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Investigation of the Effect of Layer Thickness of Adhesive Material on Metal to Composite Joints

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Abstract

In this research, fiberglass-reinforced epoxy composite plates and additively manufactured titanium inserts are adhesively bonded. The samples are investigated by tensile and shear bond test methods. After the mechanical tests, topographical evaluations are conducted over the failure surface areas. A 3D profiling method for the inspection of bonded joints has been developed to quantify and compare failure types. It was found that varying the thickness of the adhesive has a significant effect on the load-carrying capacity of the structure under normal direction loading, whereas under shear loading the effect is modest. The research methodology used allows for the qualification and comparison of further bonded structures.

Keywords: *adhesive bonding, metal-composite joint, tensile bond test, shear bond test, topographical examination.*

1. Introduction

The significance of adhesives, used to manufacture load-bearing structures is rapidly increasing in recent years in modern industries (such as in the automotive, construction and E&E industries **[1]**.

Structural adhesives are used for applications, where adherends may be exposed to large stresses. Establishing joints with structural adhesives are favorable in multi-material systems (where materials with dissimilar chemical structure are joined together), thanks to potential advantages such as flexibility in design, simple fabrication, and exceptional strength-to-weight ratio. On the other hand, the load-bearing capacity of adhesively bonded structures is usually limited and several parameters play important roles that can influence the lifespan of these products **[2]**.

Therefore, it is necessary to examine the effect of different parameters in the fabrication of adhesively bonded structures, such as the adhesive layer thickness.

1.1. Failure modes of adhesive bonds

Adhesive bonding is a phenomenon where the connection between two dissimilar structures is established with an adhesive in a way that the transmission of load occurs between the two bodies until the failure of the bond. An adhesive material, when applied on the surfaces of structures (**Figure 1**) connects them as a result of the adhesive bonding process **[3]**.

There are three different failure modes that need to be considered when designing and investigating adhesive joints. In the case of adhesive failure (**Figure 2a**), separation occurs between the adhesive and one of the adherends. In the case of cohesive failure, subsequent failure can occur in the adhesive layer while all the adherends' surfaces remain covered with the adhesive material (**Figure 2b**), or failure can occur in one of the adherends further away from the bond (**Figure 2c**) **[4, 5]**. In many cases, the failure of the bonded joint occurs as a combination (partly adhesive and partly cohesive) of these failure modes **[6]**.

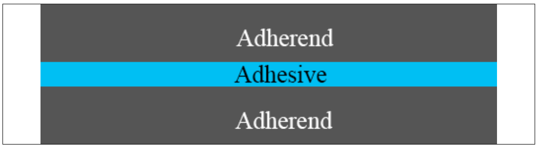


Figure 1. *Typical structure of an adhesive bond.*

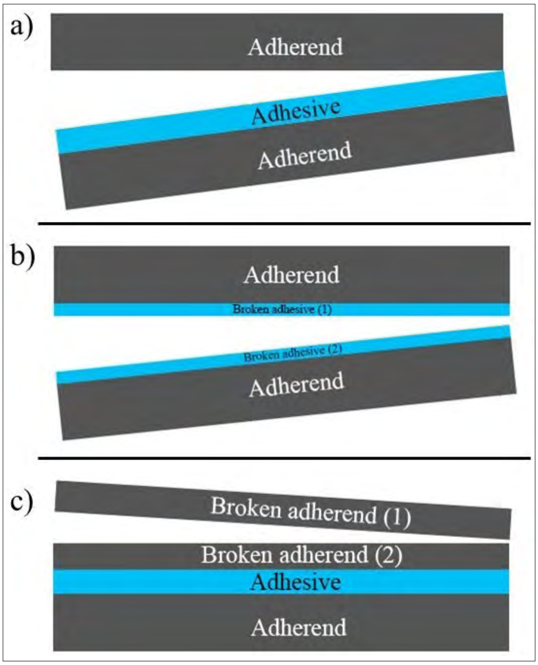


Figure 2. *Typical failure modes of adhesive bonds: (a) adhesive failure, (b) cohesive failure in the adhesive layer, (c) cohesive failure in one of the adherends.*

1.2. Test method

One of the most common methods for evaluating the strength of an adhesively bonded joint is to perform mechanical tests until failure, such as tensile bond strength, and shear bond strength tests [7]. These measurements are suitable to examine the performance and load-bearing capacity of adhesively bonded structures [8, 9].

The quality of adhesive joints cannot be determined by destructive tests alone, there are several properties of the structure that can only be revealed by topographical examinations. This is because, in many cases, the combination of basic failure modes occurs. The ratio of adhesive and cohesive failure areas is an indicator of the quality of the adhesive joint and the whole bonded structure [10, 11].

In this research, normal and shear bond tests were carried out on adhesively bonded multi-material hybrid structures, and the failure surface areas were subjected to visual surface topography. The manufacturer has specified the optimum adhesive thickness (0.05 - 0.1 mm) for shear-loaded joints only, so our aim is to determine its suitability for normal directional loading [12].

2. Materials and methods

2.1. Materials

For the fabrication of composite plates EPIKOTETM Resin MGS LR 235 with EPIKURETM MGS LH 235 two-component (100:35) medium viscosity casting, laminating, and resin system was used as matrix material, with bidirectionally woven glass fiber sheets as reinforcement.

EOS Titanium Ti64 powder (Ti6Al4V), with a grain size of 20 µm was used in the additive manufacturing process of the titanium inserts.

For the adhesive bonding, Araldite™ 2011 two-component (100:80) epoxy adhesive by Huntsman Ltd. Corporation was used.

2.2. Preparation of specimens

2.2.1. Fabrication of the composite plates

The composite plates in the research were manufactured by vacuum-infusion method. In each case, 4 sheets of glass fiber ([0,90]) with a size corresponding to the chosen plate size were placed on top of each other. Particular attention was paid to the surface quality and the uniformity of the structure of the whole plate in order to ensure the repeatability of measurements. Following the crosslinking of the composite, the edges were removed, and 80×80 mm square-shaped pieces were cut from the plates.

2.2.2. Additive manufacturing of the titanium inserts

The titanium inserts were additively manufactured by selective laser melting (SLM) technology using an EOS M100 metal 3D printer. 6 titanium inserts with a base diameter of 25 mm and a height of 14 mm were additively manufactured uniformly and with the same process parameter values.

2.2.3. Establishing the adhesive bonds

For the mechanical and topographical tests, samples were created with five different adhesive layer thickness values. To set the thickness of the glue, metal wires with specified diameter values were distributed between the composite plates and the titanium inserts.

In the first group, as a control group, no metal wire was used. In the following groups metal wires with a diameter of 0.18 mm, 0.23 mm, 0.43 mm, and 1.30 mm were used consequently.

The steps of creating the bonded structure in all cases were similar (Figure 3). All samples were left to crosslink for at least 24 hours in room temperature.

2.3. Methods of measurement

The load-bearing capacity and failure topography of the fabricated samples were evaluated with mechanical and macrostructural investigations. Firstly, after the crosslinking of the adhesive, the specimens were subjected to tensile-, or shear bond tests. For these tests, the same 6 titanium inserts were used in each case, and at the end of each test, the adhesive was burnt off their surfaces at 550 °C so that they could be reused. After the destructive tests, the fractured area of each specimen was examined by a surface 3D optical profilometer.

2.3.1. Tensile bond tests

The tensile bond tests were performed with a Zwick Z005 universal testing machine. The machine was equipped with a ±5 kN measuring cell. The measurements were implemented with a preload speed of 2 mm/min and a test speed (speed of the crosshead) of 10 mm/min. To carry out the measurement, a special clamping device had to be used in the setup (Figure 4).

2.3.2. Shear bond tests

The shear bond tests were implemented with a Zwick Z250 universal material testing machine. The device was equipped with a ±20 kN measuring cell. The same measurement speeds were applied as in the case of the tensile bond tests. In this case, a different clamping tool was necessary in order to perform the tests (Figure 5).

2.3.3. Surface topography visualization

The visual investigation was carried out by a Keyence VR-5200 optical microscope. During the examination, a low magnification (12×) was used with a wide field of vision. The measurement accuracy of the device is ±2.5 µm, and it is equipped with a 4-megapixel monochrome CMOS image-capturing system. After setting the base layer on each specimen, the ratio between the area of adhesive and cohesive failure was calculated using the program of the measuring device. During evaluation, the modes of failure were determined by the height differences on the surface area.

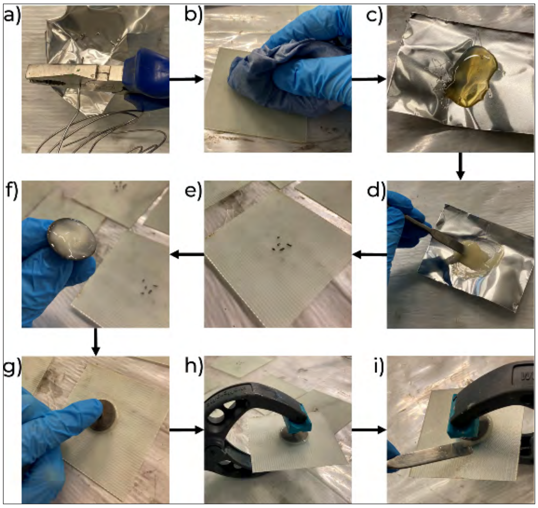


Figure 3. *Steps of establishing the adhesive bonds: (a) cutting wires, (b) cleaning the surface with acetone, (c) proportioning the components of the adhesive, (d) mixing the components, (e) distributing the wires, (f) spreading the adhesive evenly, (g) placing the insert on top of the plate, (h) compression, (i) removing residual adhesive.*

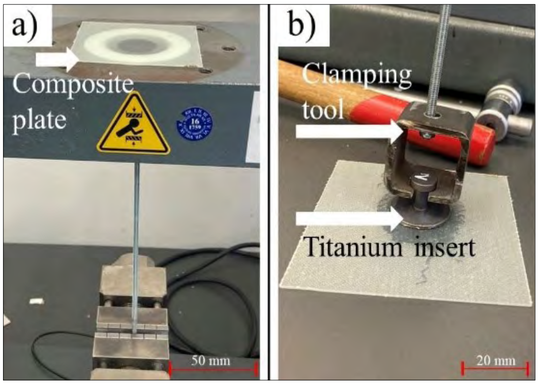


Figure 4. *Tensile bond test: (a) special clamping tool, (b) test setup.*

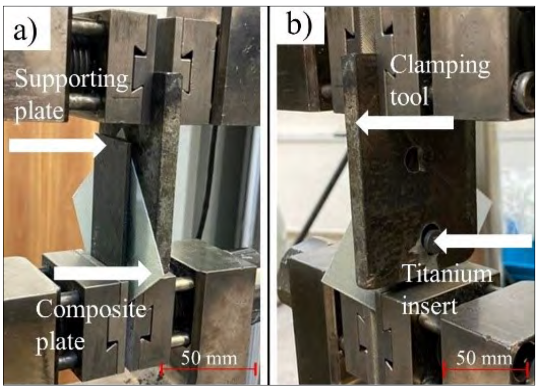


Figure 5. *Shear bond test: (a) backside, (b) front side.*

3. Results

Tensile tests were performed on all five previously mentioned adhesive thickness groups. There were 5 samples in the first group (the control group) and 6 in all others, summing up a total amount of 29 samples.

Shear tests were performed on the first and the fifth group (in which samples were manufactured using 1.30 mm thick wire pieces). Both groups consisted of 6 samples, but one sample had to be excluded from the latter mentioned group due to errors during sample preparation, resulting in a total of 11 samples.

Surface topography was applied to all 40 samples. From the obtained data and the help of the analysis software, the ratio of adhesive (**Figure 6**) and cohesive failure (**Figure 7**) area was determined for each sample.

3.1. Results of the tensile bond tests

The result of the tests can be observed on the depicted diagrams below, where the tensile breaking force as a function of the diameter of the applied wire (and thus, adhesive thickness) is displayed (**Figure 8**).

After the tensile tests, the topographical tests were performed on the same samples. The results are represented below, where the percentage of cohesive failure as a function of wire thickness is depicted (**Figure 9**).

3.2. Results of the shear bond tests

Figure 10 illustrates the outcome of the shear bond tests, with the wire diameter on the x-axis, and the shear breaking force on the y-axis.

Similarly to the tensile tests, the topographical investigation was carried out for all samples after the shear bond tests (**Figure 11**).

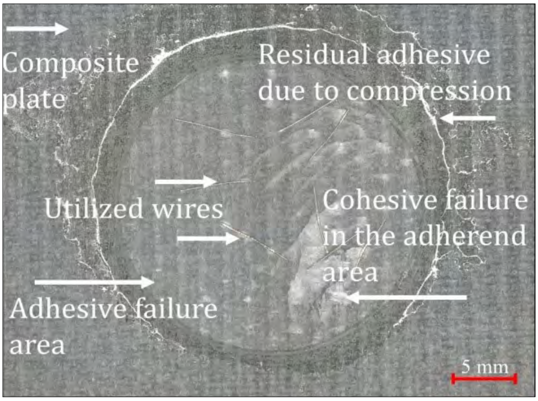
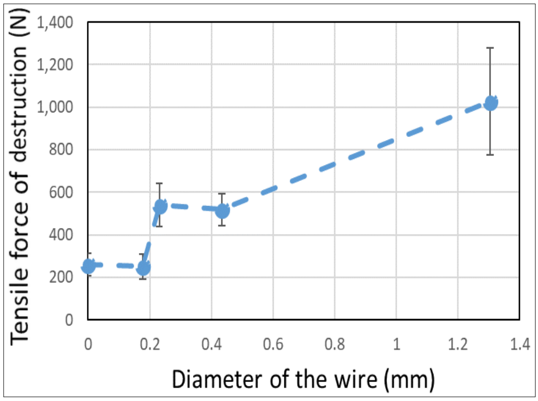


Figure 6. *Surface topography image of a sample with adhesive failure*



8. ábra. *Results of the tensile bond tests*

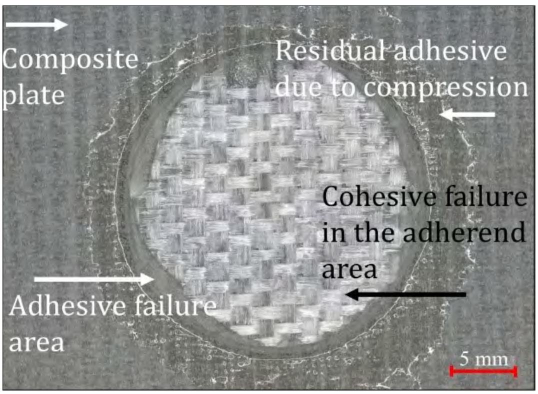


Figure 7. *Surface topography image of a sample with mainly cohesive failure*

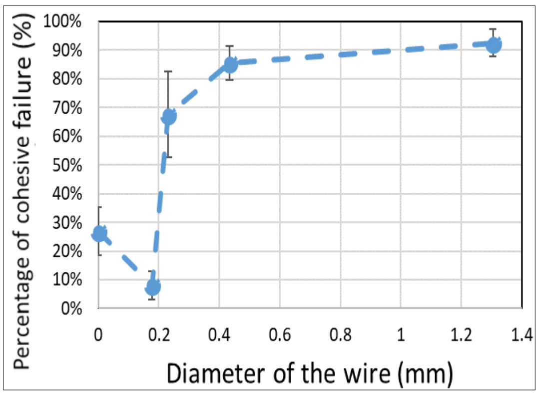


Figure 9. *Topographical investigation results of the tensile bond tests.*

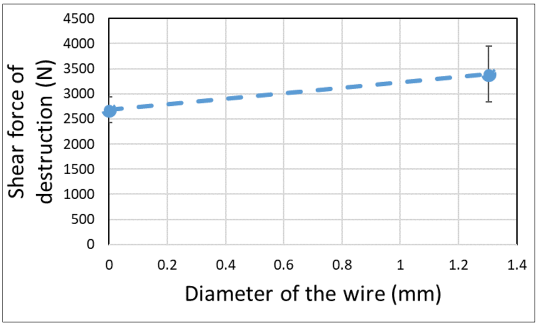


Figure 10. *Results of the shear bond tests*

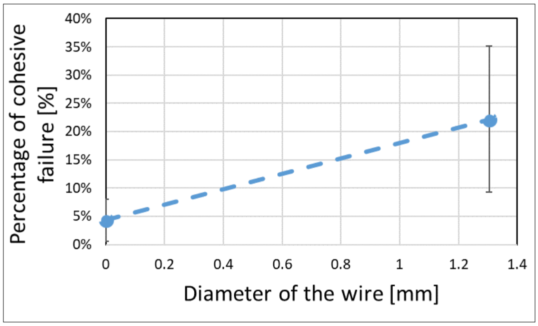


Figure 11. *Topographical investigation results of the shear bond tests.*

4. Conclusions

A total of 40 specimens were made and examined by mechanical and topographical investigation methods successfully in this research. The outcome provides a basis for further comparative examinations of adhesively bonded structures. At the Department of Polymer Engineering of the Budapest University of Technology and Economics, we developed a 3D profiling method for the analysis of adhesive-bonded joints, which allows for the quantification and comparison of failure types, thus facilitating further research in this field.

Changing the adhesive layer thickness has a significant effect on the tensile breaking force. It can be stated that the load direction strongly influences the load capacity of the structure and that the optimal layer thickness is different in each direction.

It can be observed that mainly shear loads should affect adhesively bonded multi-material hybrid structures, since these can withstand remarkably greater forces under shear load compared to tensile load.

Compared to the tensile tests, the adhesive layer thickness did not affect the load-bearing capacity of the bond as substantially as in the case of shear stress.

It is shown that the optimal adhesive layer thickness recommended by the manufacturer (0.05–0.1 mm) is not adequate for normal directional loading, by increasing the layer thickness we were able to increase the bond strength by a factor of 4-5 times.

The results from the mechanical and the topographical investigations show the same tendency, and they are comparable. The percentage of cohesive failure in the fracture area of those samples that withstood greater loads was consistently higher, which may be due to a larger proportion of solid bonding material at the bonding surface.

Considering that the structures we examined are subject to complex loading modes rather than pure shear, which would be favorable from a bonding perspective, it is of great significance to investigate different directional loads. Our research can serve as the basis for further studies in this field. By employing the measurement methodology utilized here, it is possible to optimize the resistance of bonded structures against complex loading.

In summary, it can be stated that this research can provide a starting point for further perfecting adhesively bonded structures and has demonstrated the importance of adhesive layer thickness in the manufacture of complex bonded structures.

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