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Research Article

Optimization of Laser Surface Treatment Parameters on Shear Strength of Al/CFRP Adhesively Bonded Lap Joint

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ABSTRACT

Surface treatment preparation plays a key role in the strength of adhesive joints, particularly in single-lap joints. The most optimal surface conditions must be reached to achieve a strong joint. This research aims to achieve the maximum shear strength of single-lap Al/composite joints using the laser surface treatment. Four different parameters are considered, namely power, speed, the energy density of the laser on both adherends, and the laser hatch distance (HD). To predict the strength of the connection, the Design of Experiments method has been used. Several single-lap specimens with different surface parameters were created and analyzed experimentally. The results show that the hatch distance had the greatest effect on the shear strength of the specimens, followed by the mutual impact of the Al laser surface treatment power on the HD, the mutual effect of the speed of laser in Al surface treatment on the HD, and the laser power in Al surface treatment and the speed of Al laser surface treatment had the greatest effect on strength. Additionally, it was found that there is no direct or inverse relationship between the speed and laser power parameters. The optimal design obtained has a laser surface treatment speed of 1000 mm/s and 1200 mm/s, and laser power of 18 and 9 watts for Al and composite, respectively, and 50 micrometers for HD. The obtained optimal specimen has an average shear strength and failure force of 8.6 MPa and 6.676 kN, respectively, which shows about 102% improvement compared to the sandpaper method.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) are widely used in various industries, especially in aerospace, due to their high strength, high elastic modulus, and good resistance to fatigue and corrosion [1-3]. In addition, Al alloys are expected to be used more in future industries due to weight savings and reduction of greenhouse gases [4]. Traditional technologies for connecting parts in engineering industries, such as mechanical joints like bolts, nuts, or rivets for composites, usually cause the cutting of fibers and stress concentration in the connected area. This results in a decrease in the capacity of joints [5]. To improve the performance of engineering structures and, at the same time, reduce costs, adhesive joints have gained attention from researchers. Designing structures based on the properties of different materials and the combined use of several different materials, especially the combined use of composites and metals, has become an important consideration [6]. Bonding technology between carbon fiber-

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reinforced polymers and other materials is a significant issue in mechanical systems. Adhesive joints have good fatigue performance, uniform stress distribution, less stress concentration, high strength-to-weight ratio, flexibility in design, reduced construction costs, and a significant reduction in structure weight compared to traditional mechanical joint methods [7-10].

The shear strength of joints between Al and composite materials is often limited by the low quality of the adherents' surfaces and their improper preparation. To address this issue, it is recommended to pretreat the surfaces of Al materials to increase the strength of their bond with the composite material. This can be achieved through surface preparation methods that enhance the molecular interaction and physical absorption of the adhesive on the surface, which in turn increases its wettability. By increasing the energy of surface molecules, the wettability is improved according to Young's law [11]. Surface treatment also helps to remove surface contaminants such as dust, micro-organisms, fats, and oxides, which in turn improves the wettability and surface energy of the Al material [12]. In the aerospace industry, chemical surface preparation processes such as etching with chromic-sulfuric acid, anodizing with phosphoric acid (PAA), and chromic acid anodizing (CAA) are commonly used to create a porous oxide layer on the surface of Al. This enhances the durability of the structure's connection. However, these processes are not environmentally friendly due to their chemical interactions [13, 14]. There are many mechanical methods to change the surface parameters of adherents before bonding, which include manual abrasion with sandpaper, peel ply, sand blasting, and other methods, which are usually used due to high implementation costs and difficulty in controlling surface parameters. It complicates the surface preparation [15, 16]. On the other hand, laser surface preparation has many advantages, including high efficiency [17], high surface cleaning ability, controllability of all variables affecting the surface quality, high speed and accuracy, as well as the absence of environmentally incompatible materials [1, 18, and 19].

Numerous researchers have studied the influence of surface treatment, particularly laser surface preparation, on the quality of bonding surfaces. In 2018, Zhan et al. investigated the influence of infrared laser treatment and peel ply processing on the microstructure of composite/composite adhesively bonded joints. The mechanical tests conducted on the single lap joints showed a significant effect of surface treatment on joint strength. After comparing 6 specimens with different variables of laser surface treatment with a peel ply specimen (PP), the result showed that the peel ply process-treated specimen had better surface roughness than the laser surface-treated specimens. It exhibited approximately 61% more shear strength than the specimen treated with infrared laser treatment. Additionally, the surface roughness of the peel ply-treated specimen was higher than that of the lasered specimen [2]. Belcher et al. investigated the influence of laser surface preparation on the strength of composite adhesive joints in the aerospace industry and compared it with manual sanding. After comparing the results of mechanical tests, they concluded that all the lasered specimens failed with the fiber-tear pattern, indicating strong bonding of the adhesive with the adhesive surface. Meanwhile, the other specimens suffered a mixed failure with minimal fiber tearing [20]. Yang et al. conducted a study to examine the influence of sanding surface treatment on the strength of adhesive joints in single lap and scarf joints. They used four grades of sandpaper with grit sizes of up to 60, 220, 400, and 800 micrometers, as well as polish grit, to investigate the effects of grit sizes and sanding direction (parallel, perpendicular, and random) on tensile properties. The study found that sanding in a random direction resulted in a more homogeneous surface and, therefore, greater bond strength. For single lap joints, the best shear strength was achieved when specimens were prepared using 220 μm sandpaper, increasing by 17.62% and 22.31%, respectively, compared to applying 60 micrometers and polish grit. To investigate the effect of laser surface treatment on the strength of adhesive joints in ambient conditions and after soaking in water, Zhou et al. conducted experiments on Al alloys under three different manufacturing processes, including sheet, extrusion, and cast Al alloys. The study found that laser ablation treatment improved the joint strength for all three Al alloys by modifying surface characteristics and exceeding the target bond strength. Increasing the laser energy also increased the adhesion of the glue to the adherent surfaces. However, the phenomenon of mechanical interlocking was increased by laser treatment, which could severely influence joint strength. On the other hand, laser treatment created a new oxidized layer with a thickness of approximately 0.5 micrometers and changed the surface properties of the Al alloy substrates. This caused complete wetting by the adhesive, resulting in increased bond strength. The surface roughness of the Al alloy substrates was significantly increased by creating uneven surfaces. In 2020, Bora et al. conducted a study to investigate the influence of laser and chemical surface treatment on the shear strength of AA2024-T3 aluminum single lap joints and unidirectional carbon fiber composite. To bond the materials, they used Loctite EA 9396 AERO epoxy-based two-part adhesive and performed chemical surface treatment using silane with three different volume concentrations of 1%, 3%, and 5%. They also used laser treatment, employing a 50-watt fiber pulse laser. The findings of the study revealed that the silane bonds created on the aluminum surface create a strong chemical bond between the metal and the epoxy. Additionally, the laser surface treatment helped to remove the pollution from the aluminum surfaces and facilitated the formation of oxide on the surface. After the laser surface treatment, the fracture surfaces were fiber tears on the composite surface, indicating a stronger bond as compared to non-laser specimens. It is important to note that the mechanical interlockings were reduced in the specimens that were subjected to laser surface treatment at high speed, which reduced the strength of the joint [22]. In a study conducted by Good et al., the relationship between surface properties (roughness and surface energy) and mechanical properties of adhesive joints was investigated. The experimental tests conducted by them showed that the main mechanism of adhesion was mechanical interlocking. They concluded that the surface roughness did not have much effect on the shear strength of these joints, while the increase of surface energy had a significant effect on the shear strength [23]. Similarly, Sun et al. conducted research on the impact of surface treatment by laser on chemical properties, morphology, and shear strength of composite/composite adhesively bonded joints. They examined the effect of increasing laser energy density on shear strength in 10 cases. The finding showed that the shear strength improved by increasing the laser energy density to a certain extent [24]. Dadian et al. worked on improving the strength of composite/steel joints [25]. These researchers used carbon and glass fibers to grade the overlap area and also used the reverse steps method to create mechanical interference. Their findings showed that by grading the overlap area with carbon and glass fibers, the distribution of shear and peel stress became more uniform. The results of this study increase the load and fracture displacement by about 34% compared to the reference specimen. The researchers also observed that creating the reverse step changed the failure mode. The presence of one step improved strength by 40%, and placing carbon at the joint interface of that step increased strength by 112%. However, the greatest increase in strength and displacement failure was achieved using two reverse steps along with carbon in the joint surface, with a significant about 172% increase. Dadian et al. compared the bonding strength of their method with conventional resin by grading the overlap area and adding CTBN in different amounts to the resin. In the first stage, they increased the shear strength by 206% compared to the base specimen. By optimizing the adhesive properties in different ways, they were able to achieve a 299% increase in the bonding strength of the specimens [26]. Li et al. investigated the Influence of high pulse (12.7 J/cm2) fluence infrared laser surface pretreatment parameters on the mechanical properties of CFRP/aluminum alloy adhesive joints [27]. Following experimental investigations, it was determined that subsurface damage and mechanical interlocking effects significantly influence the shear strength of CFRP when subjected to a higher pulse fluence. By taking into account both the efficiency of the treatment and the quality of the adhesive joints, the researchers established optimized parameters for the laser surface processing. Zou et al. worked on the effect of laser spot overlapping and pulse fluence to enhance the adhesive bonding between steel and CFRP [28]. The findings indicated a strong correlation between surface roughness, surface energy, the polar component of surface energy following treatments, and the interfacial bonding strength between steel and adhesives. Higher pulse fluence has the potential to enhance the surface roughness of steel, resulting in a decrease in the contact angle and an increase in surface energy. This alteration not only facilitates a more effective mechanical interlocking effect but also enhances the wettability of the adhesive on the steel surface. When the laser spots exhibited a 50 percent overlap, there was a notable enhancement in the surface wettability. Furthermore, the application of laser surface treatment markedly improved the strength of steel-CFRP joints that were bonded using the epoxy adhesive E-120HP and the polyurethane adhesive PU6700. This improvement was particularly pronounced in the joints adhered with E-120HP, which is characterized by its high strength and low toughness; the shear strength experienced an increase of 299 percent, rising from 4.10 ± 0.17 MPa to 16.35 ± 0.89 MPa following the laser treatment. Kariman and Rahnama investigated the effects of laser surface treatment on the fracture behavior of CFRP/Al Adhesive Joints by changing the nominal laser powers, scanning speeds, and hatch distances on the average roughness, morphology, and composition of the CFRP and AL surface. Finally, the mode I test results showed an increase in the bonding strength of 13.55% compared to the sanding method due to the fibers tearing at the CFRP fracture surface and the fibers bridging using laser surface treatment [29]. Guo et al.

optimized friction stir spot-welded Al 6061 and CFRTP PA6 parameters with surface treatment and interfacial adhesion. This study identified the optimal parameters, which encompass rotational speed, displacement, and dwelling time. A significant tensile shear force of 10.282 kN was attained at a rotational speed of 2000 rpm, a displacement of 3 mm, and a dwelling time of 10 seconds [30].

Liu et al. developed a robust hybrid joint of aluminum and carbon fiber-reinforced polyamide through the friction stir lap joining technique. They subsequently conducted a comprehensive analysis of the surface micro-texture, joint interface morphology, chemical bonding, and mechanical properties, which enabled them to significantly minimize the occurrence of interfacial voids and cracks. This meticulous approach led to a well-bonded interface between aluminum and CFRP, increasing the shear strength of the hybrid joint [31]. Wang et al. investigated on Influence of laser texturing on the properties of fusion joints between aluminum alloys and carbon fiber-reinforced thermoplastic composites. They found that the microstructure spacing has a significant influence on the surface morphology, polymer infiltration, and bond strength of aluminum alloys. A specific microstructure spacing can optimize the bond strength by facilitating polymer penetration and controlling the failure mechanism. For example, when the microstructure spacing is 90 μm, the polymer could completely infiltrate the groove structure between the recast layers, and the cohesive failure of the polymer in that region, at that time, the joint connection strength is the highest, 25.05 MPa [32].

So far, many studies have been conducted to investigate the influence of various surface treatment methods and parameters on the shear strength of single lap joints. However, most of these works focused on individual parameters or qualitative trends, and little research has focused on the optimization of laser surface treatment and its special parameters. In this study, specimens were prepared by adhesively bonding single lap aluminum/composite with a 0.4 ± 0.02 mm adhesive thickness, and a uniaxial tensile test was performed to evaluate the shear strength of joints. The present study systematically optimizes four independent laser surface treatment parameters: power, scanning speed, energy density, and HD using the Design of Experiment (DOE) approach. The effect of different parameters of laser surface treatment was investigated compared with surface treatment using sanding in random directions. This study checked the impact of each parameter and obtained the optimal parameter for laser surface treatment. It is worth noting that the variable parameters in the laser surface treatment included the speed, power, and energy density of the laser in both adherents, as well as the HD. So, this work not only identifies the dominant effect of HD on joint shear strength but also clarifies the combined influence of aluminum-side laser power and hatch distance, offering a quantitative guideline for achieving maximum bonding performance in hybrid Al/CFRP adhesive joints.

2. Materials and Methods

In this section, firstly, the various stages of preparing and manufacturing unidirectional carbon fiber composite are explained, and the method of creating single lap joints with aluminum is presented. Then, the steps to obtain the value of shear strength and failure force for different values of laser treatment variables are investigated with mechanical tests.

2.1. Materials

In this research, the Vacuum Injection Process (VIP) was used to make a unidirectional carbon fiber composite laminate. This method is highly accurate in manufacturing parts due to the prevention of voids, the entry of contamination, and minimal hand intervention [1]. A unidirectional carbon fiber fabric (T300, 200 g/m^2 areal weight) was used to fabricate the composite laminate. According to ASTM D2584 standard [33], eleven plies were stacked and infused with LR660 epoxy resin using the Vacuum Infusion Process (VIP), resulting in approximately 40% fiber volume fraction. This method ensures high laminate quality by minimizing voids and contamination during processing. After injection, it takes about 4 to 5 hours for the resin to gel and about 20 hours for the primary curing to be done. The secondary curing was done in a laboratory oven. It should be noted that the increase or decrease in temperature during secondary curing is done on a slow basis to prevent sudden changes in temperature within the part. The secondary curing of this type of resin is done at a temperature of 70 degrees Celsius after 10 hours. Then, T6-6061 aluminum and the composite laminate were cut to final dimensions using a waterjet machine according to ASTM D5573 standard [34]. Single lap joints were prepared as shown in Fig. 1. The mechanical properties of the composite adherent are shown in Table 1, which was obtained from the experimental test according to the ASTM D3039 standard [35]. Also, the mechanical properties of aluminum T6-6061 [36] and Araldite 2015 adhesive (according to its catalog) are shown in Table 1. The composition by mass of 6061 Aluminum alloy was presented in Table 2. It is necessary to explain that to keep the overlap length constant and to create uniform pressure on the joint during different stages of adhesive curing, a special fixture was used. Figures 2(a) and 2(b) show the diagram and the actual form of this fixture, respectively. In this joint, Araldite 2015 (two-component adhesive) with an epoxy base made by Huntsman Company of America is used.

The fixture, schematically shown in Figs. 2, was designed to precisely control the bondline thickness of the adhesive. The total thickness of the Al adherend (3 mm) and the CFRP adherend (2.6 mm) sums up to 5.6 mm. The fixture uses two main spacers: Spacer 1 (3.4 mm) and Spacer 2 (3 mm). The distance between the base plate and the holder plate is 6 mm along the entire length of the joint. This spacing is maintained by spacers in all regions except the overlap area, where an exact clearance of 0.4 is left between the two adherends. This gap ensures a uniform adhesive layer thickness of 0.4 ± 0.02 mm. This fixture maintained constant pressure and alignment during the adhesive curing process.

2.2. Surface Treatment

Two methods were used to prepare the joint surfaces: manual sanding (S) and laser surface treatment (LA). For manual sanding, sandpaper with a grade of 60 was used in random directions. For laser surface treatment, a YB: fiber laser system with a maximum average power of 50 W, a wavelength of 1050 nm, and a frequency of 20 kHz was used. The pattern specified in Fig. 3 was used for the laser surface treatment. Different variables were considered for laser surface treatment, including laser scanning speed (v) in mm/s, average power (P) in W, and HD of laser lines in µm. The energy input for the laser treatment is characterized by the Energy Density (ED), which is critical for defining the resulting surface morphology. The formula for the linear Energy Density (J/mm2) applied to the surface is defined as Eq. (1):

$$E_D = \frac{P}{V \times HD} \quad (1)$$

where P is the average laser power (W), V is the scanning speed (mm/s), and HD is the hatch distance (mm). This calculation allows for a physical comparison across the different treatment conditions listed in Table 3. A total of 14 different combinations of laser surface treatment parameters and one manual sanding according to Table 3 were made and tested, and each group of parameters was repeated three times. The laser used a 20 kHz pulse frequency with a spot diameter (Dspot) of 50 µm. The zigzag pattern, illustrated in Fig. 3, was generated by linear scanning with the Hatch Distance (HD) controlling the overlap between adjacent laser passes. Specifically, an HD of 50 µm corresponds to 0% theoretical overlap, while smaller HD values (though not tested in this DOE) would introduce overlap.

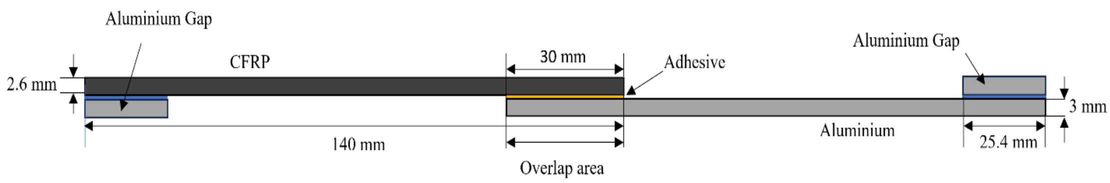


Fig. 1. Geometrical parameters of the single lap joint

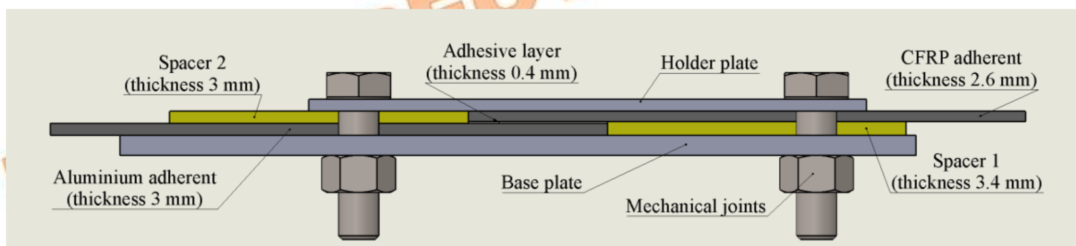


Fig. 2. (a) Schematic of Adhesive bonding joint fixture.

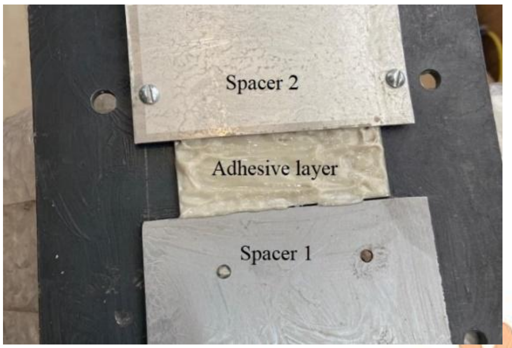


Fig. 2. (b) Produced fixture.

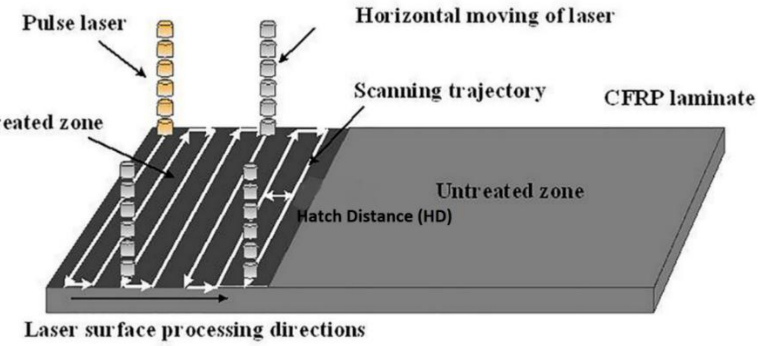


Fig. 3. Schematic diagram of laser processing path

Table 1. Mechanical properties of materials

	$\nu_{12} = \nu_{13} = \nu_{23}$	E_{33} (GPa)	E_{22} (GPa)	E_{11} (GPa)	E (GPa)
Composite	0.29	7.43	7.43	94.5	-
Aluminum T6-6061	0.33	-	-	-	68.9
Araldite 2015	0.3	-	-	-	1.85

Table 2. 6061 Aluminum alloy composition by mass

Constituent element	Minimum (% by weight)	Maximum (% by weight)
Al	95.85%	98.56%
Mg	0.80%	1.20%
Si	0.40%	0.80%
Fe	0	0.70%
Cu	0.15%	0.40%
Cr	0.04%	0.35%
Zn	0	0.25%
Ti	0	0.15%
Mn	0	0.15%
(Others)	0	0.15% total (0.05% each)

The laser used a 20 kHz pulse frequency with a spot diameter (Dspot) of 50 µm. The zigzag pattern, illustrated in Fig. 3, was generated by linear scanning with the Hatch Distance controlling the overlap between adjacent laser passes. Specifically, an HD of 50 µm corresponds to 0% theoretical overlap, while smaller HD values (though not tested in this DOE) would introduce overlap.

3. Calculation of Joint Strength

The shear strength of the joint is determined by calculating the overlapping area and failure force of the joint using Eq. (2).

$$\sigma = \frac{N}{A} \qquad (2)$$

where N is the failure force, A is the overlapping cross-sectional area, and σ is the shear strength.

3.1. Uniaxial Tensile Test

Tensile tests were conducted to determine the shear strength of single lap joints based on the ASTM D5573 standard [34]. The Zoeik-250 tensile test machine was used for this purpose, which had a 5-ton capacity and a 2 kN dynamometer, as shown in Fig. 4.

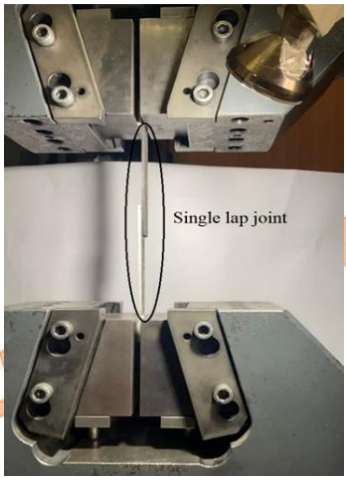


Fig. 4. The equipment of uniaxial tensile test

A digital camera with a recording speed of 240 frames per second and HD quality was also used during the test process. To conduct the test, the overlap dimensions of the specimen were first measured using a digital caliper. Then, a tensile force was applied to the joint at a rate of 2 mm/min using a 2 kN dynamometer, as per the device standard. The force-displacement diagram and failure forces were recorded. In this research, 15 samples with different properties were fabricated. To ensure the accuracy of the results and reproducibility in the experiments, three samples with the same properties were fabricated and tested from each sample. Among them, there were 14 samples with different laser processing parameters, and the values of the variables are presented in Table 3. In one case, sandpaper was used to prepare the surfaces. So, a total of 45 specimens were tested for each mode. For example, the force-displacement diagram for three samples of SLJ05 is presented in Fig. 5.

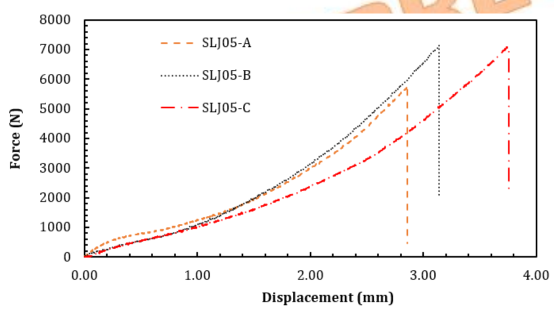


Fig. 5. Displacement force diagram for three fabricated samples SLJ05

4. Results

In this section, the results obtained from experimental tests are compared and interpreted according to the failure morphology.

4.1. Results of Experimental Tests

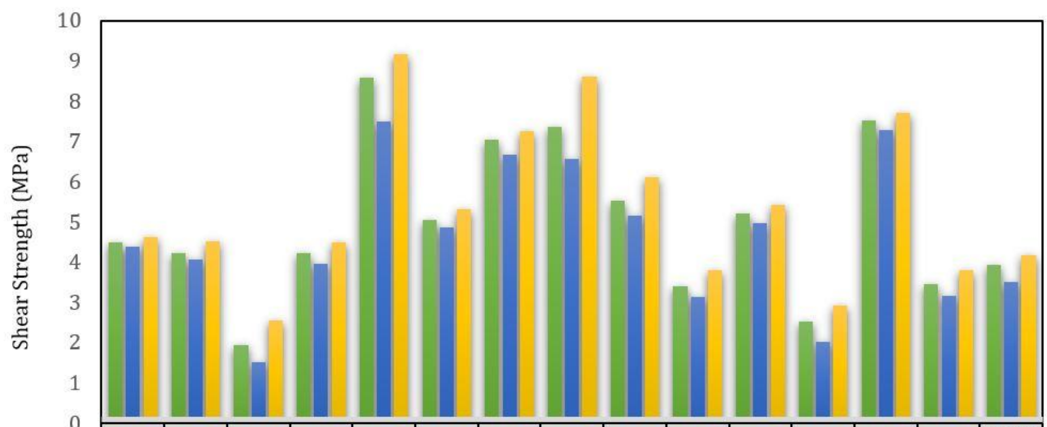
The average shear strength of the specimens, after different modes of laser surface treatment and sanding, is presented in Fig. 6 as a bar graph. After analyzing the diagram in Fig. 6 and calculating the average breaking strength of the joints, it was determined that the average strength is approximately 5.2 MPa. There are six joints, namely SLJ05, SLJ07, SLJ08, SLJ11, SLJ09, and SLJ13, that have a higher fracture strength than the average. An important point among about 83% of these joints was the 50 µm spacing for HD, which has a significant influence on improving the shear strength of the joint. The results of the tests show that reducing the distance of laser lines from each other causes a significant increase in fracture strength. This could be due to the increase in mechanical interlockings. It was found that the joint with the highest shear strength was the SLJ05 with 8.6 MPa, while the lowest strength was exhibited by the SLJ03 with 1.52 MPa. On the other hand, the high power of laser surface treatment in aluminum and composite in SLJ05, as well as the slower laser advance speed on the composite, have been factors contributing to the strength of this connection.

The test results were analyzed with the DOE method (design of experiment) to ensure accuracy. The results are presented in the Pareto diagram in Fig. 7. The fracture strength of the joint is influenced by several factors, including A (aluminum laser surface processing speed), B (aluminum laser power), C (composite laser surface processing speed), D (composite laser power), and E (HD). The hatch distance is the most influential parameter on the shear strength of this type of joint. In addition, the aluminum laser power has a reciprocal effect on the hatch distance. The Pareto chart highlights the significant influence of the interaction effects, particularly BE (Alpower × HD) and AE (Alspeed × HD). These terms collectively demonstrate that the efficacy of the Hatch Distance (E)-the most influential factor-is intrinsically dependent on the energy density supplied by the aluminum laser parameters. For instance, the BE interaction shows that high Al laser power (B) coupled with a small HD (E) can result in an excessively high local energy density. This condition can lead to detrimental effects such as over-melting, the formation of a thick, non-uniform recast layer, or an increase in porosity on the aluminum surface, thereby compromising the quality of the mechanical interlocking sites required for optimal adhesion.

Also, by comparing two methods of surface treatment (manual sanding and laser surface treatment), a graph based on the percentage increase in the strength of the joint of specimens with different parameters of laser surface treatment compared to the sanding method that was manually adjusted as shown in Fig. 8. The joints that have higher shear strength than the manual sanding method include SLJ01, SLJ05, SLJ06, SLJ07, SLJ08, SLJ09, SLJ11, and SLJ13 samples, and the highest increase is related to SLJ05 with a 101.8% increase compared to the manual sanding method. By examining these joints, it can be seen that 75% of them have been lasered with a hatch distance of 50 micrometers, which shows the strong influence of this parameter on the shear strength of these joints.

Table 3. The laser processing parameters of the experiments

	CFRP				Aluminum		
Specimen no	HD (μm)	Energy density (J/mm²)	Speed (mm/s)	Power (W)	Energy density (J/mm²)	Speed (mm/s)	Power (W)
SLJ01	50	0.085	1500	4.5	0.17	1000	6
SLJ02	100	0.085	1500	4.5	0.17	1000	6
SLJ03	50	0.085	2000	6	0.34	1000	12
SLJ04	100	0.085	2000	6	0.34	1000	12
SLJ05	50	0.21	1200	9	0.51	1000	18
SLJ06	100	0.21	1200	9	0.51	1000	18
SLJ07	50	0.21	1000	7.5	1.14	300	12
SLJ08	100	0.21	1000	7.5	1.14	300	12
SLJ09	50	0.25	1500	13.5	1.71	300	18
SLJ10	100	0.25	1500	13.5	1.71	300	18
SLJ11	50	0.37	800	10.5	3.81	90	12
SLJ12	100	0.37	800	10.5	3.81	90	12
SLJ13	50	0.57	600	12	5.71	90	18
SLJ14	100	0.57	600	12	5.71	90	18



	SLJ01	SLJ02	SLJ03	SLJ04	SLJ05	SLJ06	SLJ07	SLJ08	SLJ09	SLJ10	SLJ11	SLJ12	SLJ13	SLJ14	SLJ15 (SP)
average	4.5	4.22	1.93	4.23	8.59	5.06	7.03	7.36	5.52	3.4	5.2	2.52	7.52	3.44	3.92
min	4.39	4.06	1.52	3.96	7.48	4.86	6.67	6.57	5.15	3.13	4.96	2.02	7.27	3.17	3.5
max	4.63	4.51	2.55	4.48	9.18	5.31	7.26	8.61	6.12	3.81	5.41	2.93	7.71	3.79	4.17

Samples number

Fig. 6. Shear strength of specimens treated with laser and sanding

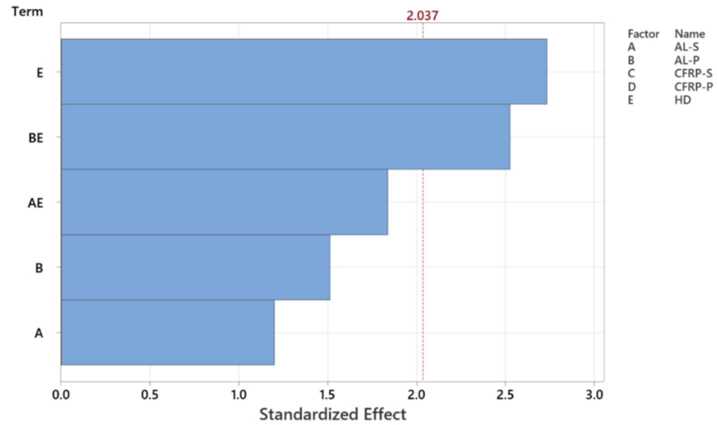


Fig. 7. Pareto chart of the standardized effects (response is shear strength and α= 0.05)

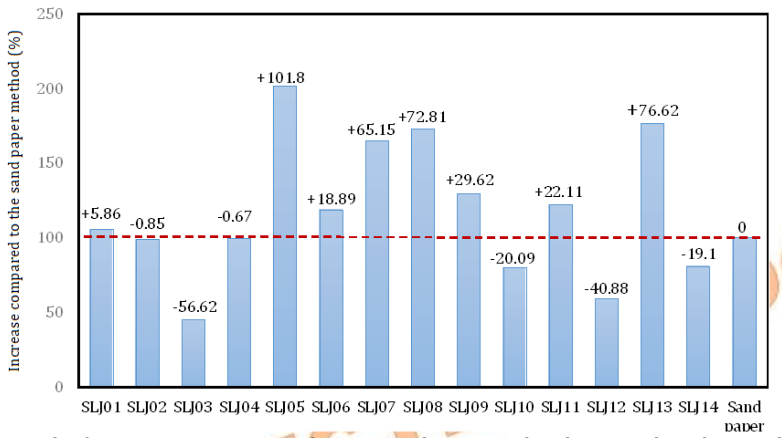


Fig. 8. Graph of percentage increase in shear strength compared to the manual sanding method

4.2. Surface Morphology

Another important parameter that can be checked in experimental tests according to ASTM D5573 [34] is the mode of failure. By examining these failure modes, it is possible to examine the effect of surface preparation on variables related to the specimen under test.

a) fiber tear pattern

All specimens documented in Fig. 9 failed with a Fiber-Tear pattern. Considering the integrity of their joint surfaces after fracture and their high shear strength, the positive effect of the laser surface treatment is evident. The highest strength specimens, such as SLJ05 (σ = 8.6 MPa), exhibited Cohesive Failure within the Composite Substrate (deep fiber tear, Fig. 9). This mode signifies that the adhesive-interface bond was stronger than the ultimate strength of the bulk composite itself, directly resulting from the optimal laser parameters that provided maximum surface area and the deepest resin penetration on both adherends.

Conversely, the samples referenced in Fig. 10 showed low shear strength (e.g., SLJ01-SLJ04 with σ=4–5 MPa), despite exhibiting a macroscopic Fiber-Tear pattern. Detailed failure analysis revealed that these specimens fractured closer to the interface, characterizing an Interfacial Failure near the Substrate Surface. This systematically weaker failure is attributed to parameter sets with sub-optimal energy input or large HD, which limited the development of strong mechanical interlocking on the Al side and/or hindered adequate resin wetting and penetration into the CFRP surface.

In summary, although both Figs. 9 and 10 display the same general Fiber-Tear failure method macroscopically, the specimens in Fig. 9 consistently demonstrate higher shear strength than those in Fig. 10, highlighting a significant difference in the achieved bond quality. One of the important reasons is the significant difference in shear strength of the specimens shown in Fig. 9, which had high strength (SLJ01, SLJ02, SLJ03, SLJ04) with the specimens of Fig. 10 (SLJ05, SLJ07, SLJ09), according to their fracture surface and the significant adhesiveness of the adhesive to the aluminum surface, it can be pointed to the relatively high speed of the laser surface treatment of the composite surfaces and the creation of less mechanical interlockings and, as a result, less shear strength in the specimens of Fig. 10.

b) adhesive failure

Figure 11 displays two specimens that have failed with a fracture pattern on the joint surface. The significant point to note in the variables of the laser surface treatment of these two surfaces is that the HD is 100 micrometers, and the laser surface treatment speed is relatively low in these two samples.

c) mix failure (combination of several failure models)

Figures 12 and 13 show that some specimens, namely SLJ06, SLJ08, SLJ11, and SLJ13, have parts with a failure pattern of cohesive or adhesive and fiber tear, which results in a mixed failure pattern. This is due to the strong bond between the adhesive and the composite fibers, resulting in a high-strength fiber tear pattern. However, the SLJ10 had a very low shear strength surface because of a break in the adhesive.

The SLJ15 sample, which was surface prepared with sandpaper in random directions, created a heterogeneous surface in the fracture area due to low adhesive penetration in the bonding surfaces and fewer mechanical locks. By creating a fracture pattern in the adhesive and bonding surface, it has a low shear strength.

To establish a clearer relationship between the failure mechanisms and the corresponding shear strength, the main failure modes were categorized and correlated with the measured results, as summarized in Table 4.

Fig. 9. Failure with fiber tear pattern in specimens after the tensile test

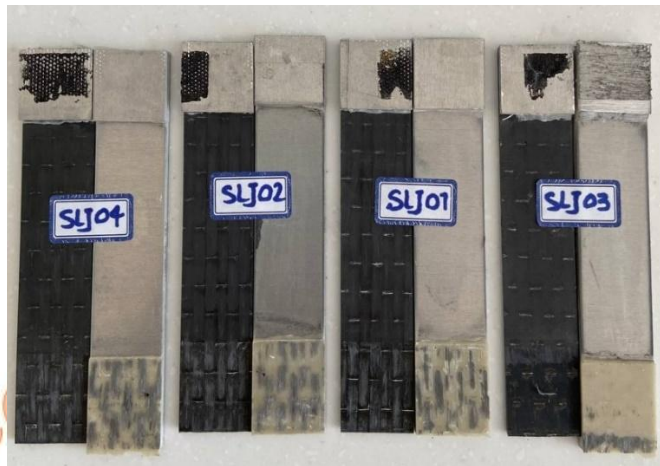


Fig. 10. Failure with thin-layer fiber tear pattern in specimens after tensile test

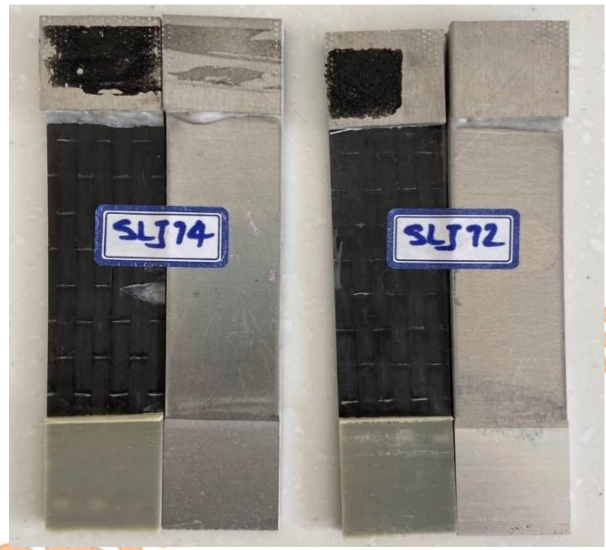


Fig. 11. Adhesive failure pattern in specimens after the tensile test

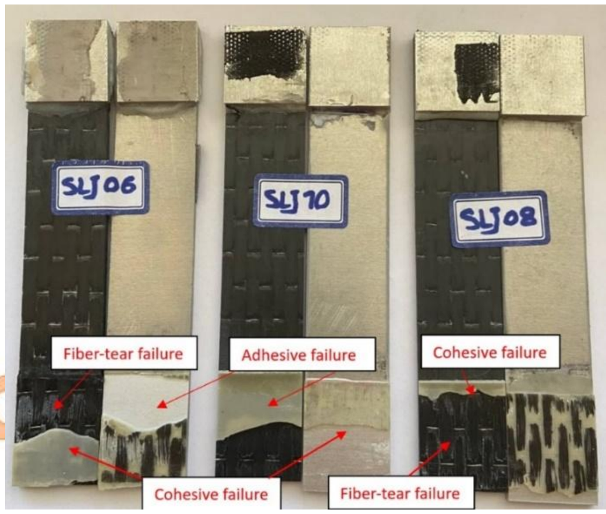


Fig. 12. Mix failure pattern in specimens after the tensile test

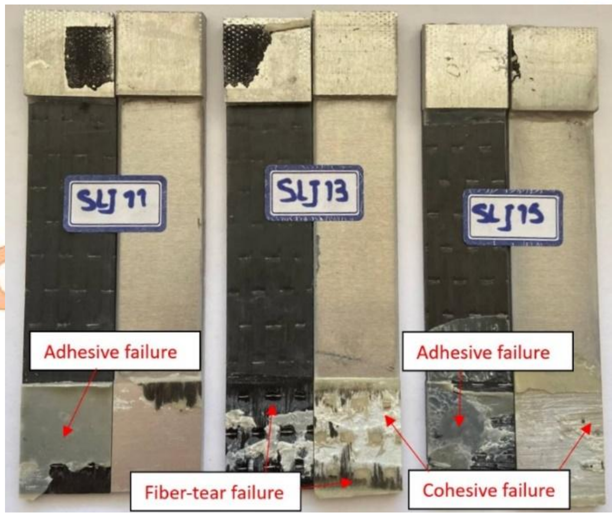


Fig. 13. Mix failure pattern in specimens after the tensile test, including SLJ15

Table 4. Relationship between the failure mechanisms and the shear strength

Failure Mode	Representative Specimens	Shear Strength (MPa)	Observations
Fiber-tear	SLJ05, SLJ07, SLJ09	7.5–8.6	Strong adhesion and cohesive failure within the composite
Mixed (fiber-tear and adhesive)	SLJ06, SLJ08, SLJ11	5.0–7.0	Partial fiber tearing, moderate bonding
Adhesive failure	SLJ10, SLJ15	2.0–4.0	Poor wetting and weak adhesion

5. Conclusions

The strength of adhesive joints between aluminum and CFRP depends on various factors, such as surface preparation before joining. In this study, the effects of some of these factors have been investigated. The fracture morphology and tensile test results of specimens treated with laser and sanding methods were compared. The study found that changing surface parameters can increase the shear strength of the joint by up to 102%. By comparing the fracture strength of laser surface treatment specimens with sanding specimens, the study found a total increase of 18.3% in the strength of the laser-treated specimens compared to the sanding method.

SLJ05 exhibited the highest shear strength among all the specimens tested. It was treated with laser surface treatment at speeds of 1000 and 1200 mm/s for aluminum and composite, respectively, with a power of 18 and 9 watts for aluminum and composite, respectively, and a 50-micrometer layer for HD was applied. The joint displayed a failure mode of fiber-tear, which was determined to be the optimal mode of the joint. By summarizing all the results and failure states, the following can be mentioned:

1- The hatch distance of the laser is the most important parameter among the design variables considered in this study and has a direct influence on the strength of adhesive joints. This is because it creates more mechanical interlockings, resulting in significant adhesion and good penetration of the adhesive to the joint surfaces.

2- Upon comparing the laser parameters and the fracture modes of the specimens, it was observed that the scanning speed of the aluminum laser treatment exhibited a nonlinear effect. While decreasing the speed to 300 mm/s had no significant negative impact, further reducing the speed to a very low range, such as 90 mm/s, consistently resulted in a significant decrease in shear strength. This counterintuitive reduction is attributed to a critically high energy density (as per the ED formula) at low speeds. This excessive energy causes the formation of a thick, brittle oxide layer on the aluminum surface, creating a weak boundary layer that prevents the formation of robust chemical and mechanical bonds.

3- In the adhesive bond between CFRP/aluminum, the fiber tear state is the desirable mode of failure, as it increases the strength of the joint. The joint failure in this state occurs in a uniform and homogeneous manner, with a pattern of fiber tear.

4- Although the hatch distance has a direct influence on the shear strength of the tested specimens, the results show that there is an optimal distance for the joint. This means that the graph representing the relationship between shear strength and hatch distance has a point of extremum.

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Conflicts of Interest

The authors declare no conflict of interest.

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