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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Mechanical and Failure Analysis of Multi-Materials Adhesive Joining

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DOI: https://doi.org/10.30880/ijie.2021.13.07.019
Received 16 August 2021; Accepted 2 September 2021; Available online 30 September 2021

Abstract: The evolvement of joining dissimilar materials using adhesive joining has been vastly improved over the years and has been used in various industries such as medical, automotive and construction. In the automotive industry specifically, the use of multi-materials has proven to improve material properties. However, fewer studies have been done to understand the failure mechanism of multi-material adhesive joining. This study investigates the mechanical failure for lap joints of different materials that have undergone mechanical abrasive treatments and chemical etching, before adhesively joined together. The result showed that sandblasting as surface preparation is very important as it increases the surface roughness of the material, giving a better adhesion bond. Chemical etching also increases the surface roughness minutely and is considered an important step for the purpose of degreasing. Tensile tests were conducted as a destructive test and it was found that mild steel, aluminum, and PVC materials were deemed to be the best choice for multi materials adhesive joining.

Keywords: Multi-material, failure analysis, adhesive joining, automotive

1. Introduction

Nowadays, the joining technique is the key technology that has been identified to enable innovative and sustainable manufacturing. Therefore, joining is an important process in manufacturing of most manufactured products in modern times [1,2]. Commonly, the joining of dissimilar materials has the potential to enhance product performance as well as to reduce product weight and the manufacturing cost [1,3].

The joining of dissimilar materials can be obtained by various joining techniques. Adhesive joining is opted to be the best method, due to its ability to minimize the manufacturing time and the weight of the product, compared to the mechanical fastening technique. Moreover, the use of adhesive joining, increases the stress distribution, reduces vibrations, and has resistance to metal corrosion [4,5]. The biggest advantage of using adhesive joining, is its ability to join various materials such as metals, polymers, and ceramics. Therefore, the adhesive technique is involved in most industries such as aerospace, automotive and structural industry [6,7].

A. Baldan states that adhesive bonding is the most suitable technique for joining both non-metallic and metallic structures [8]. An adhesive is defined as a substance or material, when applied, is used to join two surfaces of materials together [9]. This adhesive is then cured under its chemical compatibility to harden and produce a strong bond. Cure time may vary based on the application [10].

Surface pre-treatment modifies the adherend surface and hence, increasing the bond strength in numerous ways such as; increasing surface roughness, increasing surface tension or altering the surface chemistry [11]. The available types of surface pre-treatments are physical, mechanical, thermal, chemical, photochemical and plasma methods. Baldan [8] declared that all pre-treatments do amend the surface roughness to some extent but mechanical surface pre-treatment appears to be the most effective way to alter the surface roughness while removing contaminants from the

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surface [8]. However, it is evident that excess surface roughening can reduce the bond strength, by an increase in void formation and hence introducing localized stress [12]. Therefore, a critical roughness value is required for the strongest possible bond. Critical roughness value depends on many factors, such as the roughening pre-treatment applied, adhesive type, type of adherend, the geometry of the joint and the applied stresses. It has also been found that surface roughness affects the adherends surface free energy and wet-ability [13]. The spreading of the adhesive on the surface is also affected by roughness, either because the adhesive cannot penetrate or because the adhesive hardens before penetrating. The relationship between adhesion strength and surface roughness is said to be very challenging. Optimal surface preparation depends upon the type of stress applied [14]. The main issue in adhesive joining is to have an optimal surface pre-treatment before applying the adhesive. This includes the amount of surface preparation required, such as abrasive blasting and chemical etching, choosing the adhesive that could be used for various type of material surfaces and curing time. These preparations alter the surface roughness of the material that enhances the adhesion strength. However, there is an optimal roughness for each material and if it surpasses or falls behind the critical values, the bond strength will reduce [15].

Environmental conditions play a huge role in the durability of adhesive joints, such as temperature and humidity. In environmental stability, adhesive joints are greatly affected by water substances. In marine applications the structural bonded components are vastly exposed to water or some moist in the air, therefore, if a high relative humidity is present, then the strength of the joint will tend to decline over a period of time [16].

Currently, there are no specific trends or guidelines of what adhesive, surface treatment, or the temperature required to be used for each particular material. This is because the strength of adhesive bond depends on many factors such as the bonded area, temperature, type of surface pre-treatment used, type of adhesive and the environment in which the structure will be operating [17]. Moreover, to ensure the strength limitations of an adhesive bond, destructive tests should be carried out. Hence, this paper attempts to investigate the mechanical failure of different materials joined by adhesives that had undergone mechanical abrasive treatments and chemical treatments that altered the bonding surfaces, for adhesion, using a two-part epoxy adhesive. Furthermore, this study compares the surface roughness of each material used, with the type of failure at the breaking area.

2. Experimentation

2.1 Materials and Procedure

Material selection is very important for the engineering structure and design, taking into consideration the manufacturing, joining and assembling processes involved. The decision for selecting the base materials for this study was made due to the market requirement with respect to cost and availability [18]. The investigation was performed on low mild steel and aluminum as the metal materials. Poly (methyl methacrylate), Polyvinylchloride and Polycarbonate were used as polymer materials, in addition to the glass sheet material. Specimen were cut out of large sheets to the dimension of 80 mm x 30 mm x 3mm to produce the adherend materials.

The sandblasting process was carried out by using alumina 36 mesh on the top surfaces of the greasy specimen. It was visually evident after sandblasting, that the surface was free of oxides and rust, giving it more textured surface, indicating high surface roughness especially on mild steel and aluminum. The metals were etched in concentrated HCl acid for 30 seconds in order to remove the dust and to increase the surface roughness of the materials. Polymers and glass materials were etched for 45 seconds using C3H6O. It was observed that mild steel began to rust again if etched for a long time in HCl, therefore it did not have an optimal surface preparation. The materials were then cleaned lightly with acetone to remove any contaminants. The materials were marked 20 mm away from the specimen’s edge to indicate the joining length. Therefore, the joining area was 30 mm x 20 mm for each sample.

2.2 Adhesive Joining Procedure

The adhesive composition was prepared as a two-part adhesive that was mixed with a 2:1 ratio by epoxy resin and polyamide hardener in a 100 ml beaker container. The resin and hardener were thoroughly mixed in its volume ratio with a clean glass rod. Thick amounts of adhesive were applied in the middle of the bonding area on each surface to ensure the adhesive would evenly spread out and escape from the sides of the material. Once the adhesive and materials were attached and held firmly to the bond area, a uniform load was placed on top of the overlapping areas to ensure the same load compresses adhesive material and bonds firmly with the adherends. The bond was held together under load and left to cure for 16 hours for a group of specimens and 24 hours for another group of specimens, which were used to compare on the tensile testing machine.

2.3 Tensile Test

The machine used is the tensile strength test (ASTM D412), also known as a universal testing machine, was used to record the stress and strain behavior under axial tensile loading. The adherend sample dimensions are 80 mm x 30 mm x 3 mm with an overlap of 20 mm between each specimen as shown in the figure below.

The machine was set to load until break, so the maximum capable load for each bond will be tested and recorded until a deformation of some sort occurs. The red area indicates the overlapping of the upper and lower area for the samples. During testing all area (including the overlapping area) will be subjected to the same load.

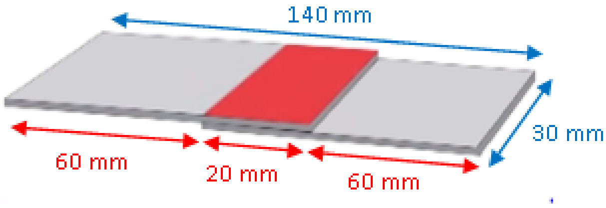

Fig. 1 - Proposed bonded specimen design

3. Result and Discussion

3.1 Evaluation of the Bonded Material

Specimens in this study were divided into two groups, the first group had been tested without exposing to any surface preparation. The second group that was tested had been subjected to surface preparation such as sandblasting and chemical etching. The surface appearances of the material are very evident with a naked eye as it can be seen in Fig. 2 below. Aluminum specimen (D) was not sandblasted. Therefore, it can be seen that (A) and (B) have greater surface roughness. Moreover, when comparing the mild steel samples, the surface roughness of (E), (F) & (G) is greater and observable compared to (H), as it was not sandblasted.

The adhesive bond of mild steel (H) that was not sandblasted, had remained on Aluminum (D) after testing, and observed grease, rust, and dust stains. Moreover, the adhesive bond that partially remained on PC (C) had no visible grease or dust, as mild steel (G) was sandblasted and chemically etched. However, a layer of rust was present on the adhesive bond as seen below, may have been formed on mild steel (G) due to over-etching of HCl.

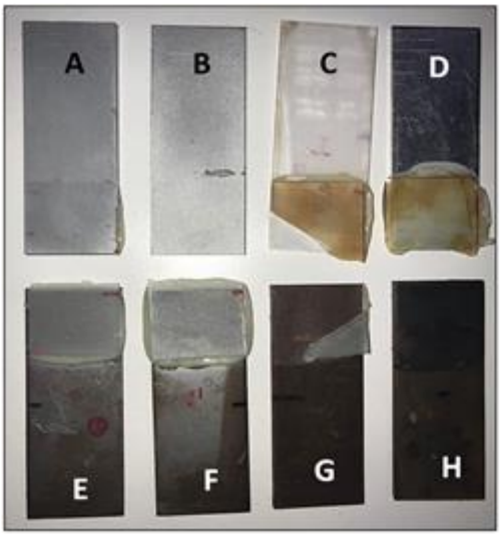

Fig. 2 - Surface roughness; (A, B, D) aluminum; (C) Poly (methyl methacrylate); (E, F, G, H) mild steel

3.2 Surface Roughness

The surface roughness results that were directly taken from the Mahr surface roughness machine, are tabulated in Table 1. Each material type was tested twice for sandblasted samples and an average was taken, once for non-sand blasted samples and once for few non-etched samples. Results have a similar and well-patterned trend. Sandblasted samples have the highest rough ness average, Ra, and then reduces in the samples which are only chemically etched and lastly, samples with no surface preparation. This illustrates the impact sandblasting has on surface roughness.

Table 1 - Surface parametric comparison of sandblasted, etched and non-sand blasted and etched samples

Material Name	R_a (μm)	R_q (μm)	R_z (μm)	R_{max} (μm)	R_v (μm)
Acrylic sand blasted & chemical etched (avg.)	1.27	1.64	7.74	10.61	3.20
Acrylic only chemical etched	0.01	0.01	0.06	0.09	0.04
Acrylic without sand blast/etching	0.01	0.01	0.04	0.05	0.02
Glass sand blasted & chemical etched (avg.)	4.32	5.61	24.36	34.27	13.47
Glass only chemical etched	0.01	0.01	0.05	0.06	0.02
Glass without sand blast/etching	0.01	0.01	0.04	0.05	0.02
PC sand blasted & chemical etched (avg.)	0.67	0.91	5.00	7.21	2.54
PC only chemical etched	0.22	0.28	1.55	1.83	1.04
PC without sand blast/etching	0.01	0.01	0.01	0.05	0.02
PVC sand blasted & chemical etched (avg.)	1.15	1.45	7.77	9.45	4.70
PVC only chemical etched	0.09	0.19	1.66	3.51	0.82
PVC without sand blast/etching	0.06	0.11	1.13	1.52	0.68
Mild Steel sand blasted & chemical etched (avg.)	1.27	1.64	8.59	12.33	3.91
Mild Steel only chemical etched	0.47	0.64	3.88	6.76	1.87
Al sand blasted & chemical etched	2.62	3.37	15.84	19.18	7.51
Al only chemical etched	0.39	0.56	2.80	3.93	1.77

3.3 Destructive Test

A static loading has been performed for all specimens in order to establish a baseline for loading rate comparison. The mechanical properties of the joined specimen were recorded after the tensile test was completed. The data of the maximum loads, maximum stress, young modulus and ultimate tensile strength of the specimens that joined adhesively were tabulated in Table 2 and correlation graph of on load versus roughness is shown in Fig.6. The specimens with the maximum load and maximum stress were observed on Al and mild steel that was sandblasted and cured for 24 hours as predicted, compared to the other combinations of mild steel and Al specimens, therefore, both materials obtained a greater bond.

PVC and PC also observed a large bond strength in all the tests. Moreover, the maximum stress observed for most specimen without sandblasting and a 16-hour cure time, had a lower value, compared to the same materials with sandblasting and a 24-hour cure time. Among all tested materials, acrylic proved to be the weakest adherend to the adhesive, as it had the lowest load and maximum stresses with all materials. However, the joint of acrylic and acrylic which are the same material produced a higher result compared to the other non-metallic specimen combinations with acrylic at 16-hour cure time.

Mild steel and acrylic had a greater load and stress, this is because the material had fractured but the machine did not detect the slight break in the bond.

3.4 Types of Failure Modes

3.4.1 Adhesive Failure

Fig. 3 image shows a completely adhesive failure at the interface of the acrylic material which implies that acrylic had poor surface preparation since abrasive blasting and chemical etching did not have much influence on the material.

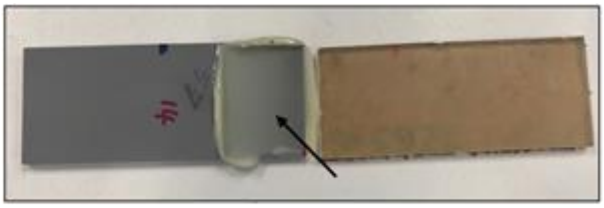

Fig. 3 - Adhesive failure (PVC & Acrylic)

3.4.2 Cohesive Failure

Fig. 4 below shows specimen that have failed cohesively near the interface of the adherents. This failure indicates a good surface preparation and good bond strength between the adhesive and adherents.

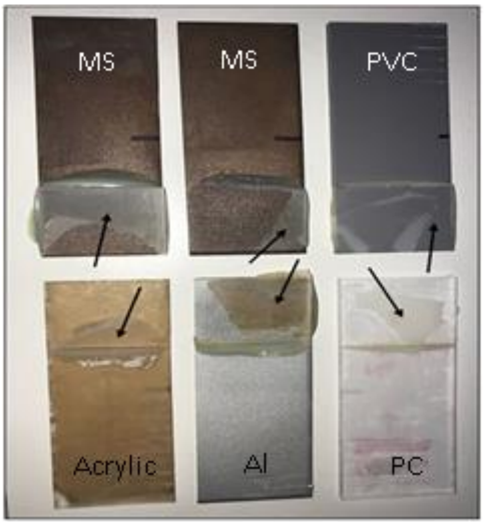

Fig. 4 - Cohesive failure

3.4.3 Fracture Failure

PVC, PC, and glass observed fracture failure during tensile testing as it can be seen in Fig. 5 below, which also indicates a good bond strength between the adhesive and adherents. PVC fractured thrice when bonded with PC and once when bonded with aluminum. However, a weak bond strength was observed when it is bonded with acrylic as seen in Fig 3. Since acrylic adhered less to the adhesive compared to other materials, hence the adhesive failed at the interface of acrylic (Fig 3). Lastly, PVC was bonded to glass which was not tested since glass tends to fracture at the clamp teeth.

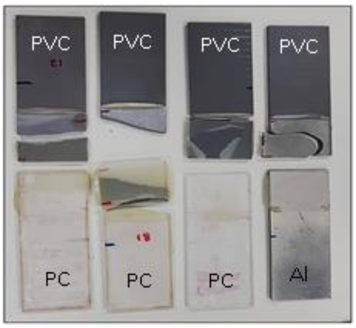

Fig 5 - Fracture failure of PVC and PC

Table 2 - Mechanical properties of the specimen samples

	Materials Bonded	Max Load (N)	Max Stress (Mpa)	Young's Modulus (Mpa)	UTS (Mpa)
16 HOURS CURE	Mildsteel and Al (without sand blast)	1981.30	11.01	49.70	3317000
	PC and acrylic (without sand blast)	683.47	3.80	41.15	1139117
	PC and PVC (without sand blast)	1786.30	9.92	102.85	3187500
	Mild steel and Al	2672.70	14.85	178.81	4454500
	Acrylic and acrylic	808.67	4.49	51.19	1347783
	Acrylic and PVC	621.89	3.46	40.27	1036483
	Mild steel and Al	2263.90	12.58	146.78	3773167
	Mild steel and acrylic	2048.60	11.38	253.59	3414333
24 HOURS CURE	Al and PVC	3568.20	19.82	121.79	5947000
	PVC and PC	1912.50	10.63	119.82	2977167
	Acrylic and PC	897.00	4.98	125.18	1495000
	Acrylic and PVC	697.40	3.87	87.24	1162333
	Mild steel and Al	4517.30	25.10	486.06	7528833
	Al and PC	4057.90	22.54	180.31	6763167
	Mild steel and PC	1904.60	10.58	77.70	3174333
	PVC and PC	1990.20	11.06	50.64	3317000
	Mild steel and glass	386.37	2.15	27.81	643950

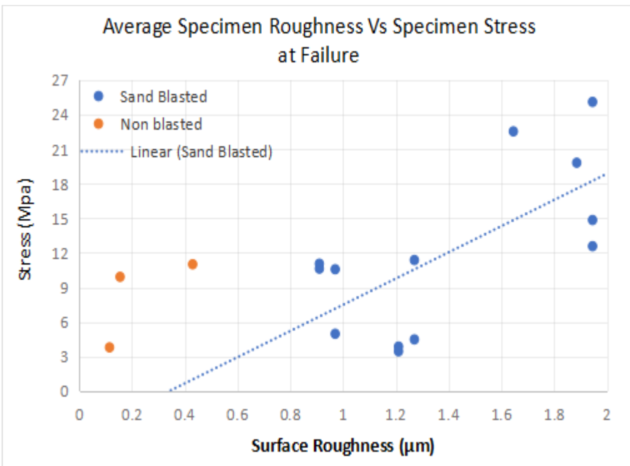

Fig. 6 - Average specimen of roughness vs stress at failure

4. Conclusion

Based on the results, it was evident that sandblasting had a large influence on the surface roughness and that surface roughness of some materials are considered good. Although, too high of a surface roughness is not recommended. Chemical etching also affected the surface roughness for all materials to some extent. In this study, it was found that mild steel, aluminum, and PVC materials were the most suitable materials for adhesive joining.

For future research, more samples of same specimen could be used as a control, with varying surface preparations and cure time, that could be used to identify which surface preparation suits each material. Also, different adhesives may be used and more tests such as impact, peel and cleavage tests could be done to further analyze failure mechanisms within the adhesive joints of multi-materials.

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