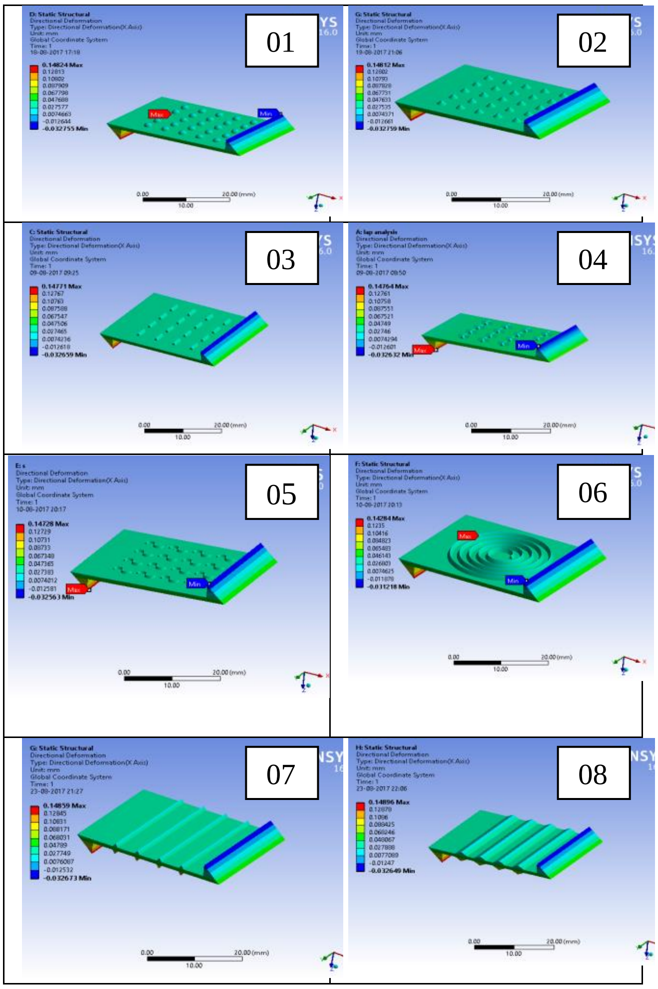


Figure 6: Total deformation for different surface texture 1) cup 2)cone 3) rectangle 4) cross rectangle 5) s-curve 6) spin 7) 30 deg horizontal milling 8) 60 deg horizontal milling.

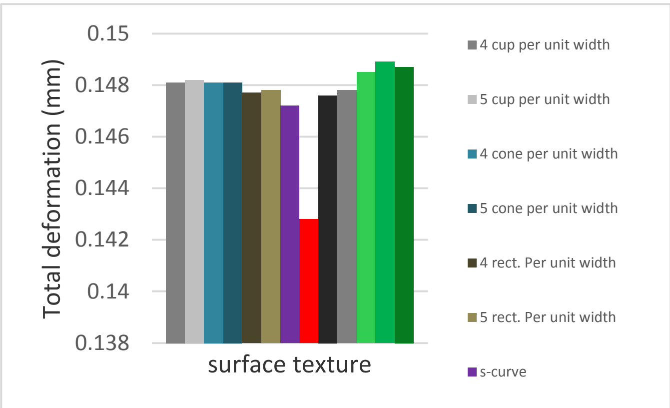


Figure 7: Comparison of all the surface texture result for total deformation.

From above analysis result it can be concluded that rather than using a straight cut of milling, it is better to use a spin or s- curve shape surface texture as it gives less deformation for the same loading and boundary conditions. But apart from using spin and s-shape surface texture here the next three textures i.e. rectangle, cross rectangle and cone are used to increased strength of single lap joint, as they are easy to manufacture.

IV. Taguchi technique for parameter selection

Taguchi method is used where number of factors and levels are large, to minimize the number of experiments and to find the optimum solution. Thus the objective of this work is to obtain optimal values of joining process parameters such as surface pattern type, adhesive thickness, adherent overlap area, concentration of surface textures and type of adhesive material for optimizing shear strength values of the joint under same loading conditions. Since here four factors at three levels i.e. 3^4 experiments were taken. As this research work is limited to two type of adhesive material, the Taguchi technique is studied for both the type separately.

TABLE 3: PROCESS PARAMETERS WITH THEIR LEVELS

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

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

TABLE 4: SUMMARIZING THE DATA OF NINE TRIALS IN L9 OA.

Trial number/ test number	A	B	C	D
1.	20	Cross rectangle	3	2
2.	20	Rectangle	4	2.5
3.	20	Cone	5	3
4.	25	Cross rectangle	4	3
5.	25	Rectangle	5	2
6.	25	Cone	3	2.5
7.	30	Cross rectangle	5	2.5
8.	30	Rectangle	3	3
9.	30	Cone	4	2

V. Numerical analysis to find result of nine combination of L9 orthogonal array (second part)

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 used 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.

TABLE 5: RESULTS FOR ARALDITE 2015

Trial number/ Test number	**Normal stress in Longitudinal direction (MPa)**	**Shear stress (MPa)**	**Von-mises stresses (MPa)**
1.	88.11	17.84	68.84
2.	96.38	19.26	75.15
3.	102.1	20.39	80.92
4.	105.2	21.54	81.53
5.	85.73	17.21	69.05
6.	97.48	20.08	74.87
7.	94.4	19.62	75.15
8.	102.8	21.14	81.5
9.	87.66	18.31	69.30

TABLE 6: RESULTS FOR LOCTITE E-30HV

Trial number/ Test number	**Normal stress in Longitudinal direction (MPa)**	**Shear stress (MPa)**	**Von-mises stresses (MPa)**
1.	91.12	19.48	70.8
2.	98.83	22.62	78.15
3.	105.21	23.93	83.82
4.	107	24.45	84.6
5.	88.37	20.28	71.02
6.	98.5	24.43	77.16
7.	98.3	24.51	79.05
8.	106	23.96	84.65
9.	93.54	21.18	72

Since adhesively bonded joint failed in shear, the shear stress is taken as comparison parameter.

VI. Taguchi and ANOVA analysis for optimum parameter selection

After calculating the results for nine different trials by numerical analysis which are based on L9 orthogonal array. The next step in statistical analysis is to analysis the same data for selecting optimum level of the parameters with the percent contribution of each in improving the result. All of the above is done in this section by doing Taguchi and ANOVA analysis.

A. Taguchi analysis

S/N calculation:

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. The smallest is better quality characteristic is chosen in SNR calculation. Factor level is calculated using the following formula.

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

Where,

S/N is the average SNR

'n' is the number of experiment conducted at level 'i

'y' is the shear stress

TABLE 7: AVERAGE SNR VALUES FOR ARALDITE 2015 AND RANKING OF PARAMETER

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 8: DESIGN OPTIMUM VALUES OF FACTORS 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

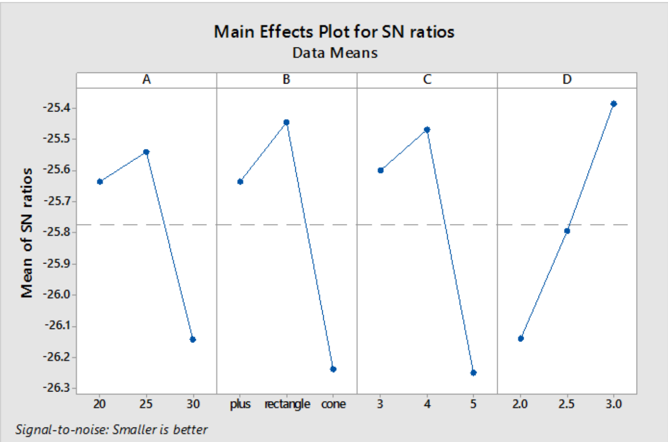


Figure 8: Graph of SN value vs. Level for araldite 2015

Table 9 : Average SNR values for Loctite E 30 and Ranking of parameter

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=(-27.72)-(26.81)=0.91

TABLE 10: DESIGN OPTIMUM VALUES OF FACTORS 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

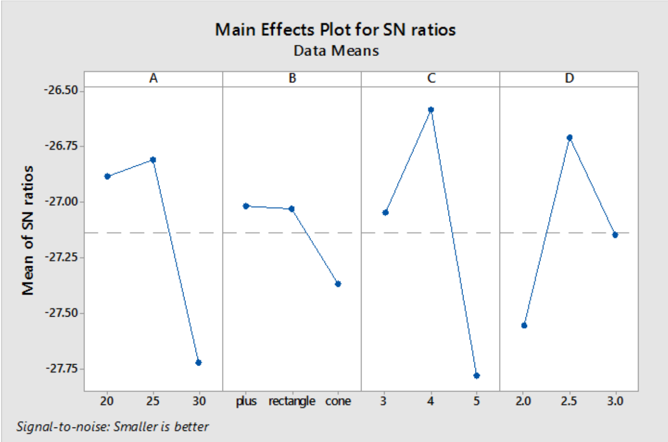


Figure 9: Graph of SN value vs. Level for loctite E 30 HV

B. 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. 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.

TABLE 11:ANOVA ANALYSIS FOR ARALDITE 2015

Factor	DF	SS	MS	F-Value	P-Value	% Contribution
A	2	3.372	1.686	0.64	0.559	17.63
B	2	7.167	3.583	1.8	0.245	37.46
C	2	4.484	2.242	0.92	0.449	23.44
D	2	4.108	2.054	0.82	0.484	21.47
Total	8	19.131				100

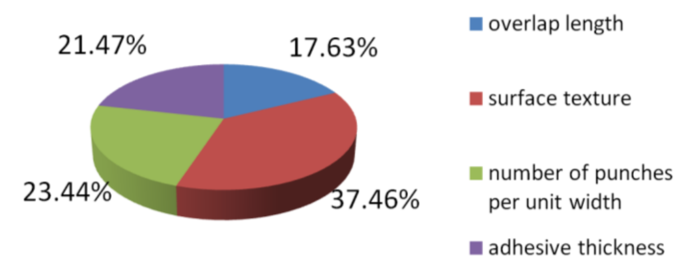


Figure 10: Percentage contribution of factors in strength for Araldite 2015

TABLE 12 : ANOVA ANALYSIS FOR LOCTITE E 30 HV

Factor	DF	SS	MS	F-Value	P-Value	% Contribution
A	2	6.807	3.403	0.79	0.498	20.75
B	2	14.24	7.122	2.3	0.181	43.41
C	2	10.23	5.114	1.36	0.326	31.17
D	2	1.533	0.7667	0.15	0.866	4.67
Total	8	32.812				100

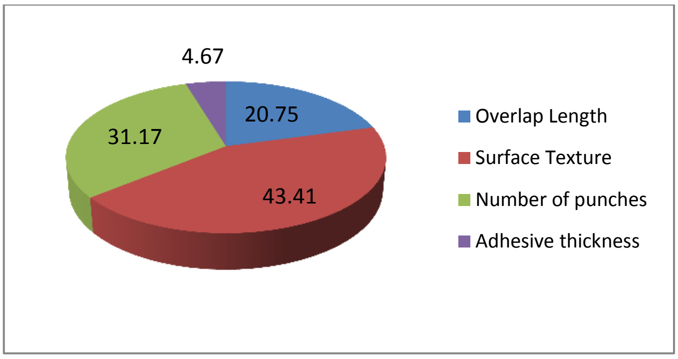


Figure 11: Percentage contribution of factors in strength for Loctite E 30 HV

VII. Experimental testing using UTM

As we know universal testing machine (UTM) is used to test the tensile strength, compressive strength and bending strength of materials. Modal TUE-C-400 of the universal testing machine has been used in this work. Fig. 9 shows the universal testing machine set-up.

Figure 12: UTM test set-up

TABLE 13: EXPERIMENTAL TEST RESULTS

Test Specimen	Design Values				Ultimate peak Loads (N)
	Overlap length (mm)	Surface texture	Number of punches per unit width	Adhesive thickness (mm)	
Araldite joint without surface texture	30	-	-	2 mm	6880
Optimum Araldite joint with surface texture	30	cone	5	2 mm	7420
Loctite joint without surface texture	30	-	-	2 mm	4680
Optimum Loctite joint with surface texture	30	cone	5	2 mm	10440

VIII. RESULTS AND DISCUSSION

1) From the first stage of numerical analysis for pattern selection: By analyzing the different surface texture pattern for same loading and boundary condition we come to know that spin and s-shape gives less deformation but apart from spin and s-shape pattern here next three surface texture pattern i.e. Rectangle, cross rectangle and cone shape are used to increase the strength of single lap joint as they are easy to manufacture. Figure 7 shows comparison of all the surface texture result for total deformation.

2) The second part of numerical analysis is as per the Taguchi optimization: here standard L9 orthogonal array for Taguchi optimization is used. The results according to the orthogonal array for same load and boundary condition are shown in table 5and 6 respectively for Araldite 2015 and Loctite E-30HV.

3) Using TAGUCHI AND ANOVA analysis signal to noise ratio evolution and ranking of parameter by Minitab software for Araldite2015 and Loctite E-30HV is found out and is given in table 7 and 9 respectively. Ranking is important as each factor has contribution in joint strength.

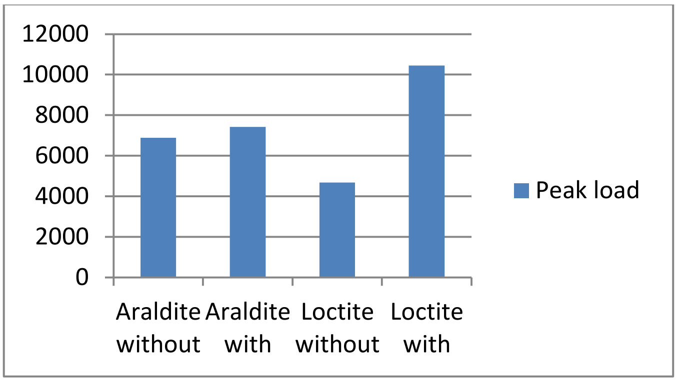
4) Percentage contribution of factors in strength for Araldite 2015:

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

5) Percentage contribution of factors in strength for Loctite E 30 HV:

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

6) Experimental results: The optimized combination of joint obtained by Taguchi method is subjected to tensile loading until failure by this way the maximum failure load as well as deformation is obtained experimentally. Surface texture raises the load carrying capacity of joint.



7) Validation of experimental and numerical results: In the validation, the optimized joint obtained by Taguchi method and joint without pattern is test experimentally. In experimental testing ultimate peak load and elongation at peak is obtained, at the ultimate peak load joint tested numerically to validate the results.

TABLE 13: COMPARISON OF EXPERIMENTAL AND NUMERICAL ANALYSIS RESULTS

Sr. No.	Joint Design Parameters					Load at Peak (N)	Deformation at peak load (mm)	
	Adhesive Material	Overlap length (mm)	Surface texture	No. of punches per unit width	Adhesive thickness (mm)		By FEA	By Expt.
01	Araldite 2015	30	-	-	2 mm	**6880**	1.840	**1.18**
02	Araldite 2015	30	Cone punch	5	2 mm	**7420**	1.947	**2.09**
03	Loctite E 30 HV	30	-	-	2 mm	**4680**	1.244	**1.36**
04	Loctite E 30 HV	30	Cone punch	5	2 mm	**10440**	2.716	**2.310**

IX. CONCLUSIONS

From this work following conclusions are made:

1. The optimized level of selected process parameter obtained by Taguchi method are (for araldite 2015 and loctite E-30-hv):
   Overlap length 30 mm.
   Surface Texture CONE.
   Number of punches per unit width 5.
   Adhesive Thickness 2 mm.
2. From detailed literature survey the first conclusion is made that as the strength of adhesively bonded joint is affected by many parameters since there is big scope for strength improvisation through design optimization of joint parameters.
3. From first stage FEA analysis it is concluded that a spin and s-shape surface texture improves the joint strength but they are difficult to manufacture. Since apart from using those next best three type i.e. cone pattern, rectangular and cross rectangular punches pattern are chosen.
4. From the ANOVA analysis it is found that a surface texture has maximum contribution in strength enhancement i.e. in araldite 2015 joint it has 37.46 % while that in loctite E 30 HV it contribute 43.41 %.
5. From Taguchi analysis it is found that the ranking of parameter is most important,

Factor	For Araldite rank	For Loctite rank
Overlap length	4	2
Surface texture	1	4
No of punches	2	1
Adhesive thickness	3	3

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