The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2020

Volume 11, Pages 33-40

IConTES 2020: International Conference on Technology, Engineering and Science

Investigation of the Effect of Varying Laser Scribe Sizes on the Adhesion Performance of the Aa2024-T3/Cfrp Joints Depending on the Number of Laser Scan Repeats

Seda AYBALIK
Kocaeli University

Onur COBAN
Kocaeli University

Mustafa Ozgur BORA
Kocaeli University

Erhan AKMAN
Kocaeli University

Belgin GENC OZTOPRAK
Kocaeli University

Abstract: One of the laser surface treatment parameters of "scan repeat number" was optimized for the adhesion performance of AA2024-T3/CFRP joints according to the variation of laser scribe sizes. Laser surface structuring was performed with previously optimized laser machine parameters from 1 to 9 "scan repeat number". After laser surface treatments with the increased scan repeat number, the characterization of the substrate was established by surface morphology and the dimensions of laser scribes. The adhesive bonding of laser-treated AA2024-T3 and untreated CFRP was applied and single-lap shear tests were then performed. The fracture surfaces of substrates were observed and analyzed to determine failure modes. The results indicated that laser scribe geometrical parameters have a significant effect on the adhesion performance of AA2024-T3/CFRP joints. The adhesive bonding strength was enhanced and the maximum value was 26.48 MPa (with 5 scan repetition) increasing by 39% compared to the adhesive joints without surface treatment of AA2024-T3 adherend. The observed failure modes on both the adherend surfaces have demonstrated that the mechanical interlocking mechanism between the adhesive and laser textured aluminum adherend with optimized scan repeat number has been well-worked.

Keywords: Laser treatment, Adhesive bonding, AA2024-T3, CFRP, Mechanical interlocking

Introduction

In order to benefit from the advantages of using composite materials widely used in aviation with light metal materials, a bonding method is developed instead of traditional (rivet and bolt) methods. There are two dominant mechanisms in adhesive bonding: the chemical adhesion mechanism between the bonding surfaces with covalent or weak van der Waals forces, and the mechanical locking mechanism where adhesion is achieved by the rough surface. Advances are being made in the field of surface engineering as these two mechanisms work together to improve adhesion strength.

Mechanical interlocking adhesion theory is defined by the fact that good adhesion occurs only when an adhesive enters the pores, holes, cracks, and other irregularities of a substrate surface and mechanically locks into the substrate (Singh, 2004). Generally, the most common methods applied for preparing surfaces are mechanical (sanding, sandblasting, brushing, etc.), chemical (chromic-sulfuric acid etching or conversion coating, etc.), electrochemical (chromic or phosphoric acid anodization, etc.), and adhesion enhancing coating agents (silane and sol-gel, etc.) (Kwakernaak, 2012). Besides, methods such as plasma and laser processing, which are much newer, controlled, reproducible, low labor, and less harmful to health and the environment, are also used. Mechanical and chemical methods applied to surfaces are harmful to human health and the environment to varying degrees. Another method that eliminates the disadvantages of existing traditional effective methods and continues to be researched is the laser surface treatment method. The changes caused by laser radiation locally in the crystal structure, chemistry, and morphology of the material cause changes in the application behavior of the material (Sugioka et al., 2010). Also, the laser's ability to transfer large amounts of energy to the material in a region close to the surface, within specified limits and in a very short time allows the properties of the material to change locally and superficially (Sugioka et al., 2010). Studies using laser processing technique in the modification of surfaces to increase the adhesion strength between aluminum alloys and structural adhesives are much less than cleaning, melting, and alloying alloys using the same laser devices.

The effect of laser parameters on surface treatments has been the subject of many studies. Wu et al. (2020) reported that the pores formed on the surface of the 5052-Al alloy as a result of laser surface treatment with different laser power are small as a result of low laser power, but the pores become narrow and long with increasing laser processing power. Feng et al. (2020), examined the effects of single-shot energy, number of pits per square millimeter, and laser surface treatment (hitting the surface) angle parameters as laser processing parameters for the adhesion strength of 30CrMnSiA steel. They concluded that increasing the adhesion surface area can be achieved by increasing the diameter and depth of the pit formed due to the increase of laser pulse energy or by increasing the density of the marks on the surface. Vidal et al. (2014) investigated the change of bond strength depending on different depths, widths and proportions opened to the steel surface in the hybrid joining of steel metal with 30% glass fiber reinforced PA6 composite. In this study, which focused on the number of pulses sent to the surface, they found that the depth, which increased with the number of pulses, increases the bond strength.

Wunderling et al. (2020), processed the surface with circular oscillations using a continuous pulsed laser in to increase the bonding surface area of the steel material. It has been concluded that the microstructures created by changing the groove spacing are highly dependent on the bond strength value. Alfano et al. (2012), examined the effect of power, scanning speed, and line spacing on the bonding strength as an example showing laser surface treatment in epoxy bonding with AA6082-T6 aluminum alloy. It was emphasized that the mechanical locking mechanism, which also increases the adhesion strength thanks to the grooved structures obtained as a result of the relevant processes, provides interface toughness by preventing energy absorption and crack propagation.

As a result of the literature review, it is concluded that the depth, width, depth/width ratio of the groove type traces, which determine the density in the adhesion area and especially activate the mechanical locking mechanism, must be investigated for adhesion performance of AA2024-T3/CFRP joints. These parameters have been studied mostly for steel materials in the literature and were chosen to fill the gap in the literature in terms of their effects on aluminum alloy and CFRP adhesion strength.

Materials and Methods

The materials selected to be bonded for this study are AA2024-T3 aluminum alloy 1.6 mm thick and unidirectional carbon fiber reinforced epoxy (CFRP) $[0]_8$-layer composite with a thickness of 2.3 mm. Each sample was cut in dimensions (t x 25.4 x 101.6 mm^3) specified in the ASTM D5868-01 standard and the samples were made ready for laser processing.

Two-component Loctite EA 9396 AERO (A-epoxy-based, B-amine-based), which is widely used in joining aviation materials, was used as an adhesive in the bonding process of AA2024-T3 and CFRP specimens. This adhesive, which has low viscosity (liquid form) and curing at room conditions, also exhibits the best strength properties in the temperature range of -55 C to 177 ºC.

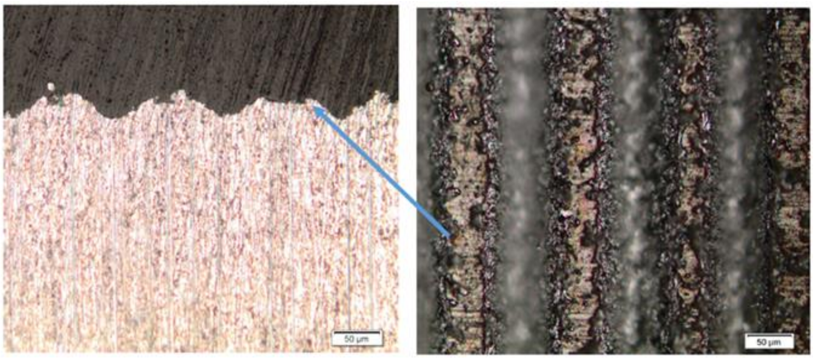
For laser processing of the aluminum sample surfaces, a pulsed fiber laser with a maximum power of 50 W was used. This laser operates at 1064 nm wavelength with a 100 ns pulse duration and a repetition rate range of 20 to 80 kHz. To process the desired surface area on the samples, a galvanometric system that provides a computer-controlled movement of the laser beam to the desired area is used with a 160 mm focal length F-Theta lens to focus the laser beam. Only aluminum surfaces were laser treated, CFRP samples were used as manufactured surfaces to investigate especially laser treatment process effect on the aluminum surface.

It was determined that the process took place without sufficient time for the laser in the parameter combination where the scanning speed, which is the most effective parameter, the highest (1500 mm/s), and the laser power the lowest (20 W). Therefore, a shallow scan forms on the material. The microstructure formed due to the lowest scanning speed (100 mm/s) and a medium level of power (35 W) has been observed to be formed as "chaotic" in the literature. It has been determined that with sufficient energy and time in terms of laser-material interaction, the permit that occurs due to the falling of another spot on the surface of the material is heterogeneous indentations rather than grooves. It has been determined that the laser scanning speed is 800 mm/s, the laser power is 50 W and the laser frequency is much deeper (30 µm) after the 80 kHz process parameters. As a result of laser processing, marks that could be effective in terms of mechanical locking were made with a single pass laser process. According to the range of these laser process parameters in our previous study Bora et. al (2020) optimized the laser process parameters in order to obtain optimum effective laser groove with single-pass as shown in Table 1.

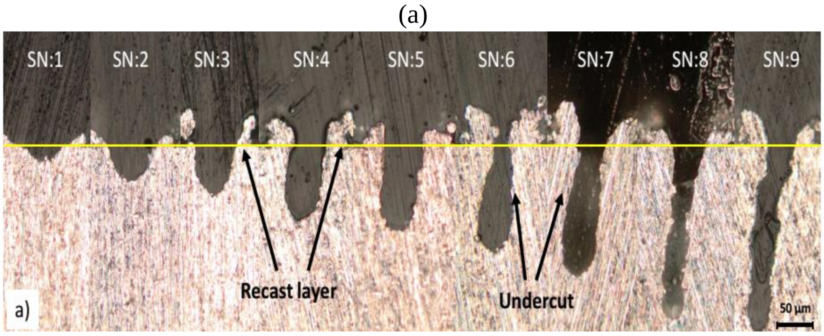
Table 1. Pre-optimized laser processing parameters for one pass

Scanning Speed (mm/s)	800
Laser Power (W)	50
Frequency (kHz)	80

Aluminum samples were processed with pre-optimized laser parameters from 1 to 9 "scan repetitions" to create grooves with different depths and widths. However, considering the laser effect area in terms of processing, the distance between the grooves is greater than 60 µm, thus allowing the geometric structure of the groove to be examined much more clearly. For this purpose, the distance between the grooves was accepted as 120 µm, and 208 grooves were processed along the width for the laser processing area of 25 x 25 mm^2 (Fig. 1-a). Depending on the increase in the laser scan repetition, the cross-sectional images of the modified AA2024-T3 surfaces were taken and given in Fig. 1-b. From these images, geometric parameters such as depth and width of the formed grooves were examined and dimensional changes were recorded.



(a)



(b)

Figure 1. (a) Top view of the grooves processed with 120 µm intervals with single-pass laser treatment (b) cross-sectional views of the grooves formed depending laser scan repetition

Zwick universal test machine was used which had a capacity of 30 kN at TUBITAK-MAM for determining the adhesive shear strength of CFRP/Al adhesive joints. The single-lap test speed was selected as 13 mm/min according to ASTM D5868-01 standard. By adding the grips (Fig. 2) on both sides of the test sample, the load transferred along the bondline region.

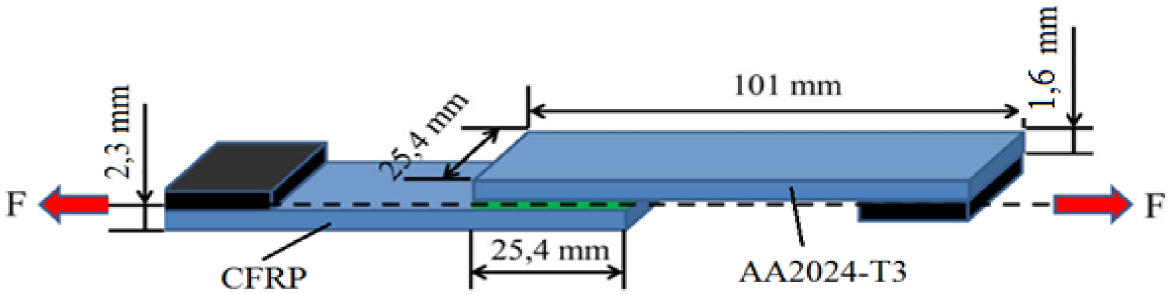


Figure 2. Dimension of single lap joint of Al/CFRP adhesive joint [Bora et. al (2020)]

Results and Discussion

The geometric parameters of the obtained grooves are measured as schematized in Fig. 3-a, and their state of change is plotted graphically and shown in Fig. 3-b and c. As seen in Fig. 1 and Fig. 3, as the laser scan repetition was increased, the depth increased linearly from approximately 25 µm to 200 µm. Contrary to increasing the depth, as the laser scan repetition increased, the width decreased up to 6 repetitions, albeit slowly, and then increased again. As it is seen in Fig 1, until the 5th laser transition, the groove went deeper in the same width without creating an under-cut ratio. In the 6th laser transition, it is seen that the lower part of the cut ratio is formed after a narrow entrance as a result of a significant decrease in the entrance width of the groove. After the 7th laser transition, it was determined that both the width and the depth continued to increase significantly. If it is added, it is seen that in the 8th scan repetition the groove depth increased while the wall becomes more indented and protruding.

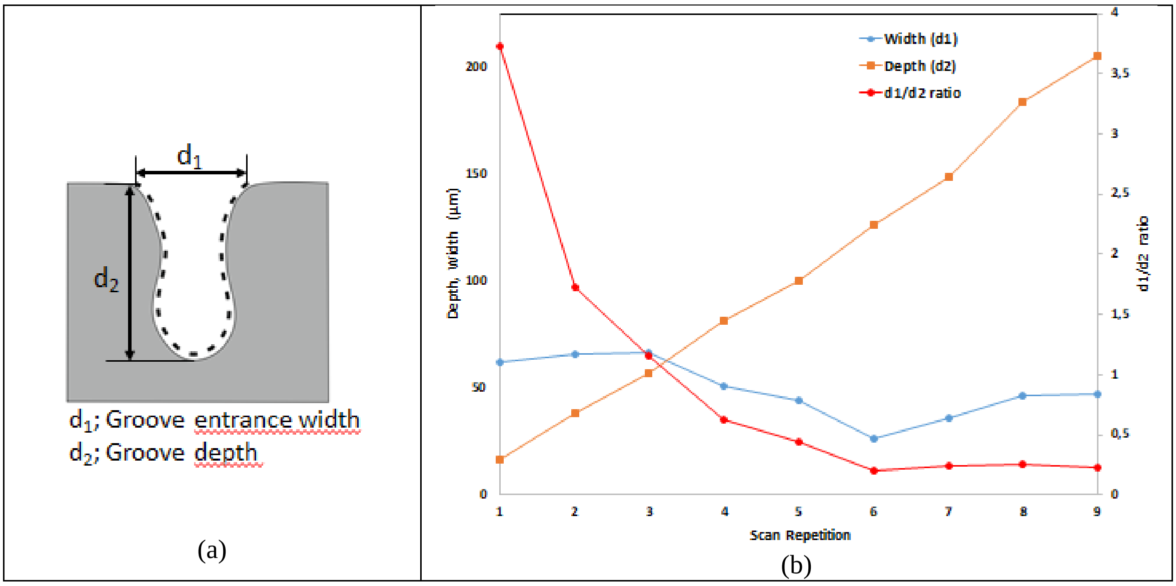


Figure 3. Schematic representation of the geometric dimensions of the groove formed by increasing the laser scan repetition of the single-scan laser processing process (a), the change of geometric parameters (b)

To evaluate the adhesion shear strength not only according to the roughness that occurs depending on the depth of the formed grooves but also in terms of the spreading ability of the adhesive, the contact angle measurements of the laser scan repetition samples were made. Very low contact angle values were obtained in single repeat processed samples. This situation supports the achievement of higher bond shear strength results than the untreated sample. Contact angle measurements were carried out to examine the effect of the laser scan repetition on the contact angle and adhesive spreading performance in the samples processed with 120 µm spaced grooves with the laser scan repetition process. While it was observed that pure water spread very rapidly by dropping it on the surface of the sample, shown by the red circle in Fig. 4; therefore, a photograph that could analyze the contact angle could not be recorded. While the situation was the same for all the laser scan repetition, the contact angles were accepted as ≈0° and it was determined that the surfaces were in super hydrophilic character in this case.

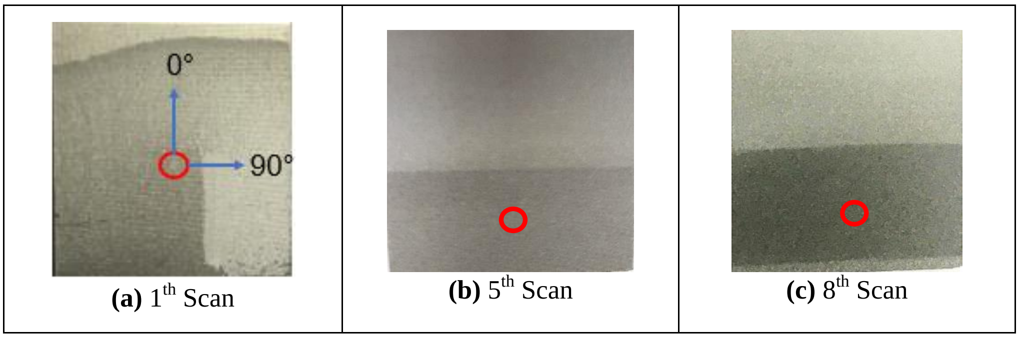


Figure 4. Contact angle results depending on the laser scan repetition

Fig. 5 shows that AA2024-T3 / CFRP adhesion shear strength was obtained as 19.03 MPa for a single repeat of the laser process. As the laser scan repetition of the same laser processing process was increased, the highest bond strength value was obtained in the 5th repeat as 26.48 MPa. This increase in adhesion shear strength has been attributed to the increase in depth, despite the slight decrease in width.

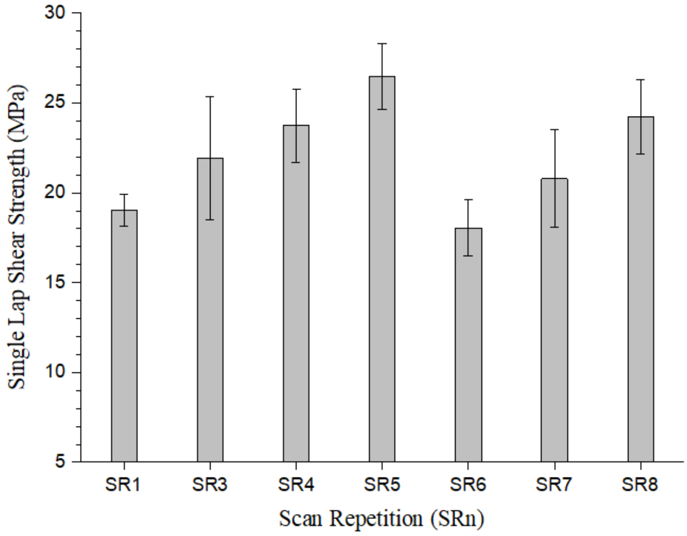
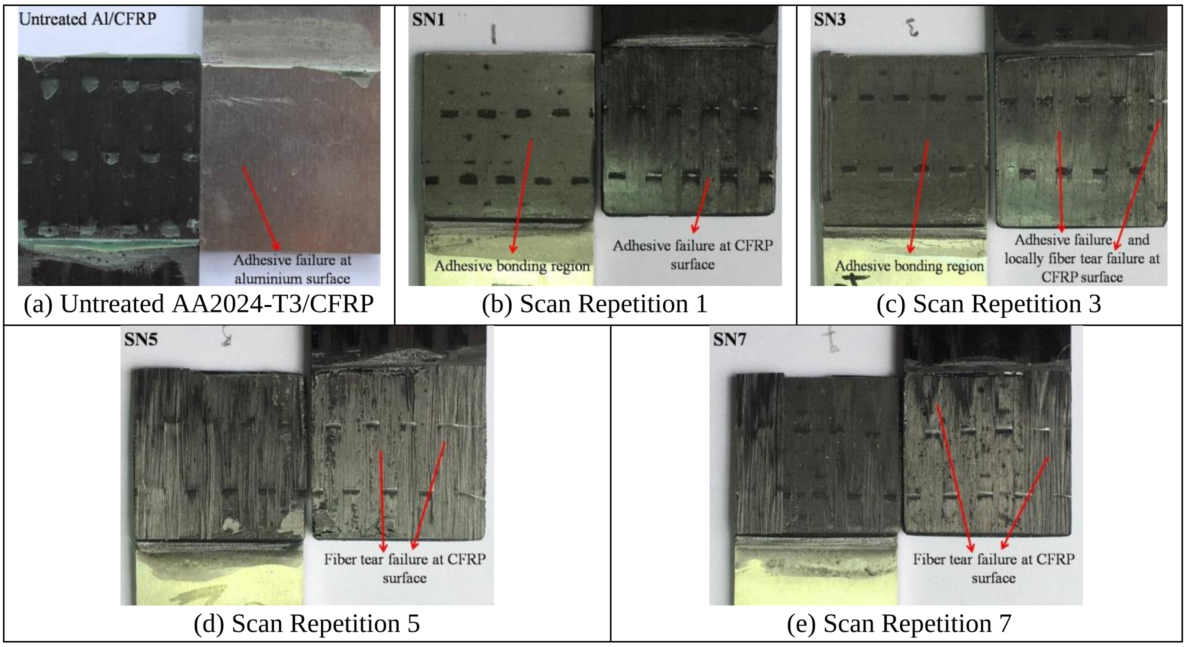


Figure 5. Single lap shear strength depending on the laser scan repetition

While the gradual increment in adhesion strength after each repetition, it is noteworthy that there is a significant decrease of 18.04 MPa in the 6th repeat. While the significant decrease seen here can be attributed to the inability of the adhesive to fill the inside of the groove, it is seen that the adhesive fills the grooves well after each repeat as seen in Fig 1-b. The reason for the decrease in adhesion shear strength was attributed to the very narrow groove width and the naturally short cross-section length of the adhesive section carrying the load in the shear direction. With the passages after the 6th repeat, it has been determined that the width of this entrance section continues to increase again, albeit slowly, and the adhesion shear strength has also begun to increase again.

Wu et al. (2020) noted that the groove depth has a negative effect on the adhesion shear strength. In this case, the viscosity of the polymer that will fill the groove is important. The researchers stated that while bonding 5052-Al alloy and polyamide 6 based CFRTP materials, the PA6 polymer in the composite structure is thermoplastic-based and melted under heat and cannot penetrate the rough structure, the depth of which increases from 120 µm to 240 µm on the aluminum alloy side, and that a gaped connection is provided and the strength is reduced. Considering this situation, the adhesive used in the study has been provided with a low viscosity considering that it will serve the target of the research better and it is seen in the section photographs in Fig. 1-b that the grooves fill the groove according to the decreasing width and increasing depth.

The CFRP material was adhesively bonded with AA2024-T3 alloy, which has been treated with different laser scan repetitions and then subjected to individual lap slip tests to determine the adhesion performance. Photographs of the broken coupon sample pairs were taken to examine the damage modes of the broken connections after the mechanical tests and are given in Fig. 6. The damage types of the joints are given in comparison to the untreated AA2024-T3 / CFRP bond joints. In Fig. 6, it is determined that the types of damage according to the untreated AA2024-T3 / CFRP bonding joints change from adhesive damage on the aluminum surface (Fig. 6-a) to adhesive damage and fiber rupture on the CFRP surface (Fig. 6-b-e). As stated in Ebnesajjad (2014) study, if the adhesive does not fully wet the bonded surface, optimum adhesion cannot be achieved. In this context, damage to the untreated AA2024-T3 / CFRP connections occurred at the aluminum / adhesive interface. It has been determined that all laser scan repetition processes performed with the fiber laser process increase the adhesion of the adhesive and aluminum material and the damages caused by mechanical tests in the bonding joint have shifted to the surface of the CFRP material without any front surface treatment. Especially, as seen in the single lap shear test results, when the laser scan repetition is 5 and 8, the shear strength values reach the highest values. From the digital images given in Fig. 6-d and e, it is obvious that fiber tear damage is at the forefront. The presence of grooves of different depths and widths created with different laser scan repetition on the aluminum material surface increased the aluminum / adhesive adhesion by providing the interlocking mechanism. It has been determined that fiber rupture damage comes to the fore as the main damage type due to the depth and adhesion width of the grooves obtained in the laser scan repetition specified in Fig. 6-d and e.



(a) Untreated AA2024-T3/CFRP (b) Scan Repetition 1 (c) Scan Repetition 3 (d) Scan Repetition 5 (e) Scan Repetition 7

Figure 6. Damage types of joints after mechanical tests for different scan repetition with untreated and sanded AA2024-T3 / CFRP bonding joints

To support the types of damage that are compatible with the literature, it was thought that fiber tear damage due to good adhesion also affected the results of the single lap shear tests. For this reason, force-elongation curves obtained in mechanical tests are drawn comparatively and given in Fig. 7. It was determined that the elongation values were also high for the transition numbers where the adhesion was high, that is, the adhesion shear force was high. Especially for the 5^{th} and 7^{th} repetition where fiber tearing damage was observed, the elongation amounts were also high. Complementing these two results with each other supports the high adhesion shear strength.

Conclusions

In this study, the laser repetitions effect on both the groove geometric parameters and the adhesion strength of AA2024-T3 / CFRP materials were investigated. The results obtained are as follows:

- By examining the effect of the laser scan repetition on the contact angle and adhesive spreading performance, it was seen that all the laser-treated aluminum surfaces exhibited nearly super hydrophilic characteristics.
- Laser groove geometric parameters have a significant and relevant effect on the adhesion strength of AA2024-T3/CFRP joints.
- This effect could be optimized for varying adherent materials by using the laser scan repetition technique.

- After the 5th laser repetition, the highest adhesion strength value was increased from 19.03 MPa to 26.48 MPa.
- This adhesion strength increment was supported with different failure modes obtained on both the adherent surfaces that especially for 5th repetition significant amount of fiber tear failure could be seen on the aluminum surface.

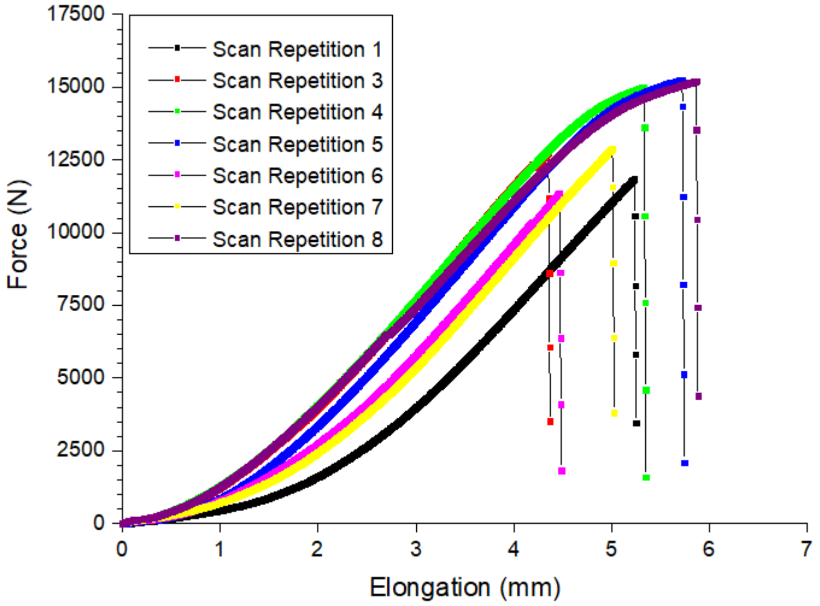


Figure 7. Individual lap shear test graphs based on the laser scan repetition

Acknowledgment

This work was supported by the TUBITAK, "The Scientific and Technological Research Supporting Program 1001" [grant number 118M280].

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Author Information

Seda Aybalik
Kocaeli University
Faculty of Aeronautics and Astronautics, 41285, Kocaeli, Turkey Address: Kocaeli University, Arslanbey Campus, Faculty of Aeronautics and Astronautics, 41285, Kartepe/Kocaeli, Turkey

Onur Çoban
Kocaeli University
Faculty of Aeronautics and Astronautics, 41285, Kocaeli, Turkey Address: Kocaeli University, Arslanbey Campus, Faculty of Aeronautics and Astronautics, 41285, Kartepe/Kocaeli, Turkey

Mustafa Özgur Bora
Kocaeli University
Faculty of Aeronautics and Astronautics, 41285, Kocaeli, Turkey Address: Kocaeli University, Arslanbey Campus, Faculty of Aeronautics and Astronautics, 41285, Kartepe/Kocaeli, Turkey

Erhan Akman
Kocaeli University
Faculty of Aeronautics and Astronautics, 41285, Kocaeli, Turkey Address: Kocaeli University, Arslanbey Campus, Faculty of Aeronautics and Astronautics, 41285, Kartepe/Kocaeli, Turkey

Belgin Genç Öztoprak
Kocaeli University
Faculty of Aeronautics and Astronautics, 41285, Kocaeli, Turkey Address: Kocaeli University, Arslanbey Campus, Faculty of Aeronautics and Astronautics, 41285, Kartepe/Kocaeli, Turkey