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Analyzing Adhesion of Epoxy/Steel Interlayer in Scratch Test

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ABSTRACT
The aim of this paper is to investigate use of an experimental technique to determine which parameters effects on the interfacial durability performance of adhesive on the metallic adherends as zinc plated mild steel (S235) by using Taguchi method. The experimental layout has been used four scratch force parameters using the L16 (4^1x2^3) orthogonal array. The statistical methods of signal to noise ratio (SNR) and the analysis of variance (ANOVA) were applied to examine effects of surface treatment, adhesive type, blade angle and thickness on scratch force and scratch energy. Besides, the surface analysis was carried out the morphological modifications as well as to perform elemental analyses of the pre-treated surfaces. Results of this study indicate that the thickness and surface treatment are main parameters influencing scratch force (by 52.4% and 19.9%) and scratch energy (by 44.0 % and 25.6%), respectively.
Keywords: Adhesive, Scratch test, Surface treatment, Taguchi method, Zinc plated mild steel

I. INTRODUCTION

The scrape (scratch) test technique attempted to grade the strength of adhesion of an adhesive to a metallic (or relatively smooth non-metallic) adherend by measuring the force required to remove the adhesive from an adherend. The scratch test is usually applied to determine the adhesive strength of coatings deposited by chemical or physical vapor deposition techniques[1, 2].This test technique appears to be very useful for rapidly detecting changes in interfacial strength of adhesive/adherend system, and for distinguishing amongst the durability performance of various surface pretreatments.Numerous research efforts have been carried out and similar commercial scratch test equipment has been employed to evaluate coatings adhesive strength [3, 4, 5, 6]rather than[2].According to Knox and Cowling [2]the residual adhesive-adherend interfacial strength was quantified by recording the required force to remove a strip of adhesive from the adherend surface by using a razor. The proposed benefits of this test method are that the adhesives are aged in “realistic” environments while gaining results within a relatively short time span.Knox and Cowling, [2] initial conclusion was that the method would be unworkable due to two main reasons; the formation of an adequately shaped bead and in some cases the epoxy bond strength would be too great and only impractically small beads can be broken free before thewire/fiber-breaks.

Xie andHawthorne[3]performed the effect of indenter geometry on the failure modes, so that proper scratch parameters can be chosen to ensure an adhesive failure is induced in the scratch adhesion test.This scratch method suggests that it appears to be very useful for rapidly detecting changes in interfacial strength of an adhesive-adherend system, and for distinguishing amongst the durability performance of various surface treatments [2].

Application of adhesives is usually independent to metallic substrate material (adherend). In adhesive bonding, the surface of elements to be joined is defined as the part of material where interactions with an adhesive occur. In the many studies, it has been demonstrated that the strength has beenaffected by surface treatment, adhesive type, adhesive thickness, geometry and durability [7, 8]. The surface pretreatment enables to have a good surface wettability, precision of properties, improved surface developments, good activation of surface elements being bonded and removal of all contaminantsthat could significantly decrease adhesive joint strength e.g. lubricants, dusts, loose corrosion layers and micro-organisms[9, 10].

The Taguchi experimental design method is a statistical approach that reduces the number of experiments necessary for investigating the effects of various parameters on the product quality and/or quantity. This method also screens the significant factors affecting the response from those with less significance, and gives the optimum condition to attain the most desirable performance[11]. Although, there are many papers recently published on different fields by using Taguchi method, but there is no report available regarding to application of experimental design analysis considering the effects of surface treatments, thickness and adhesive type parameters on the scratch force. The aim of this research was to reveal use of an experimental approach to definewhich parameter affectsinterfacial durability performance of metallic adherend (S235 zinc plated mild steel)via Taguchi method. The Taguchi L16 orthogonal array was employed to analyze experimental scratch test results obtained from eight experiments withtworepetitionsand four process parameters e.g. surface treatment, adhesive type, blade angle, and thickness. The obtained results were analyzed by using a variance analysis (ANOVA).Besides, the surface morphology of each adherend after treatments was observedvia scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDX).

II. MATERIAL METHOD

2.1. Materials

Two type of adhesives were selected; Veporal Super (HE 20-06), a unique hybrid two-component epoxy structural adhesive with high elongation up to 55% having excellent peel and shear strength. It is used for structural bonding for a wide range of substrates in the scratch tests. Shear strength, tensile strength and strain at fracture are 13 MPa, 16 MPa and 40%, respectively. The second type of adhesive was a brittle type of adhesive Carbo Resin. Carbo Resin is two component epoxy base glue with inorganic fillers. The have good adhesion to many materials. Curing is at normal room temperature. Minimum shear strength after 14 days is 13 MPa. Total curing 7 days at 20°C.

The adherend materialis a low strength mild steel (S255) whose chemical composition is given in Table 1 based on Ref.[9]. Two values of adhesive thickness were used 0.6 and 0.3 mm in the experiments. The adherend thickness was constant as 1 mm for each specimen.

Table 1.Chemical composition of mild steel (S255)

Composition [wt.%]								
C	Mn	Si	P	S	Cr	Ni	N	Cu
Max. 0.22	Max. 0.65	0.15-0.3	Max. 0.04	Max. 0.05	Max. 0.3	Max. 0.3	Max. 0.012	Max. 0.3

2.2. Test method

To investigate the effect of surface treatment on the adhesion strengths of Veporal Super (HE 20-06) and Carbo Resin, a jig at the surface was created based on Knox and Cowling's paper[2],(see in the Figure1) to strip a thick film of adhesive from an adherend see in Figure 2.

For specimens used in the scratch tests the procedure is as followings[2]

- The required area on the adherend is prepared for adhesive. This may include chemical etching, sanding (shot blasting), anodic oxidation of the surface, and followed by treatment with a primer if required.
- The adhesive was applied to adherend surface.
- The thickness of specimen and bond-line thickness were controlled by using wires above the adhesive.
- The adhesive was cured according to manufacturer's instructions involving a cure at room temperature for 24 hour. The specimens were then allowed to wait at ambient in the laboratory environment.
- The specimen thickness was verified after curing process.
- The tests were performed by using a scratch tool(Fig. 1)in a tensile testing machine (ZD 10/90) at a constant crosshead speed of 25mm/min) at ambient conditions.

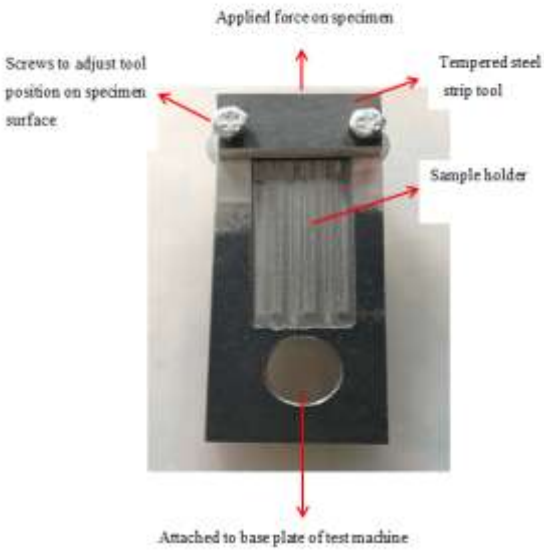

Figure 1.Design of scratch jig

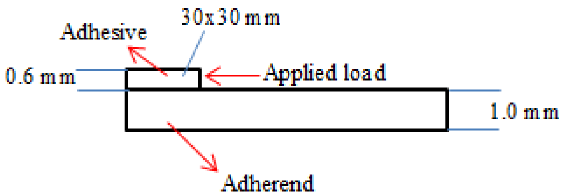

Figure 2.Scratch test specimen (not to scale)

2.3. Surface Treatment

In accordance with, the adherends were treated by four different surface treatment method i.e. sandblasting, chemical etching, and anodic treatment followed by mixture combination in this study.

2.3.1. Sandblasting- Sanding (S_1)

The sandblasting process was performed using dry sanding box with ceramic abrasive for industrial sanding application. This procedure was carried out for specimens, held at a distance of 2-3 cm approximately from the nozzle as accurately as possible and sand-blasted at a pressure of 600 kPa.

2.3.2. Chemical etching (S_2)

The chemical etching process was carried out all the zinc plated mild steel specimens immersed into acid solution. The acid solution was prepared by using 20 ml hydrochloric acid and 40 ml distilled water. During the etching process,zinc layer was completely removed from the steel substrate.

2.3.3. Anodic oxidation treatment (S_3)

In anodizing treatment, the adherend was clamped to the anode and cathode holders. The composition of solution was arranged with same percentage as phosphoric acid (10 ml); distilled water (30ml). The anodizing voltage was raised to 30 V and held for 20-30 seconds. At the end of this time the adherend was cleaned by using cold water at ambient temperature. The anodized adherends can then be air-dried, preferably blow-dry. Anodic oxidation treatment produces a very thin layer on the adherend surface. Before anodized treatment was applied, all specimens were undergone chemical etching process.

2.3.4. Mixture combination

Mixture surface treatment processes were consisted of sanding, anodizing treatment after chemical etching processes. In the first step of this surface treatment, chemical etching was applied on all zinc plated mild steel specimens. Secondly, all specimens which have been undergone treatment were sanded. Finally, anodic oxidation was applied by using electrochemical treatment.

2.4. Taguchi matrix

The Taguchi method was used to design the experiments. The Taguchi array contains four factors, or variables, corresponding to the surface treatment (A), adhesive type (B), blade angle (C) and thickness (D). If all the possible test combinations were to be tested, the number of tests would be 64 (one test, no repeating) which are impractical in terms of time andcost. The use of pre-defined orthogonal arrays on which the Taguchi method is based reduces the number of tests and permits to quantify the interactions between the variables considered. The experimental layout for the four scratch force parameters using the L16 (4^1x2^3) orthogonal array is shown in Table 2. Accordingly, eight experiments were carried out to study effect of scratch force input parameters. Each experiment was repeated two times in order to reduce experimental errors. It contains 8 rows corresponding to the number of tests with two replicates, one column with four levels) and 3 columns with 2 levels. The first column was assigned the surface treatment, the second to the glue type, the third to the blade angle, and the fourth to the adhesive thickness (see Table 3). The response studied was scratch force (F), scratch energy (SE) and it involves signal to noise (S/N) ratio factors. The influence of each variable was assessed by the average response and the analysis of variance (ANOVA). The statistical software MINITAB 17program [12] was used.

Table 2.Experimental layout using L16 orthogonal array

No	Sample No	Surface Treat. (A)	Type (B)	Angle (C)	Thick-ness (D)
1	1	1	1	1	1
2		1	1	1	1
3	2	1	2	2	2
4		1	2	2	2
5	3	2	1	1	2
6		2	1	1	2
7	4	2	2	2	1
8		2	2	2	1
9	5	3	1	2	1
10		3	1	2	1
11	6	3	2	1	2
12		3	2	1	2
13	7	4	1	2	2
14		4	1	2	2
15	8	4	2	1	1
16		4	2	1	1

Table 3.Scratch force parameters and their levels

Parameters	Level 1	Level 2	Level 3	Level 4
Surface treat. (A)	S_1	S_2+ S_1	S_2+S_3	S_2+S_1+ S_3
Adhesive type (B)	Soft	Rigid	-	-
Blade angle (C)	0°	15°	-	-
Thickness (D)	0.3mm	0.6mm	-	-

2.5. Surface analysis

The treated surfaces were characterized for microstructural evaluations by using analytical scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDX) analysis using Tescan Vega III SB electron microscope. This surface analytical technique was used to study the morphological modifications as well as to perform elemental analyses of the treated surfaces.

III. RESULTS AND DISCUSSION

3.1 Microstructureevaluation

In the EDX analysis of basic material (zinc plated mild steel), it was observed some starting of corrosion after one day even if it is in the good condition. In accordance with, we may apply surface treatment on basic material preventing the weak boundary layer occurred against to corrosion and corrosion products (see in Figure 3(a-d)). This problem is resulted from weak boundary layer theory. According to [13] this theory states that bond failure at the interface is caused by either a cohesive break or a weak boundary layers. Weak boundary layers can originate from the adhesive, the adherend, the environment, or a combination of any of the three. Weak boundary layers can occur in the adhesive or adherend if an impurity concentrates near the bonding surface and forms a weak attachment to the substrate. When failure takes place, it is the weak boundary layer that fails, although failure appears to take place at the adhesive-adherend interface. Weak boundary layers, such as those found in polyethylene and metal oxides, can be removed or strengthened by various surface treatments. Weak boundary layers formed from bonding environment are very common.

3.2 Scratch force analysis and failure mechanisms

Scratch forces for each configuration of adhesive samples including different surface treatments, adhesive type, thickness and angle of scratching were performed experimentally. The trends of scratch forces with respect to position of cutting tool are demonstrated in Figure 4 and 5. Two different behavior of fracture mechanism were achieved as ductile and brittle response. The samples having soft adhesive, are mainly characterized by relatively smooth and lower force amplitudes with low amount of oscillations as it is exhibited e.g. in sample 1, 3 and 7 in Fig. 4(a) and 4(c), and Fig 5(c). Hence, the failure mechanism for these samples is mainly dominated by interfacial fracture stimulating exponential traction and separation cohesive zone delamination as stated in literature. For almost all samples, the force increases up to traction limit corresponding to peak values on the graphs then softening mechanism takes place until the critical distance is achieved. This phoneme was also experienced for rigid adhesives, excepting large amplitudes of force oscillations caused by considerably high amount of vibrations due to brittle cracking fracture response. Contrary, the scratch force variation for the sample 5 has a brittle fracture response. This adverse effect may be evaluated as the tendency of interface adhesion to a brittle behavior due to surface treatment factor (etching plus anodic oxidation), yielding an adhesive failure at slightly lower thickness of 0.3mm in Fig. 5(a). Therefore, this mentioned brittle interface zone was considered to generate high frequency of vibrations accompanied with high scratch force amplitudes. The surface treatment option, especially anodic oxidation process had a quite negative impact on the bonding characteristic of adhesive and adherend. This situation was observed in sample 5 and 8 in Fig. 5.a and 5.d. The anodic oxidation processes led to weakening bonding strength at relatively low adhesive thickness. The mean values of scratch forces in the steady-state (separation) region were illustrated inTable 4.The samples corresponding to thickness (0.6 mm) have relatively high scratch forces at an interval of 918 N and 1020 N. The lower scratch force was obtained at thinner (0.3 mm) adhesive sections which are a sign of significant effect of thickness.

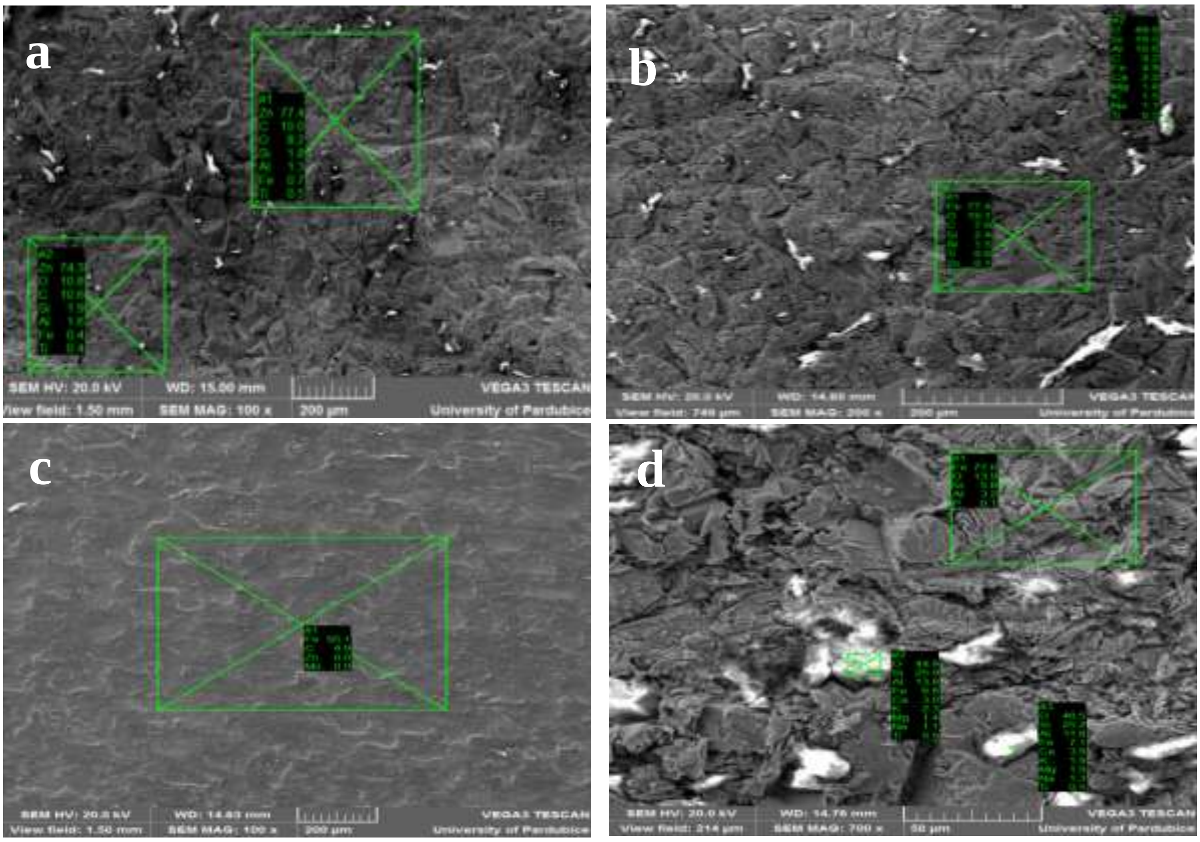

Figure 3.SEM- EDX analysis of treated surface,a-Sanding b- Chemical etching + sanding, c- Chemical etching, d- Chemical etching + sanding + anodic oxidation

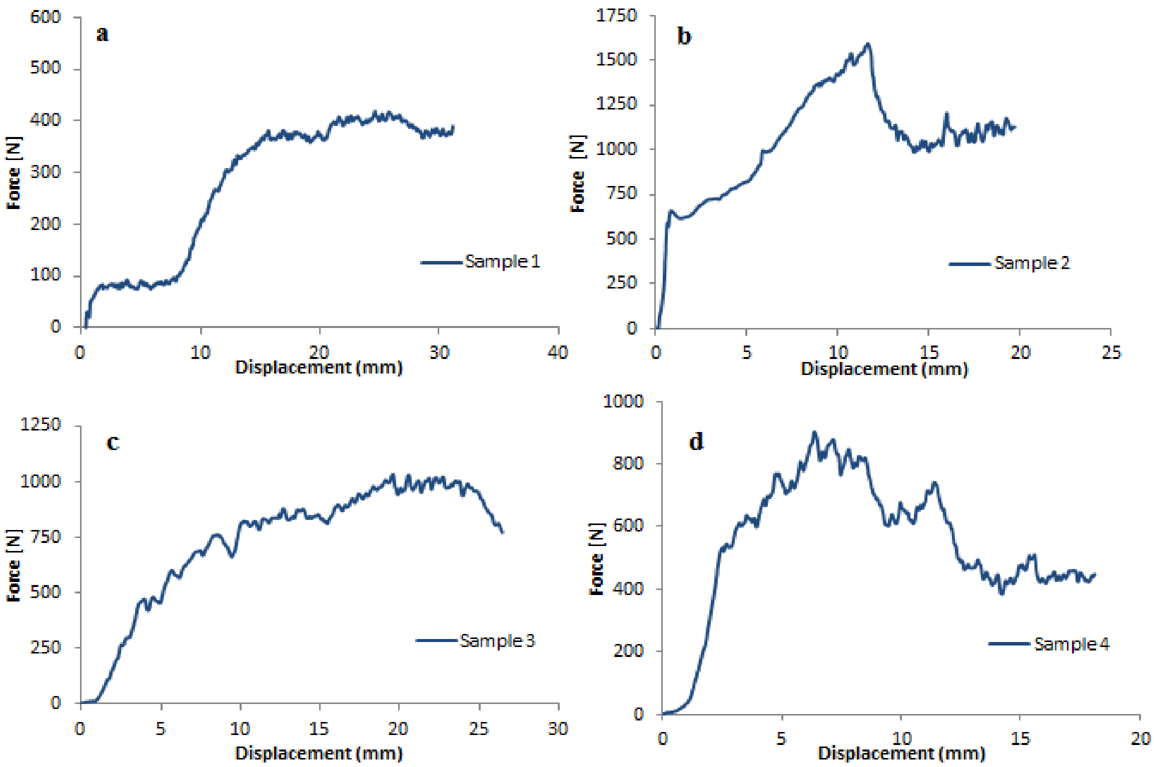

Figure 4.The scratch force-displacement graphs of samples 1-4

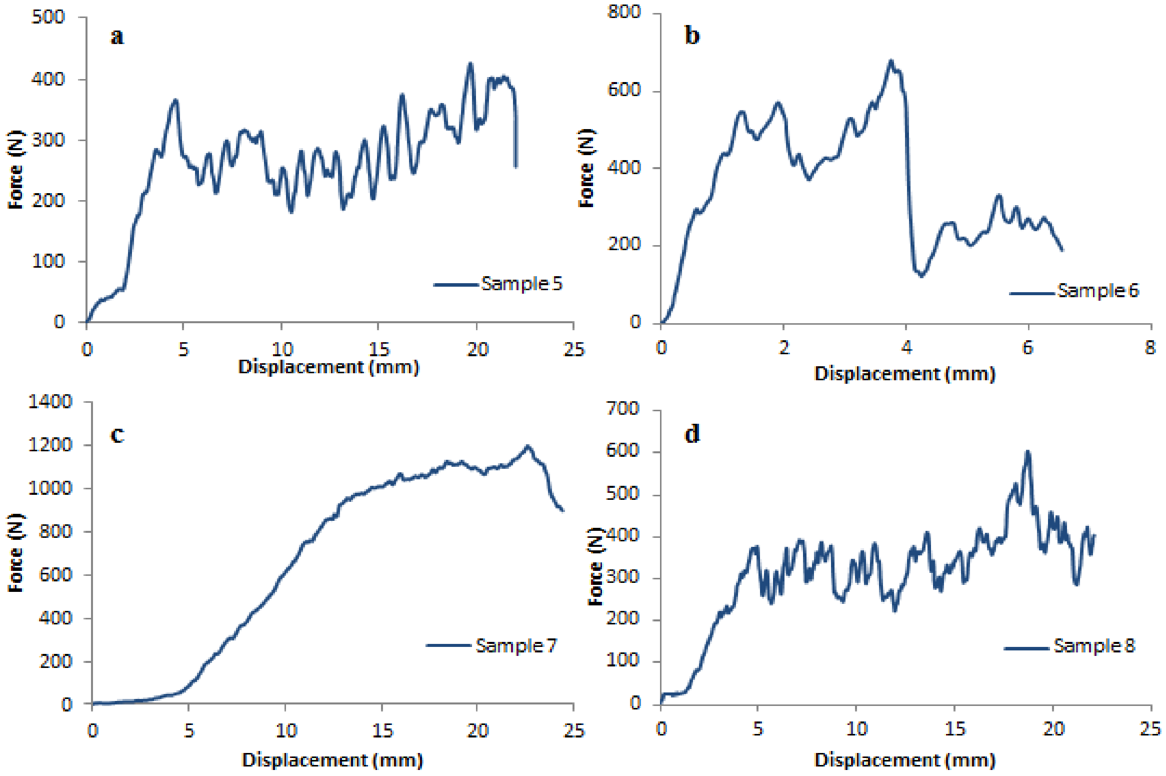

Figure 5.The scratch force-displacement graphs of samples 5-8

3.3 Scratch energy analysis

The amount of energy to drive the adhesive zone into fracture state is a better indication of surface adhesion properties. For this reason, the work done during the scratch process was evaluated in terms of area under the force-displacement curves based on trapezoidal integration rule per unit area of adhesive surface. This parameter is called specific scratch energy in kJ/m^2 to reach failure state. The specific scratch energy values of each sample were given in Table 4 and Figure 6 each represents different surface treatments, geometry parameters and etc. The highest specific energy values were obtained in the samples of 2,3 and 7 corresponding to thickness 0.6mm, expressing the substantial effect of thickness by roughly 44%. This is a reason of stacking ability and larger contact interaction of cutting blade and adhesive cross-section at increasing thicknesses against longitudinal motion. Furthermore, sharp decreases were concluded at lower thicknesses by a certain amount regardless of other parameters. However, there has been a remarkable impact of surface treatment especially for the samples of 5, 6 and 8 undergoing anodic oxidation treatment, attaining the worst surface effect on scratch resistance of adhesive. On the other hand, implementation of sanding process has produced quite better bonding characteristics comparing to the others for all samples as it was stated in previous works in literature [14]. Based on the variations of specific energy values in Table 4, no significant contribution of adhesive type was appeared although it plays an important role in fracture mode which is either adhesive or cohesive failure.In terms of fracture energy approach, samples 2 and 7 having 0.6mm thickness and subjected to sanding process in common have the optimum configurations with similar scratch energies of 36kJ/m^2 approximately. The specific fracture energy for both brittle and ductile fracture behavior were observed to be not influenced due to the fact that brittle material undergoes low displacement at high forces, whereas ductile materials exhibits opposite response.

3.4 Statistical analysis

3.4.1. Analysis of signal-to-noise (S/N) ratio

Taguchi uses the S/N ratio as the quality characteristic of choice. S/N ratio is considered as a measurable value instead of standard deviation because as the mean decreases, the standard deviation also decreases and vice versa. In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise. The higher the ratio, the less obtrusive the background noise is. ‘‘Signal-to-noise ratio’’ is sometimes used informally to refer to the ratio of useful information tofalse or irrelevant data in a conversation or exchange. In other words, the standard deviation cannot be minimized first and the mean brought to the target [15]. Taguchi has empirically found that the two stage optimization procedure involving S/N ratios indeed gives the parameter level combination, where the standard deviation is minimum while keeping the mean on target. The target mean value may change during the process development. Two of the applications in which the concepts of S/N ratio are useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by Equations (1) – (3), when the characteristic is continuous [16]:

- Nominal is the best characteristic

$$\frac{S}{N} = 10\log\frac{\bar{y}}{S_y{}^2} \quad (1)$$

- Smaller is the better characteristic

$$\frac{S}{N} = -10\log\frac{1}{n}\sum y^2 \quad (2)$$

- and larger the better characteristic

$$\frac{S}{N} = -\log\frac{1}{n}\sum y^2 \quad (3)$$

Where $\bar{y}$the average is observed data, $S_y{}^2$ the variation of y, $n$the number of observations, and y the observed data or each type of the characteristic, with *S/N* ratio, the better results when we consider surface treatment, adhesive type, blade angle and thickness. Factor levels that maximize the appropriate S/N ratio are optimal. The goal of this research was to produce maximum scratch force (F) and energy. Larger F and energyvalues represent better adhesive resistance to scratch. Therefore, a larger-the-better quality characteristic was implemented and introduced in this study. As mentioned earlier, there are three categories of performance characteristics, i.e., the lower-the-better, the higher-the-better, and the nominal-the-better.

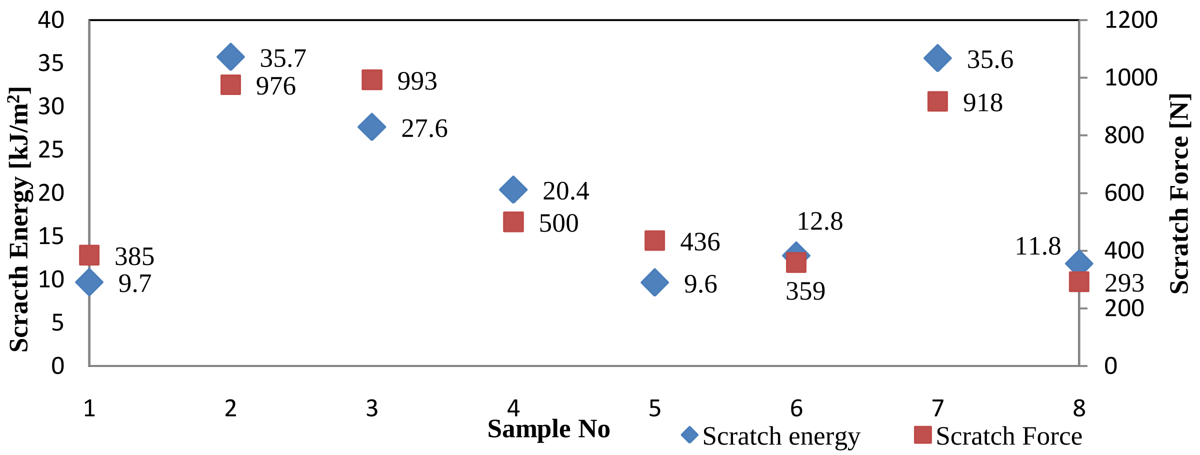

Figure 6.Specific scratch energy and forces

The Taguchi L16 orthogonal array was employed to analyze experimental results of scratch force, scratch energy, S/N ratio and failure modes obtained from 8 experiments which are given in Table 4.The level values obtained from MINITAB 17 software program[12]according to the Taguchi design are given in Table 4 and Table 5.Table 5 shows the experimental results for scratch force, scratch energy and the corresponding S/N ratio using Equation(3).

Table4.Experimental results

Sample	A	B	C	D	Scratch Force (N) Set 1	Scratch Force (N) Set 2	S/N ratio	ScratchEnergy (KJ/m^2) Set 1	Scratch Energy (KJ/m^2) Set 2	S/N ratio	Failure mode
1	S_1	Soft	0°	0.3 mm	388.7	384.6	51.8	8.6	9.7	19.1	Adhesive
2	S_1	Rigid	15°	0.6 mm	1020.0	976.0	59.9	28.3	35.7	29.9	Cohesive
3	$S_{2+}S_1$	Soft	0°	0.6 mm	993.4	1000.7	59.9	27.6	33.2	29.6	Adhesive
4	$S_{2+}S_1$	Rigid	15°	0.3 mm	495.3	500.4	53.9	20.4	17.3	25.4	Cohesive
5	$S_{2+}S_3$	Soft	15°	0.3	492.0	435.5	53.2	14.0	9.6	21.0	Adhesive

6	$S_{2+} S_3$	Rigid	0°	0.6 mm	372.1	359.3	51.25	7.1	12.8	18.85	Adhesive
7	$S_{2+}S_{1+}S_3$	Soft	15°	0.6 mm	918.0	910.2	59.22	35.6	27.4	29.74	*Hybrid
8	$S_{2+}S_{1+}S_3$	Rigid	0°	0.3 mm	292.5	276.9	49.08	11.8	9.4	20.36	Cohesive

*Hybrid: Adhesive plus cohesive failure mode

Table 5.Response table mean signal to noise ratios for scratch force

Scratch Force					Scratch Energy				
Level	A	B	C	D	Level	A	B	C	D
1	55.86	56.05	53.01	52.01	1	24.54	24.87	21.98	21.49
2	56.96	53.56	56.60	57.61	2	27.48	23.64	26.52	27.02
3	52.26	-	-	-	3	19.93	-	-	-
4	54.15	-	-	-	4	25.05	-	-	-
Delta	4.69	2.49	3.59	5.60	Delta	7.55	1.23	4.54	5.53
Rank	2	4	3	1	Rank	1	4	3	2

Total mean S/N ratio= 54.81 Total mean S/N ratio= 24.25

Accordingly, Figure 7shows that the second level of A factor (surface treatment), the first level of B factor (adhesive type) and the second level of C factor (blade angle) and the second level of D factor (thickness) are higher as both left and right side.

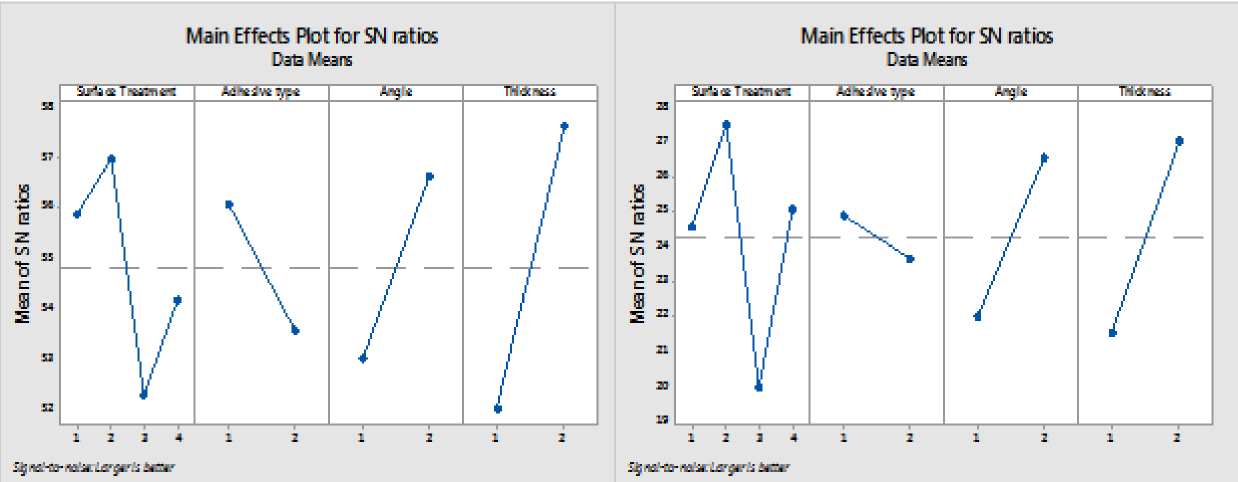

Figure 7.Mean of S/N ratios versus factor levels for scratch force (at left side) and scratch energy (at right side)

3.4.2. Analysis of variance for scratch force and scratch energy analysis

The analysis of variance (ANOVA) is a powerful technique in Taguchi method that explores the percent contribution of factors affecting the response. The strategy of ANOVA is to extract the variations that each factor cause relative to the total variation observed in the results. The results of the ANOVA for scratch force and scratch energy with surface treatment (A) adhesive type (B), blade angle (C), thickness (D) and interaction (E) parameters are shown in Tables 6and 7. This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Tables 6 and 7 show the P-values, that is, the realized significance levels, associated with the F-tests for each source of variation. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures. The other/error term, in the last row of ANOVA table, contains thus the information about three sources of variability of the results including uncontrollable factors, factors that are not considered in the experiments, and the experimental error [11]. It should be emphasized that the interpretation of ANOVA table is valid just in the range of considered levels for the factors. That's why the determination of levels is of great importance in any experimental design approach.

The ANOVA table (see Table 6 and 7) of the experimental results gives the relative importance of all the variables. The main factors influencing the scratch force are thickness 52.4%. The second factor is surface treatment also significant contributionat about 19.9%. The other factors; blade angle and adhesive type have contribution, 13.7% and 7.3% respectively. On the other hand, the interaction between adhesive type-angle-thickness parameters was determined as 6.5%.In case of analysis of variance analysis for scratch energy, the trend of contribution is similar to scratch force. Thickness 43.9% is main factor effect on scratch energy. The other parameters; surface treatment 25.6%, blade angle 17.8% and adhesive type 2.0% whereas the interaction between adhesive type-angle-thickness parameters were shown 3.7% given in Table 7.The F-ratio in ANOVA table is a reliable criterion for ranking the factors with respect to their influence. A higher value of the calculated F-ratio for a factor means a greater influence of that factor on the experiment outcome. Moreover, if the percent contribution of a factor would be equal to or less than 10% of that of the most affecting factor, this factor can be pooled with error terms [11]. According to Table 6 and Table 7, P value is scratch force and scratch energy at the reliability level of 95%,because the results are lower than 0.05.

Table 6.Results of the analysis of variance analysis for scratch force

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Surface Treatment	3	255750	19.87%	339493	113164	314.31	0.000
Adhesive type	1	94660	7.35%	178411	178411	495.53	0.000
BladeAngle	1	176114	13.68%	8448	8448	23.46	0.001
Thickness	1	674051	52.36%	141155	141155	392.05	0.000
Adhesive type*Angle*Thickness	1	83913	6.52%	83913	83913	233.07	0.000
Error	8	2880	0.22%	2880	360		
Total	15	1287369	100.00%				

The optimum conditions to attain scratch force/displacement can be determined from maximum points in main effect. Applying the optimum condition, the contribution of each factor on improvement of response can be found using Taguchi approach [11]. A prediction for scratch force with regarding factors and their levels was performed in the MINITAB 17 Software program [12]. This prediction based on S/N ratio's highest values is in the parameter level chosen as (A2, B1, C2 and D2). As a result of this prediction, the scratch force and scratch energy are calculated 1062.04 N and 37.00 KJ/m^2, respectively.

Table 7.Results of the analysis of variance analysis for scratch energy

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Surface Treatment	3	416.25	25.63%	474.83	158.28	11.31	0.003
Adhesive type	1	32.93	2.03%	91.19	91.19	6.52	0.034
BladeAngle	1	289.29	17.81%	42.71	42.71	3.05	0.019
Thickness	1	713.32	43.92%	179.39	179.39	12.82	0.007
Adhesive type*Angle*Thickness	1	60.32	3.71%	60.32	60.32	4.31	0.072
Error	8	111.92	6.89%	111.92	13.99		
Total	15	1624.03	100.00%				

IV. CONCLUSION

In this paper, an optimization process was implemented in order to analyze influence of different surface treatment processes, geometrical parameters and material types on the scratch resistance of two different adhesives onto one substrate of S235 zinc plated mild steel. For experimental procedure, eight different configurations were prepared and subjected to scratch tests including some surface examinations via SEM and EDX analysis. The failure modes,mean of scratch forces at stable region, specific scratch energy and statistical calculations based on application of the parameter design of the Taguchi method were carried out. Consequently, a variance of analysis (ANOVA) was introduced to estimate contribution of each design parameter on the scratch resistance of adhesive bondline in terms of force and energy. The following conclusions can be drawn based on the experimental results of this study are;

- Taguchi method of experimental design has been carried out for optimizing scratch force response parameters, evaluated with L16 orthogonal array. This design method is suitable to predict the scratch force as described in this paper.
- It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the scratch force parameters.
- The experimental results demonstrate that thickness of adhesive layer and surface treatment are main parameters influencing scratch force (52.4% and 19.9%) and scratch energy (44.0 % and 25.6%), respectively.
- Although the adhesive type has an ignorable effect on scratch energy, it was observed to be very sensitive to changing of peak scratch forces.
- Sanding process was observed to give better bonding ability as a result of mechanical interlocking for almost all samples. However, anodic oxidation process has a degradation behavior on bonding ability and is not suggested as an effective surface treatment.
- Blade angle was also concluded as a notable parameter in the evaluation of scratch force and energy by an amount of 13.8% and 17.8%, respectively.
- SEM-EDX evaluations show that it is necessary to apply a surface treatment on adherend to prevent weak layer at interface adhesion due to adherend surface corrosion.

Further study could consider more factors (e.g. curing conditions, wetting angle of adherend, primer application etc.) in the research to see how the factors would affect scratch force and scratch energy. Also, further study could consider the outcomes of Taguchi parameter design when it is implemented as a part of management decision-making processes.In experiments the fracture mode is either adhesive or cohesive. Further investigations are necessary to determine the dependence of the traction–deformation relation on the thickness of the adhesive layer, shear deformation rate, type of adhesive etc.

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