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Experimental Study of Single-Lap Adhesive Joints to Analyze and Predict the Tensile Strength Values of Aluminum Alloy 6061 Substrates using Artificial Neural Networks

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Keywords:
Adhesive bonding; Surface roughness; Overlap distance; Adhesive strength; Artificial neural network; Prediction values.

Highlights:

- *The effect of the surface roughness and the overlap distance of single-lap adhesive joints on the tensile test values were studied.*
- *The mathematical model representing the relationship between the tensile test value with the surface roughness and the overlap distance was determined.*
- *The mathematical models and artificial neural network (ANN) method were used to predict the tensile strength values and compared the results with the practical experiments.*

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Abstract: Adhesive bonding is one of the essential methods applied in wide fields, mainly automotive and aerospace, because the adhesive can be used with various materials, weighs less compared to other methods, is easy to work with, and does not require many tools. The present research focuses on determining and predicting the ultimate tensile values for single-lap adhesive joints. The mathematical models and artificial neural network (ANN) method predict the tensile strength values. Two variables were used: the surface roughness and the bonding area. To determine tensile test values, ten samples were used with different surface roughness and an overlap distance of 25 and 40 mm. The results showed that the bonding distance had more effect than the surface roughness on the ultimate tensile load. Also, the predicted error values through mathematical models did not exceed 3.209% for the samples, while the ANN samples' error values did not exceed 8.312.

دراسة تجريبية للمفاصل اللاصقة المفردة لتحليل والتنبؤ بقيم قوة الشد لركائز سبائك الألومنيوم ٦٠٦١ باستخدام الشبكات العصبية الاصطناعية

عباس ميثم جابر، عمر هاشم حسون، أسامة حاتم حسين، لجين حسين كشكول
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الخلاصة
يعد الربط بالمادة اللاصقة أحد الأساليب الأساسية المطبقة في مجالات واسعة، وخاصة السيارات والفضاء، لأن المادة اللاصقة يمكن استخدامها مع مواد مختلفة، وتزن أقل مقارنة بالطرق الأخرى، وسهلة العمل، ولا تتطلب العديد من الأدوات. يركز هذا البحث على تحديد وتوقع قيم الشد النهائية للوصلات اللاصقة ذات اللفة الواحدة. تتنبأ النماذج الرياضية وطريقة الشبكة العصبية الاصطناعية بقيم قوة الشد. تم استخدام متغيرين؛ خشونة السطح ومنطقة الترابط. لتحديد قيم اختبار الشد، تم استخدام عشر عينات مختلفة خشونة السطح ومسافة تداخل ٢٥ و٤٠ ملم. أظهرت النتائج أن مسافة الترابط لها تأثير أكبر من خشونة السطح على قيم حمل الشد النهائي. كما أن قيم الخطأ المتوقعة من خلال النماذج الرياضية لا تتجاوز ٣,٢٠٩٪ للعينات، في حين لا تتجاوز قيم الخطأ لعينات الشبكة العصبية الاصطناعية 8.312.

الكلمات الدالة: الترابط اللاصق، خشونة السطح، مسافة التداخل، قوة الالتصاق، الشبكة العصبية الاصطناعية، قيم التنبؤ.

1.INTRODUCTION

In recent years, many car manufacturers have focused on using aluminum in the automotive industry because aluminum is light, highly durable, and corrosion-resistant. The joining process of aluminum with the traditional methods faced many problems and challenges, which led to the search for other ways of the bonding process, such as adhesive. In addition, with the development of the adhesive industry, many engineering industries and automotive industries have used adhesive in the joining process of parts instead of the traditional methods, increasing the part's weight, the energy required to run the mechanical system, and harmful emissions produced from the manufacturing operations and assembly of parts. The adhesive bonding process is an efficient and highly reliable method, knowing that this method does not require cutting or distorting the adherend material. The adhesive bonding process is an efficient and highly reliable method, knowing that this method does not require cutting or distorting the adherend material. Also, the mechanical systems parts are divided into loadable and non-loadable parts, and the adhesive can be used to bond various mechanical components, considering the location and function of the mechanical part to choose the appropriate adhesive for the bonding process. The sample preparation process is done by joining the pieces with the adhesive. The sample quality prepared with adhesive depends on many factors, such as adhesive type, overlap length, and substrate roughness. The surface roughness is an essential factor affecting the bonding strength, as the surface roughness increases the bonding area, increasing the bonding strength. However, increasing surface roughness decreases the bonding strength due to the air bubbles that isolate the bonding process between the adherend pieces [1-4]. Many studies analyzed the preparation and the effect of surface roughness on wettability. They noted that the electrochemical treatment did not affect the machined surfaces by the milling machine but increased wettability. Also, the sandblasting method increased the surface roughness and decreased wettability because this process reshaped the surface topography. Sometimes, more than one mechanical (sandpaper abrasion and grit blast) and electrochemical etching treatment is used to study its effect on surface roughness and wettability. In addition, mechanical and electrochemical treatments improve and increase the sample surface area and surface roughness, significantly affecting the adhesive's bonding quality [5-9]. Predicting outputs is considered one of the essential and widely applied methods in scientific fields because this method reduces sample preparation time costs and is easy to use. The neural network method is considered one of the methods widely used in scientific fields to predict output values based on some experiments prepared in advance based on specific scientific rules. Mathematical models for signal processing use neural networks. The neural network's key benefits include its ability to work with imperfect information and operate autonomously. Many researchers have studied and analyzed using adhesive in the bonding process. Calik A [10] studied the effect of adherend shape on stress concentration reduction using a single lap joint and adhesive material. Aluminum joint material was used for the examined and analyzed samples using six types of jointing to find the best type of bonding during the peel and shear stresses examination process. The results proved that the bonding shape and properties of the adhesive material significantly reduced the stress concentration. Also, the conical, rounded, and tapered shapes showed the highest percentage of decrease in stress concentration. Kai Wei K et al. [11] analyzed the strength and failure of adhesive bond single-lap joints of composite steel. The composite material (Carbon fiber-reinforced plastics (CFRP)) steel single lap joints), two levels of adhesives (7779 and MA830), and four levels of overlap length concerning tensile loading were used. All experiments were analyzed, and cohesion failure was observed when using both adhesives. Stress concentration was observed at the overlap edge, and shear stress was one of the main reasons for the adhesive failure. Jairaja R and Naik GN [12] used two types of adhesives, single and dual adhesive bonds, to analyze lap joint strength between dissimilar materials. The adhesive materials were Araldite-2015 ductile and AV138 brittle separately between different materials (CFRP and Aluminum). The ductile adhesive was placed at the edges of the overlap for its high shear and peel resistance, while the brittle material was placed in the bonding region's center. The results proved that the failure happened at a single adhesive-bonded interface. At the same time, binding strength was more significant in dual bonding when brittle adhesive (20% of bond length) was used in the bond's center; when the brittle adhesive was increased by 40% of the bonding area, it decreased the bonding strength of the dual adhesive bond. Barbosa NG et al. [13] studied the effect of the bonding shape and the type of adhesive material to identify its suitability for engineering joints. Four types of joints (SLJ, DLJ, stepped-lap, and scarf) and three types of adhesive were used. The results proved that the optimal type of joint depends mainly on the adhesive material. The ductile and less brittle adhesive was recommended for the joint geometry subjected to stress variation. Still, the strong and brittle adhesive was better for the joint geometry subjected to regular stresses. Gajewski J et al. [14] used numerical models and neural networks to simulate dual adhesive single-lap junctions through a uniaxial tensile test. To develop a dual adhesive junction that was rigid and strong, various criteria, including adherents thickness, the point bonded joint radius, and material parameters for the adhesive layers were used. A point-bonded joint in the overlap's axis was more rigid and strong, and on the outside, a bonded joint was constrained by the overlap's margins and had less stiffness and strength. A key finding from the studies was that the thickness of one adherend has little impact on variations in maximum force and fracture energy. Additionally, testing joints with a radius between 2 and 6 mm did not impact the maximum force and fracture energy, whereas a radius between 8 and 16 mm produced more sensitive responses. Furthermore, the study demonstrated how sensitive dual adhesive joints were to the proper choice of material parameters for both adhesives. Tosun E and Calık A [15] used artificial neural networks of single-lap adhesive joint specimens subjected to tensile loading to predict the failure load. All the tensile data from the literature included two input parameters covering the length and width of the bond area and the ultimate failure load as output. The results proved that the artificial neural network model was a significant method to estimate failure load acceptable error with training and testing data equal to 3.523 and 3.524, and 0.997 and 0.992, respectively. The research objective is to investigate the effect of surface roughness and overlap area on ultimate tensile load. Also, to determine the mathematical model based on practical experiments to predict the tensile values. In addition, to support the results, ANN is used to obtain the best results, considering the error percentage between the practical and the predicted values.

2.EXPERIMENTAL SETUP

2.1.Materials and Methods

The aluminum alloy 6061 specimens were overlapped and joined in this research by the adhesive materials SikaPower 4720. The mechanical properties of the aluminum alloy 6061 and adhesive materials are shown in Table 1. The specimen dimensions were 125×25 mm with a thickness of 2 mm. The surface has adhered to the adhesive with different surface roughness to produce various cross-linking between the adhesive and the specimen surface.

Table 1 Specimens and Adhesive Materials Properties [16, 17].

Aluminum alloy 6061		**Adhesive materials-SikaPower 4720**	
Density (kg/m³)	2.70 g/cc	Density (kg/m³)	1080
Elastic modulus (GPa)	68.9	Elastic modulus (GPa)	-
Poisson's ratio	0.33	Poisson's ratio	0.36
Yield strength (MPa)	276	Yield strength (MPa)	23.28

Experimental specimens were divided into two groups according to the type of overlap distance (25 and 40 mm) for ten specimens with various surface roughness values used to prepare the specimens. Some samples were made to verify the validity of the experiments.

2.2.Sample and Surface Roughness Preparation

All samples were prepared to investigate the effect of overlap distance and surface roughness variables on ultimate tensile load. The samples were prepared to be cut according to the required dimensions, and any unwanted metal parts were removed from the edges of the metal pieces. After that, sanding paper was prepared to produce the components used to prepare the samples. Different sandpaper roughness was used to obtain different surface roughness and increase the bonding between the adhesive and the sample surface. The preparation of a surface for each aluminum piece took 30 minutes. Five types of sandpaper were used to prepare the surface: 40, 60, 80, 120, and 400 grit. The surface roughness was measured after using sandpaper for each piece to obtain data on the prepared surfaces. In addition, the Mahr-

MarSurf PS1 device (Measurements Lab-Department of Production and Metallurgy Engineering / University of Technology) was used to test the roughness of all specimens after the surface preparation. Figure 1 shows all the dimensions and details of the specimen. The thickness of the adhesive was 1 mm, while the thickness of the shim was the thickness of the adhesive material plus the thickness of the aluminum specimen. The overlap method was used for bonding by adhesive. Also, after adding the adhesive, some fixtures were used to protect and immobilize the sample.

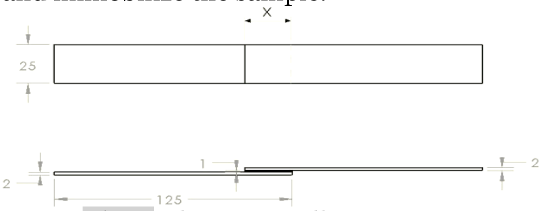

Fig. 1 Aluminum Alloy Specimen Configuration with Single-Lap Adhesive Joints.

After increasing the surface roughness with sandpapers, the first step in the sample preparation process was preparing the adhesive and mixing it well before using it. Then, the shims, plates, and holders were prepared to obtain the required thickness of the adhesive, not incline the sample, and fix the sample and not move it until the process of adhesive cohesion was completed. These precautions led to obtaining high-quality specimens, see Fig. 2.

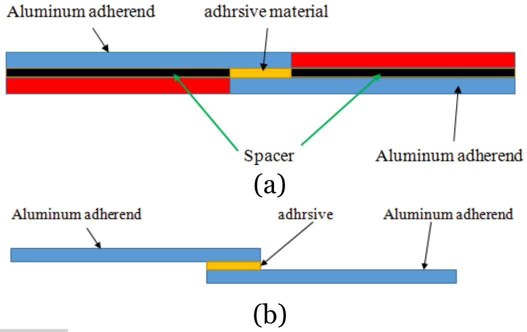

Fig. 2 Specimens' Preparation (a) Sample with Holder and Spacer (b) Sample After Removing the Holder and Spacer.

2.3.Testing Results

Ten tensile test experiments were conducted for samples with different surface roughness and overlap areas. The results proved that the surface roughness and the samples' overlap area affected the tensile strength, as shown in Table 2. Figure 3 shows the effect of the adhesion surface roughness and the overlap zone of the sample on the ultimate tensile load. The samples had an overlap distance of 25mm, with a gradual rise in the most significant ultimate tensile load. The greater the roughness, the ultimate tensile load of the sample increased. As for the samples with an overlap zone of 40 mm, there was a fluctuation of the ultimate tensile load; however, the 40mm of the samples remained higher than the samples with an overlap of 25 mm.

Table 2 Experiments Details and Tensile Test Results.

Overlap distance (mm)	Surface roughness	Ultimate tensile load (KN)
25	5.26	4.352
25	4.793	3.712
25	4.563	3.672
25	3.832	3.168
25	1.852	3.352
40	5.734	6.68
40	5.374	6.4
40	4.346	6.32
40	3.829	6.64
40	1.737	6.36

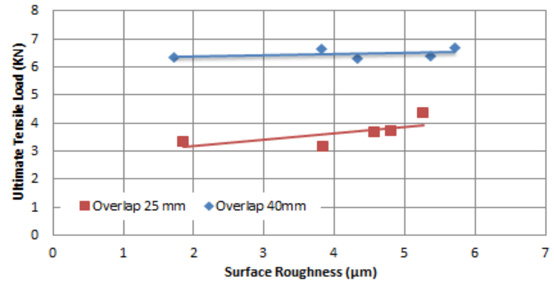

Fig. 3 Relationship between Surface Roughness and Ultimate Tensile Load of Different Overlaps.

3.DATA ANALYSIS

Data analysis is considered one of the most critical processes for analyzing the results by relying on the input variables to obtain information that can be used in supporting research and future experiments and clarifying vague information in scientific research.

3.1.Mathematical Models to Predict the Ultimate Tensile Load

The mathematical model of the ultimate tensile load was determined based on the roughness of the adhesion zone and the overlap distance to predict the value of the ultimate tensile load for samples. Two mathematical models were determined based on the results of the first tensile test for 25 overlap samples and the second model for 40 overlap samples, as shown in Eqs. (1) and (2).

$$y = 0.2675x2 - 1.6202x + 5.4378 \quad (1)$$

$$y = 0.0047x2 + 0.0076x + 6.354 \quad (2)$$

where y is the ultimate tensile load, and x is surface roughness.

3.2.Prediction Process

A neural network is a machine learning method that deals with data that use the same neurons as the human brain in multiple layers. The predicted values were obtained using Eqs. (1) and (2). Also, the artificial neural network (ANN) method was used to predict the ultimate tensile load value using the MATLAB program. Samples data were entered with the tensile test results to predict the ultimate tensile load and ten hidden layers were used to predict the ultimate tensile load values. Error values were also calculated, and all results were less than 9%, as shown in Table 3.

Table 3 Experiments Details, Tensile Test Results, and Predicted Values.

Overlap (mm)	Surface roughness	Ultimate tensile load (KN)	Predicted Value (KN)	% Error	Predicted value (KN)-ANN	%Error
25	5.26	4.352	4.302	1.148	4.313	0.901
	4.793	3.712	3.805	2.508	4.021	8.312
	4.563	3.672	3.603	1.872	3.734	1.696
	3.832	3.168	3.149	0.597	3.186	0.574
	1.852	3.352	3.352	0.005	3.435	2.468
40	5.734	6.68	6.493	2.798	6.333	5.189
	5.374	6.4	6.508	1.693	6.400	0.007
	4.346	6.32	6.523	3.209	6.321	0.022
	3.829	6.64	6.514	1.900	6.640	0.002
	1.737	6.36	6.366	0.094	6.360	0.001

The results showed that the amount of the predicted value of the ultimate tensile load was close to the experimental results, so this step is considered vital to reduce the number of practical experiments and rely on the mathematical model determined to predict the samples' ultimate tensile load, see Fig. 4. While analyzing the readings of the sampling process using the ANN method, the Levenberg–Marquardt (trainlm) algorithm was used to determine the connection values representing the relationship between the output and the target. The R values, whenever they are close to one, indicate a close relationship, and vice versa. Two R values were determined, one for overlap 25 and 40 mm overlap samples, where the values were close to one for two types of samples (0.99778 and 0.9999), see Fig. 5. By comparing the research results with previous research [18], some critical common points were identified in this research, as the surface roughness and the overlap area are considered essential factors that help increase the ultimate tensile load, significantly increasing the overlap area. Furthermore, the method of determining the mathematical model and ANN are considered successful methods in scientific research to predict the values of outputs without the need to prepare new experiments, considering the same variables used in preparing the mathematical model. The results were close to the actual results, with some deviations between the practical sample tests and the predicted values. It was noted that the ultimate tensile load for the overlap samples was 25 mm millimeters compared to previous research. It was noted that the results in this research of ultimate tensile loads were slightly less for the 25 mm overlap samples than the previous study due to the large thickness of the adhesive used, which was 1 mm. However, the ultimate tensile load increased when the overlap area increased to 40 mm, indicating that the overlap area is an essential factor influencing the increase or decrease in the ultimate tensile load of the specimens.

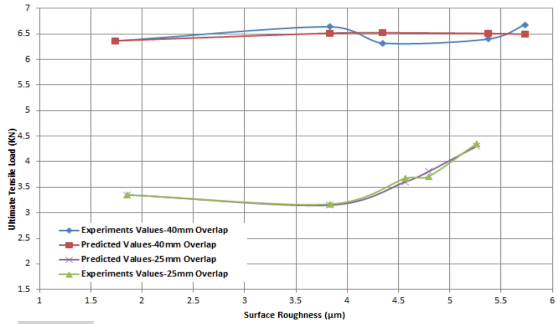

Fig. 4 Experimented and Predicted Values of Ultimate Tensile Load.

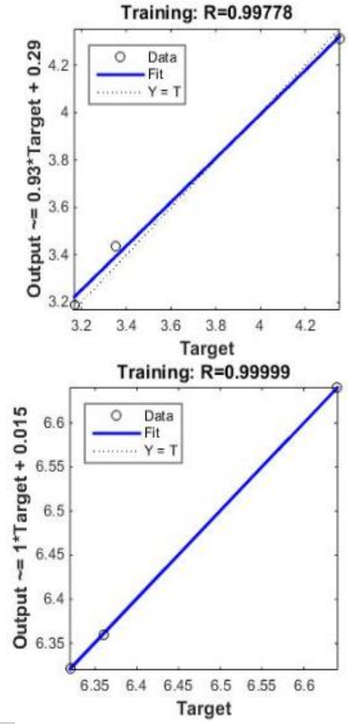

Fig. 5 Regression Plots of 25 and 40 mm Overlap Samples.

4.FAILURE ANALYSIS

After conducting the tensile test, the failure analysis of the samples is an essential point that the researchers focus on to identify the failure in terms of its type and how it started and evolved while applying a tensile load to the samples. The tensile strength of the samples depends on many factors; however, there are essential factors, such as surface roughness, load, and the length and width of the overlap, so it is necessary to search and understand the variables that affect the samples to increase the samples' strength. There were three types of adhesive material failure: adhesion cohesion failure, adhesion failure, and the third type was a combination of the first and second types. In the first type, failure occurred in the center of the adhesive parallel to the surface. In the second type, the adhesive will be completely separated from the surface of the adhesion, while in the third type, approximately fifty percent failure occurred in the adhesive's center in the longitudinal direction, and the other half of the material completely separated from the adhesion surface. Figure 6 (a) shows one of the sample failure types, where the failure process occurred due to adhesive failure through cracks in the adhesive. Figure 6 (b) shows sample failure due to the growth of cracks from the separation area between the adhesive and the adhesion surface, causing the sample to fail from the middle. Figures 6 (c), (d), and (e) show samples failure due to separation of the adhesive from the adhesion surface causing sample failure. Figure 6 (f) shows the sample failure due to the growth of cracks on one side until the adhesive material separated from the adhesion surface. Also, after the overlapping process of the pieces by the adhesive, attention must be paid to the edges of the adhesion areas, where the adhesive must be leveled with the edges of the adhesion surface regularly and not let the adhesive material come out randomly and irregularly from the edges of the pieces in the place of adhesion to avoid the growth of cracks and the formation of air bubbles that accelerate the failure of samples during the tensile test process.

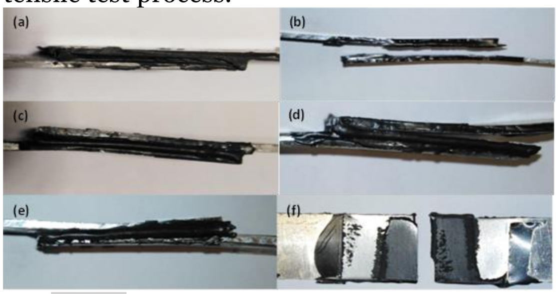

Fig. 6 Failure Types of Specimens that Happen During the Tensile Test.

5.CONCLUSION

This work predicted the ultimate tensile values by changing the samples' surface roughness and overlapping distance. Five experiments were conducted for each type of overlap distance, 25mm, and 40mm, to determine the mathematical model of the ultimate tensile value. Also, the neural network method was used for predicting the load amount to improve the results and compare the results with the mathematical models' results. The overall conclusions of the research can be summarized as follows:

- The ultimate tensile value of the sample increased as the surface roughness of the adhesion region increased due to the increase in the cohesion area between the adhesive and the sample surface.
- Increasing the overlap distance from 25mm to 40 mm with almost 5.3 surface roughness increased the ultimate tensile value from 4.352 to 6.68 KN.
- The overlap area is a significant factor in increasing the ultimate tensile load, as there is a direct proportionality; increasing the bonding area increases the ultimate tensile load.
- The error values for the predicted ultimate tensile load did not exceed 3.209 percent and 8.312 percent of the mathematical model and ANN, respectively.

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