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Effect of Laser Scanning Speed on Wettability and Lap Shear Strength of Laser-Engraved Carbon/Epoxy Single-Lap Joints

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Abstract

Adhesive bonding is widely used for joining CFRP composite structures because it provides a lightweight, continuous, and structurally efficient connection compared with conventional joining methods. However, the relationship between laser scanning speed, surface characteristics, and bonding performance in CFRP single-lap joints remains insufficiently clarified, particularly compared with conventional mechanical abrasion. In this study, the effect of laser scanning speed on wettability and lap shear strength of laser engraved carbon/epoxy single-lap joints were investigated. Untreated and 800-grit sanded surfaces were used as references. The carbon/epoxy adherends were manufactured by Vacuum-Assisted Resin Infusion (VARI) and bonded with Araldite 420 according to ASTM D5868. Surface properties were studied by contact angle and roughness measurements, mechanical performance was studied by lap shear testing. The maximum lap shear strength was achieved at 50 mm/s, 12.530 ± 1.230 MPa, which is more than 45% higher than the untreated and sanded conditions. However, the difference in contact angle was not statistically significant but laser-treated specimens showed higher joint strength, indicating that the improvement of bonding was mainly due to the surface morphology modification by laser and mechanical interlocking. These results further show the importance of the laser scanning speed for the improvement of adhesive bonding of CFRP.

Keywords: laser engraving, single lap joint, CFRP, adhesive bonding, wettability

1. Introduction

Adhesive bonding is a crucial joining method for carbon fiber reinforced polymer (CFRP) structures, particularly in aerospace applications, due to its ability to provide lightweight and continuous load transfer compared to conventional mechanical fastening methods (Banea & da Silva, 2016; da Silva et al., 2018). Adhesive bonding can mitigate the localized discontinuities that arise from the use of mechanical fasteners as compared to bolted or riveted joints and can be advantageous in preserving the integrity of composite laminates and thus is well suited for lightweight structural applications. However, the performance of adhesively bonded joints is very sensitive to the surface condition of the adherend, with the existence of resin-rich layers, release agents or contaminants that form a weak boundary layer that can adversely affect the interfacial bonding and lead to premature failure (Yang et al., 2019).

Surface preparation is important thing to improve the performance of bonding by increasing the moisture, increasing the surface energy and encouraging the mechanical interaction (Shakeri & Akbarzadeh, 2017). Among conventional methods, mechanical abrasion or sanding is widely used as it is simple and effective in modifying surface roughness. It was found that sanding parameters, particularly grit size, have a significant effect on the performance of adhesive bonded composite joints, where the optimal grit can provide sufficient roughness without damaging the substrate (Abdurohman et al., 2024; Zhang et al., 2020). According to these results, the grit 800 can be considered an effective reference condition for surface preparation, since it provides a compromise between better adhesion and lower surface damage.

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But sanding is still very operator dependent and sanding can affect surface quality and bond performance.

Laser-based surface treatment is gaining more and more interest as a controlled and repeatable surface preparation technique for the improvement of bonding performance of composite and polymer materials. It has been demonstrated that in CFRP adhesive joints, laser treatment modifies the surface morphology of the materials to be bonded, and improves the joint performance through enhanced interfacial interactions (Sorrentino et al., 2020). Furthermore, recent studies have shown that laser texturing of CFRP can influence surface roughness, wettability, failure modes and lap shear strength suggesting that the laser-induced surface properties are vital in determining the ultimate bond behavior (Mendiratta & Prakash, 2025). The effectiveness of laser engraving or laser microtexturing is generally attributed to the creation of grooves, microcracks or textured patterns that increase the effective bonding area, promote the penetration of the adhesive and improve the mechanical interactions at the adhesive–substrate interface (Zhang et al., 2024; Peng et al., 2024; Stribick & Alhadad, 2025). In addition, processing parameters like scan speed, power, and surface texturing have a significant effect on surface characteristics and joint strength following laser treatment (Gai et al., 2024; Shin et al., 2021). However, the improvements in the bond performance are not only governed by the surface roughness or wettability, as inadequate or excessive laser exposure can result in different surface conditions and interfacial responses.

Recent reviews on adhesively bonded joints have indicated that the bond performance is not only controlled by the joint configuration and adhesive properties, but also by the manufacturing quality, surface preparation, defect formation and the interfacial characteristics (Wei et al., 2024). The measurement of surface energy and adhesive spreading in surface-treated CFRP joints is usually carried out by wettability and contact angle. However, a better wettability does not necessarily lead to higher joint strength because bonding performance is also affected by surface morphology, chemical modification and mechanical interlocking (Wen et al., 2024). For laser-treated CFRP-based joints, recent studies have shown that laser processing parameters can alter surface morphology, wettability, contact area, and tensile-shear strength, demonstrating the importance of linking processing parameters to interfacial structure and mechanical performance (Liu et al., 2024; Mendiratta & Prakash, 2025). Therefore, the present study is framed using a process–structure–property perspective, where laser scanning speed is considered as the processing variable, surface roughness and wettability as surface characteristics, and lap shear strength and failure mode as indicators of bonding performance.

Despite the growing interest in laser-based surface treatment, the quantitative relationship between laser scanning speed, surface roughness, wettability, failure mode, and lap shear strength remains insufficiently clarified for CFRP single-lap adhesive joints. In addition, systematic comparisons between laser engraving and conventional abrasion methods under consistent bonding and testing conditions are still limited. Thus, the present study investigated the influence of laser engraving surface treatment with different scanning speeds on the wettability and lap shear strength of CFRP single-lap joints. The results are compared to untreated surfaces as a baseline and to mechanically abraded surfaces with 800 grit sandpaper as a reference condition. The present study aims at revealing the process-structure-property relationship between laser parameters, surface characteristics and joint performance by combined surface characterization and mechanical testing.

2. Methodology

2.1. Materials

The adherends in this study were made from carbon fiber reinforced polymer (CFRP) laminates. The laminates were fabricated by Vacuum-Assisted Resin Infusion (VARI) of epoxy resin into eight plies of unidirectional carbon fiber reinforcement. The VARI lay-up was a dry unidirectional carbon fiber lay-up on a flat mold sealed by vacuum bagging system. Resin was introduced through the inlet line, while the outlet line was connected to a vacuum pump to assist resin impregnation through the fiber preform. During infusion, the vacuum pressure was maintained at approximately -0.9 bar gauge pressure. After the resin had fully impregnated the fiber preform and started to gel, the resin inlet was closed while the vacuum line remained connected to maintain compaction. The vacuum pump was operated for several hours after infusion, and the laminate was kept sealed inside the vacuum bag during room-temperature curing. The laminate was then left to cure at room temperature, approximately 25°C, for at least 24 h before demolding. No additional post-curing was applied. The VARI method was selected to promote resin impregnation through the fiber preform and reduce the possibility of void formation under controlled vacuum and resin flow conditions (Kuentzer et al., 2007; Chen et al., 2015). Obvious surface defects like dry spots, resin starved areas, delamination or visible voids after curing were checked by visual inspection of the fabricated laminate panels. Specimens were prepared only from laminate areas without visible defects. There was no specific quantitative measurement of the void content in the study. The laminates were cut into specimens for single-lap joint (SLJ) testing according to ASTM D5868.

The bonding agent used was a two part structural epoxy adhesive Araldite 420, because of its suitability for structural applications and its proven performance in composite bonding (Kinloch, 2012). The preparation of adhesive and bonding procedure is described in detail in section 2.3.

Three surface conditions were studied: untreated, mechanically abraded and laser treated surfaces. Baseline for the as-manufactured composite surface was the untreated specimens. The mechanical abrasion was carried out using 800-grit sandpaper, chosen as a reference condition due to previous studies that showed its effectiveness in improving the performance of adhesive bonding. The purpose of the sanding process was to remove weak boundary layers and to increase the surface roughness for a better adhesion.

The laser surface treatment was performed using a laser engraving system with different scanning speeds as the main process parameter. The aim of this variant was to modify the surface morphology and wettability of the CFRP adherends to allow a direct comparison with untreated and mechanically abraded surfaces.

Table 2-1: Material Specifications and Laser Processing Parameters

Component	Material Specification	Details / Manufacturer	Key Properties / Parameters
Reinforcement	Unidirectional carbon fiber (UD)	Aerospace grade	Areal weight: 200 g/m²
Matrix	Epoxy resin	Low-viscosity infusion grade	Viscosity: 200–400 mPa·s
Adherend (CFRP)	Carbon/epoxy composite (VARI process)	8 plies	Thickness: 1.0 ± 0.1 mm; Fiber volume fraction ≈ 55%

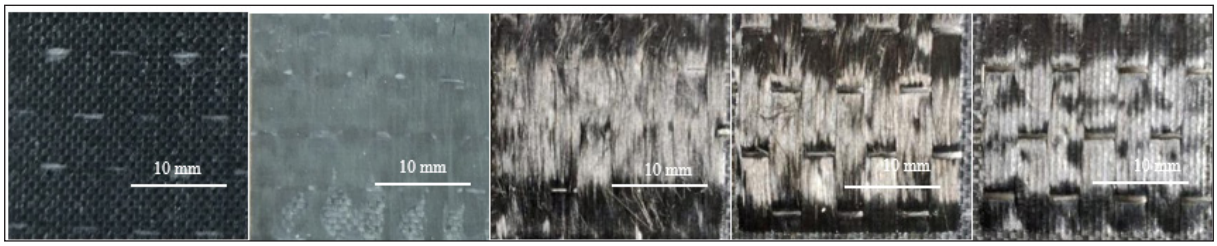
Component	Material Specification	Details / Manufacturer	Key Properties / Parameters
Adhesive	Araldite 420 (two-part structural epoxy)	Huntsman	Shear strength: 25 MPa (bulk); Cure: room temperature for 24 h
Laser system	CO_2 laser (10.6 μm wavelength)	Power: 30 W	Spot size: 0.2 mm
Laser parameters	Scanning speed	Low: 50 mm/s Medium: 100 mm/s High: 200 mm/s	Power setting and software-controlled parameters were kept constant

2.2. Surface Treatment

Prior to bonding, CFRP laminates fabricated using the VARI method were prepared as adherends and subjected to different surface treatment conditions. Five surface conditions were investigated: untreated, mechanically abraded, and laser-treated surfaces with three variations of scanning speed (50, 100, and 200 mm/s).

The untreated specimens were used as a baseline condition representing the as-manufactured surface. Mechanical abrasion was performed using 800-grit sandpaper, which was selected as a reference condition based on its effectiveness in improving adhesive bonding performance. The sanding process was applied uniformly over the bonding area to remove weak boundary layers and increase surface roughness.

Laser surface treatment was conducted using a CO_2 laser engraving system with a nominal power of 30 W. The scanning speed was selected as the main variable, with three levels of 50, 100, and 200 mm/s. Other software-controlled laser parameters were kept constant for all laser-treated specimens. The software power setting was maintained at 75%, and the treatment was performed using a single pass, as indicated by the repeat setting of 1 time. Pixel setting was 2 steps, rectangular marking frame, top-left reference position, zero X-Y reference offset and zero outside offset. When engraving, the boundary line setting was on. Physical hatch spacing, line spacing and focal distance were not varied independently but kept according to the fixed machine setup; their exact physical values were not recorded however. The engraving depth was neither set as an independent processing parameter nor directly measured in the present study. Laser energy density was not calculated because the actual calibrated laser output power and physical hatch spacing were not measured. Surface roughness and morphology measurements were performed to evaluate the resulting surface modification. The treatment was meant to alter the surface morphology and to remove weak surface layers by controlled ablation.



(a) (b) (c) (d) (e)

Figure 2-1: Appearance of CFRP adherends after different surface treatments: (a) Non-Treatment, (b) Sandpaper 800, (c) Laser 50 mm/s, (d) Laser 100 mm/s, and (e) Laser 200 mm/s. Scale bar: 10 mm.

2.3. Adhesive Bonding Procedure

The CFRP single-lap joint specimens were bonded with two-component epoxy adhesive Araldite 420. The adhesive was prepared by mixing the hardener and resin at a mass ratio of 40:100 according to the manufacturer's recommendation. Prior to bonding, cleaned adherend surfaces were cleaned to remove loose particles and surface contaminants. Then the adhesive was uniformly applied to the overlap region of the adherends.

The overlap length was kept at 25.4 mm according to ASTM D5868. The adhesive thickness was controlled to approximately 0.76 mm using a thickness feeler gauge as a reference. Two adherends were assembled in a single-lap joint configuration post-adhesive application and aligned as per the specimen configuration specified in ASTM D5868. Sheet-metal clamps were used to lock the overlap geometry and adhesive thickness during curing. Before bonding, the clamp opening was adjusted by using two CFRP adherends and the reference gap of 0.76 mm feeler gauge. The clamping pressure was not quantitatively measured but the same clamping configuration was applied to all specimens in order to maintain the consistency between the treatment groups.

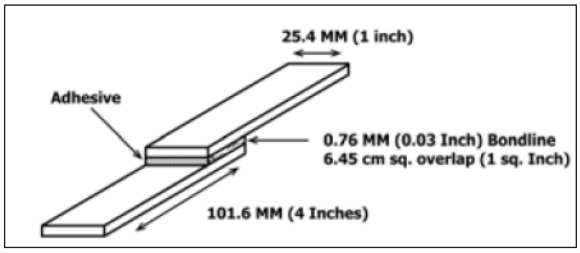


Figure 2-2: Schematic of single lap joint (SLJ) specimen configuration, ASTM D5868.

The bonded samples were cured at room temperature for 24 h. After curing, the excess adhesive on the edges of the joint was removed carefully and the bonded specimens were checked visually for correct alignment and absence of obvious bonding defects before mechanical testing.

2.4. Surface Characterization and Mechanical Testing

Surface characterization was performed before adhesive bonding to evaluate the effect of each surface treatment on the CFRP adherend surface. The wettability was measured using a KRÜSS DSA25 Drop Shape Analyzer in accordance with laboratory procedure IP-BRIN-MMG-6.4-14. The test liquid was distilled water. The static contact angle was determined by optical drop shape analysis of the droplet profile on the treated surface of the CFRP. Measurements were taken for five surface conditions: untreated, Sandpaper 800, Laser 50 mm/s, Laser 100 mm/s and Laser 200 mm/s. To obtain representative values of wettability, contact angle measurements were performed at three different points in the treated bonding area of each specimen.

The surface roughness was measured by a portable surface roughness tester Mitutoyo Surftest SJ-301 according to ISO 21920-2:2021. The roughness parameters measured were Ra, Rz and Rq. In present study, the average roughness parameter Ra was used to evaluate the effect of surface treatment. The measurement was performed with a cut-off length $\lambda c = 0.8$ mm, five sampling lengths and a Gaussian filter setting based on JIS2001. For each specimen, three different points were measured in the area of the treated bonding. The roughness test was performed in the laboratory environmental conditions of approx. 21 °C and 60% relative humidity.

The mechanical performance of the bonded specimens was evaluated by lap shear tests according to ASTM D5868 . The test was performed on A&D TENSILON universal testing machine (UTM) under the tensile loading mode. Specimens had a nominal length of 101.6 mm, width of 25.4 mm, overlap length of 25.4 mm and an adhesive thickness of approximately 0.76 mm as shown in Figure 2-2. Prior to testing, specimen dimensions were measured with caliper and screw micrometer to determine the bonded overlap area for stress calculation. The lap shear strength was calculated as the maximum load divided by the bonded overlap area. The test was carried out under displacement controlled loading with a crosshead speed of 13 mm/min. The laboratory test environment was about 22.5–24.2°C with relative humidity about 50.7%. For each surface treatment condition, five specimens were tested to assess repeatability.

Statistical analysis was used to determine the effect of surface treatment on wettability and lap shear strength. The average contact angle values and lap shear strength data obtained for the five surface conditions (untreated, Sandpaper 800, Laser 50 mm/s, Laser 100 mm/s and Laser 200 mm/s) were each subjected to a one-way analysis of variance (ANOVA). Statistical significance was determined by a significance level of $p < 0.05$.

3. Result and Analysis

3.1. Surface Roughness and Morphology

Surface roughness is an important parameter influencing the adhesive performance of composite joints since it determines the mechanical interlocking and wettability (Yang et al., 2019). In this study, the surface roughness of CFRP adherends with different surface treatment conditions was evaluated by the average roughness parameter Ra according to ISO 21920-2.

The distribution of surface roughness values for untreated, mechanically abraded, and laser treated specimens is shown in Fig. 3-1. The highest roughness values are seen for the untreated surface with Ra values of about 10–13 μm. The relatively high roughness is due to the as-manufactured composite surface with resin-rich areas and inherent surface irregularities from the fabrication process.

Mechanical abrasion with 800-grit sandpaper reduces the surface roughness mostly giving Ra values of about 0.7–1.3 μm. It shows that sanding works by eliminating irregular peaks and weak boundary layers to smooth the surface. Such a condition is often accompanied with better surface uniformity and improved adhesive bonding performance (Zhang et al., 2020).

For laser treated surfaces the surface roughness is a strong function of the scanning speed parameter. At lower scanning speed (e.g. 50 mm/s) a relatively moderate surface roughness (around 2 μm) is observed, which indicates controlled material removal and surface texturing. At higher scanning speeds (100–200 mm/s) roughness variations are observed with a trend towards higher and more scattered Ra values indicating a less uniform surface modification.

In terms of adhesion mechanism, surface roughness is beneficial only when it offers sufficient micro-scale anchoring sites without compromising the effective contact between adhesive and adherend. Very smooth surfaces can limit the mechanical interlocking, while very rough or highly irregular surfaces can limit the spreading of adhesive, cause the formation of local voids, reduce the effective contact area or create local sites of stress concentration. Thus, the optimum roughness condition is not necessarily described by the highest Ra value, but rather a balanced and uniform surface morphology which permits adhesive penetration and stable interfacial contact. The laser 50 condition in this study provided a moderate roughness compared to the untreated surface with a more controlled texture for mechanical interlocking. The untreated surface showed high roughness due to the surface irregularities

as manufactured. At higher laser scanning speeds the roughness values were more scattered indicating less uniform surface modification.

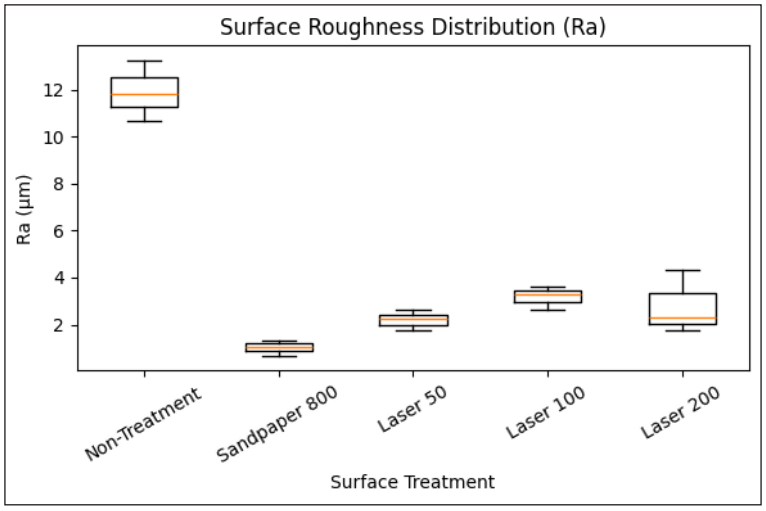


Figure 3-1: Surface roughness (Ra) of CFRP adherends for different surface treatment conditions: Non-Treatment, Sandpaper 800, Laser 50, Laser 100, and Laser 200.

The results suggest that laser surface treatment is a controllable way to engineer surface roughness. Depending on process parameters, laser treatment can result in a greater variety of surface morphologies than mechanical abrasion (Shakeri & Akbarzadeh, 2017). However, over-roughness or uneven roughness may not always improve the bonding performance, because it can reduce the effective contact area or create stress concentration sites.

Overall, the results show that an optimal range of roughness is needed to reconcile the mechanical interlocking, the adhesive spreading and the quality of interfacial contact. Under the studied conditions, moderate and better controlled roughness from laser treatment at 50 mm/s is expected to generate a more advantageous bonding surface than the very rough untreated surface or the excessively smoothed sanded surface. In the subsequent sections, these results on wettability and lap shear strength are further used to evaluate this interpretation.

3.2. Wettability (Contact Angle)

The wettability of the CFRP adherend surfaces was also assessed by optical contact angle measurements as indicative of the ability of the adhesive to wet the surface. Lower contact angle values generally means better wettability and higher surface energy, both of which are desirable for adhesive bonding (Kinloch, 2012; Petrie, 2013).

The distribution of contact angle values for various surface treatment conditions is shown in Fig. 3-2. The untreated surface shows a contact angle of 111.05 ± 5.02° indicating relatively low wettability due to the existence of resin-rich layers and possible surface contaminants. Similarly, the mechanically abraded surface (800-grit sanding) showed a similar contact angle of 111.63 ± 4.24°, indicating that even though sanding changed the surface roughness, its effect on surface energy and wettability was relatively minor.

The contact angle on the laser treated surfaces depends on the scanning speed. The specimen processed at 50 mm/s exhibits a contact angle of 113.22 ± 4.22°, while the contact angles are higher for increased scanning speeds of 100 mm/s and 200 mm/s, measuring 115.97 ± 2.31° and 116.33 ± 10.21°, respectively. This trend indicates a gradual decrease

in wettability with increased scanning speed, with increased variability at 200 mm/sec that might be an evidence of non-uniform surface modification.

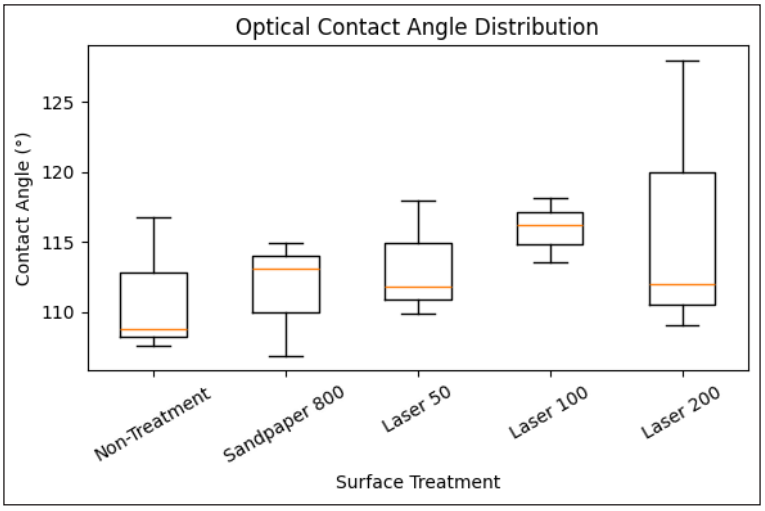


Figure 3-2: Static contact angle of CFRP adherends under different surface treatment conditions.

To further investigate the relation of surface roughness and wettability, the correlation of Ra and contact angle is shown in Fig. 3-3. The results indicate that there is no obvious linear relationship between surface roughness and wettability. The untreated surface has the maximum surface roughness but it does not correlate with the minimum contact angle. On the contrary, the lower roughness is found for the sanded surface, but with only a slight improvement in the wettability.

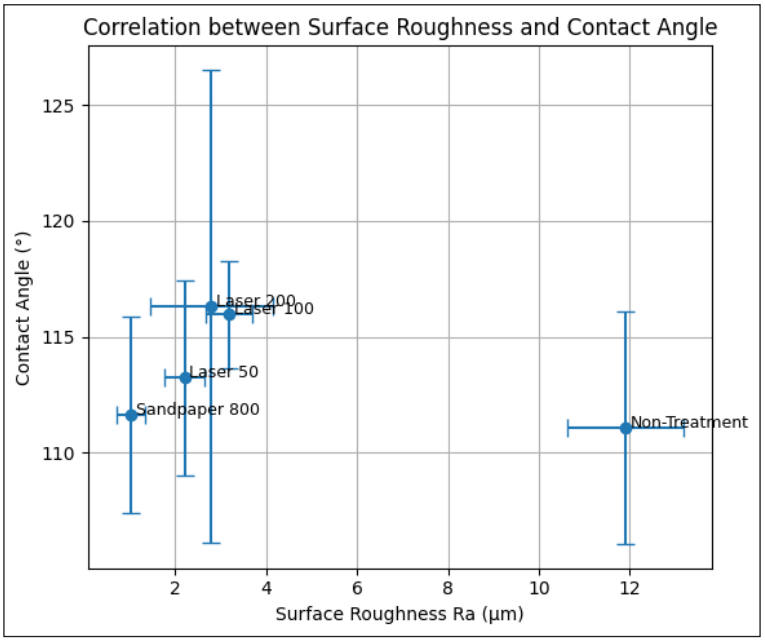


Figure 3-3: Correlation between surface roughness (Ra) and contact angle for different surface treatment conditions.

For laser-processed samples, moderate roughness (e.g. laser 50) is associated with intermediate values of contact angle and the higher the scanning speed, the higher the contact

angle and the data dispersion. This behavior indicates that wettability is not only defined by surface roughness but also by surface chemistry and microstructural changes caused by the treatment process (Shakeri & Akbarzadeh, 2017; Shin et al., 2021).

Statistical significance of the observed differences in contact angle was tested by performing a one-way ANOVA on the average contact angle values (θ_{avg}). The ANOVA result indicated that the effect of surface treatment on contact angle was not statistically significant, $F(4,10) = 0.519$, $p = 0.724$. This suggests that the differences in mean contact angle between untreated, Sandpaper 800 and laser-treated surfaces are statistically insignificant at the 95% confidence level. Therefore, the wettability results should be interpreted carefully, especially since the Laser 200 condition showed relatively high variation in the data.

The lack of marked decrease of contact angle following laser treatment can be attributed to the complex interplay between surface roughness, surface chemistry and the apparent wetting state. Laser engraving can strip off poor boundary layers and create surface texture, but the surface engraved is not always more hydrophilic. The laser ablation can locally expose the carbon-rich areas, thermally affected resin or re-deposited ablation products on the carbon/epoxy surfaces, which can sustain or even increase the apparent hydrophobicity of the surface. In addition, laser-induced grooves and irregular microtextures may trap air beneath the water droplet, leading to a higher apparent contact angle rather than improved wetting. Therefore, the contact angle response observed in this study suggests that laser treatment mainly modified the surface morphology rather than producing a clear wettability improvement. Since no chemical surface analysis such as FTIR or XPS was conducted, this interpretation should be regarded as a physically plausible explanation based on the measured contact angle and roughness trends.

This statistical result supports the interpretation that wettability was not the dominant factor controlling the lap shear strength in this study. Although the laser-treated specimens exhibited higher lap shear strength than the untreated and mechanically abraded specimens, this improvement was not accompanied by a statistically significant reduction in contact angle. Therefore, the enhancement in joint strength is more likely associated with laser-induced surface morphology modification, possible adhesive penetration into textured features, and improved mechanical interlocking rather than wettability improvement alone.

Overall, these findings suggest that the bonding performance of CFRP single-lap joints cannot be explained by wettability alone. Instead, the effectiveness of each surface treatment should be evaluated through the combined contribution of surface roughness, surface morphology, interfacial interaction, and mechanical performance, as discussed in the following section.

3.3. Lap Shear Strength and Failure Modes

The mechanical behaviour of the adhesive bonded joints was evaluated by lap shear testing according to the ASTM D5868 standard (ASTM D5868-01, 2014). For each condition five specimens were tested to confirm repeatability. The average lap shear stress-strain curves of the CFRP single lap joints under different surface treatment conditions are presented in Figure 3-4 while the corresponding lap shear strength values are summarized in Figure 3-5. Representative failure modes seen after testing are also shown in Figure 3-6.

The stress-strain curves in Figure 3-4 allow a quantitative comparison of the mechanical response of the joints under different surface treatment conditions. Generally, the untreated sample presents the lowest stress response, which is consistent with a limited load transfer capacity associated with a weaker interfacial condition. The response of the Sandpaper 800

specimen is slightly better and more stable than the untreated condition, showing that mechanical abrasion plays a role in giving a more uniform bonding surface.

Conversely, laser-treated specimens all exhibit higher stress responses than untreated and Sandpaper 800 conditions. This behavior indicates that the laser surface treatment improves the interfacial interaction between adhesive and adherend and thus improves the load bearing capacity of the bonded joints. Differences among the laser-treated curves also suggest that the scanning speed affects the mechanical response of the joints, reflecting differences in surface modification induced by the laser process. The stress-strain curves shown in Figure 3-4 provide a quantitative measure of the deformation behavior of the joints while the maximum lap shear strength values shown in Figure 3-5 are used for direct comparison of joint performance between the treatment conditions.

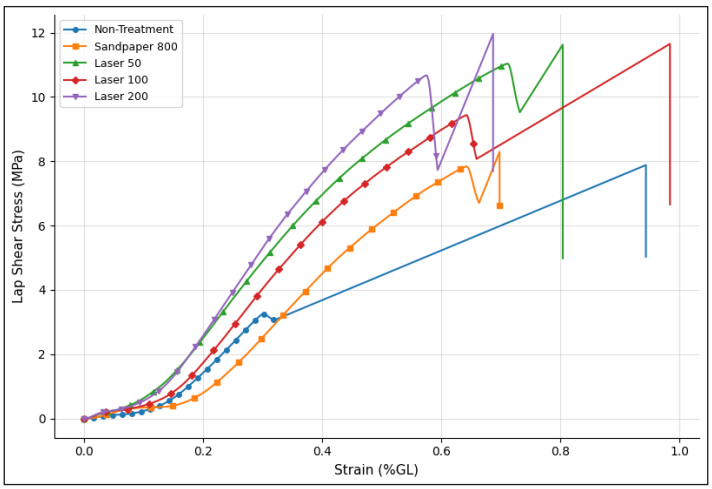


Figure 3-4: Average lap shear stress–strain curves of CFRP single lap joints under different surface treatment conditions.

The quantitative results presented in Figure 3-5 indicate that the untreated specimens have an average lap shear strength of 8.150 ± 4.230 MPa, which implies a relatively low and highly variable bonding performance. This behavior is attributed to the presence of weak boundary layers and poor surface conditions which prevent proper adhesion between adherends. Mechanical abrasion with Sandpaper 800 increases the value slightly to 8.460 ± 0.130 MPa. The reduced variability of the values compared to the untreated specimens indicates a more uniform bonding surface offered by sanding. The overall increase in strength is however rather limited, which indicates that mechanical abrasion alone may not be sufficient to enhance the bonding performance.

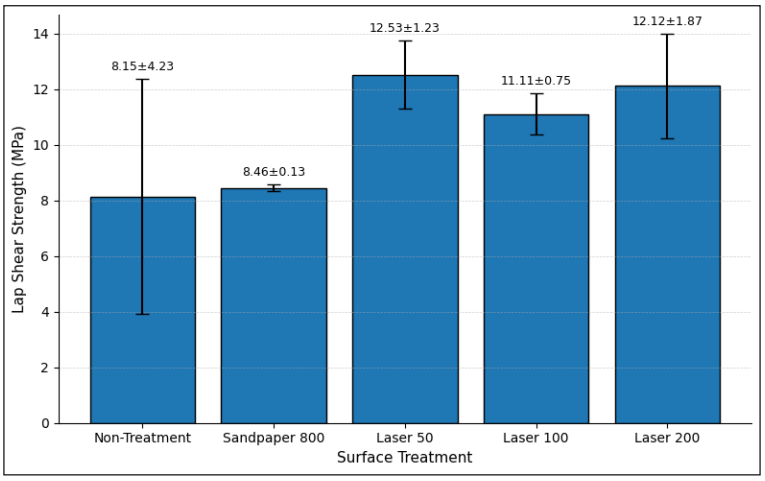


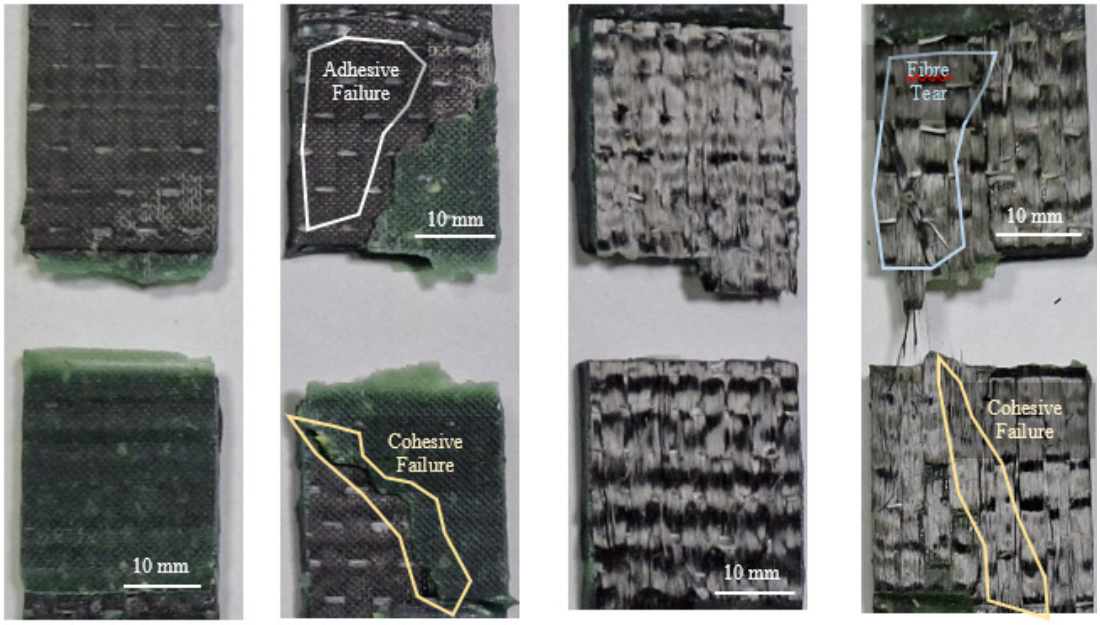
Figure 3-5: Lap shear strength of CFRP single lap joints under different surface treatment conditions.

In contrast, laser treated specimens show improvement in lap shear strength. The highest lap shear strength was observed in the Laser 50 condition with a value of 12.530 ± 1.230 MPa. This means an improvement of more than 45% compared to untreated as well as to Sandpaper 800 conditions. Increasing the scanning speed causes a slight decrease in the average lap shear strength to 11.110 ± 0.750 MPa for Laser 100 and 12.120 ± 1.870 MPa for Laser 200, but both values are still higher than those obtained by the conventional surface preparation methods. These results show that the laser treated surface is more effective than the mechanically abraded surface to improve the joint strength of CFRP single lap joints.

A one-way ANOVA was performed using the lap shear strength data from the five surface conditions to determine if the differences in lap shear strength were statistically significant. The results of the analysis indicated that the lap shear strength was significantly influenced by the surface treatment $F(4,20) = 4.471$ and $p = 0.0096$. This result confirms that the increase in joint strength after laser treatment was not only a descriptive trend, but also statistically confirmed at the 95% confidence level.

The superior performance of the laser-treated joints, especially at 50 mm/s, is attributed to the combined effect of surface roughness and microstructural modification. The laser treatment results in a moderate surface roughness, which is beneficial for mechanical interlocking, as discussed in Section 3.1. Moreover, laser processing is expected to alter the surface in a more controllable manner and to eliminate the weak boundary layers more effectively than mechanical abrasion, which enhances the adhesion between the adhesive and the adherend (Banea & da Silva, 2016). Interestingly, the contact angle results discussed in Section 3.2 show that the laser-treated surfaces do not have the lowest contact angle. This indicates that the wettability is not the only dominant factor for bonding performance. Instead the interaction of surface morphology, surface energy and interfacial bonding seems to play a more important role in the final joint strength.

The failure observations clearly demonstrate differences between the investigated surface treatment conditions. The untreated joints are mostly characterized by adhesive failure, with some specimens also presenting local mixed adhesive/cohesive regions. This suggests that the interfacial bonding in the untreated condition is still relatively weak, which is consistent with the lower lap shear strength observed in Figure 3-5. However, the failure characteristics of the treated specimens are generally dominated by the substrate.



(a) (b) (c) (d)

Figure 3-6: Representative failure modes observed after lap shear testing: (a) adhesive failure in the Non-Treatment specimen, (b) mixed adhesive/cohesive failure in the Non-Treatment specimen, (c) fibre tear in the Laser 50 specimen, and (d) mixed fibre tear/cohesive failure in the laser-treated specimens (Laser 100 & Laser 200). The marked regions indicate the observed failure locations within the bonded overlap area. Scale bar: 10 mm.

For the Sandpaper 800 samples, there is mainly fibre tear which shows that the bond strength is strong enough to transfer the failure from the adhesive interface to the composite substrate. A similar trend is observed for the Laser 50 specimens which also predominantly shows fibre tear. The main failure mode for Laser 100 and Laser 200 is still fibre tear, but some specimens exhibit also local mixed fibre tear/cohesive regions. This suggests that the interfacial bonding is still strong, while part of the failure propagates through the adhesive layer or through the regions with non-uniform stress distribution. In summary, the observations suggest a shift from a predominantly interfacial failure in the untreated state to fibre-dominated or mixed failure in the treated conditions, which is in agreement with the higher lap shear strength following surface treatment.

In agreement with earlier findings suggesting that improved surface preparation can change the failure mode from adhesive-based failure to cohesive failure or substrate-related failure, suggesting stronger adhesion at the interface (Shin et al., 2021; Gai et al., 2024), such failure behaviors are observed. However, interpretation of the failure mode should be considered as preliminary since the current analysis is based on macroscopic fracture observations. A more detailed analysis of the fracture surface, e.g. by imaging at higher magnification, would be desirable in order to allow a more quantitative classification of the failure mechanisms.

The combined results indicate that the enhancement in lap shear strength was governed by the interplay of surface morphology, wettability response and failure behaviour. The lowest contact angle was not achieved with the Laser 50 condition but a moderate and more controlled roughness profile that was advantageous for adhesive anchoring and mechanical interlocking. This indicates that the enhancement mechanism was not only dominated by the wettability improvement. Rather, laser engraving at the appropriate scanning speed sufficiently altered the CFRP surface morphology to enhance interfacial load transfer without creating excessive

irregularities. This interpretation is supported by the change in failure mode from adhesive-dominated failure for the untreated specimens to fibre tear or mixed fibre tear/cohesive failure for the treated specimens, which implies a stronger adhesive-adherend interaction. Therefore, the best performance of the Laser 50 condition could be related to the balanced surface state with controlled roughness, enhanced mechanical interlocking, and stronger interfacial bonding.

In conclusion, the results show that laser surface treatment is a more effective and reliable method for improving the adhesive bonding performance compared to the traditional mechanical abrasion. The stress strain curves in Figure 3-4 mainly illustrate the general deformation behavior of the joints. However, the quantitative comparison as shown in Figure 3-5 clearly shows that Laser 50 is the optimum condition among the investigated treatments. Furthermore, the change in failure characteristics from adhesive-dominated failure in the untreated condition to fibre tear or mixed fibre tear/cohesive failure in the treated specimens further supports the beneficial effect of surface treatment on the interfacial bonding performance.

4. Conclusions

In this study, the effects of different surface treatment methods, i.e. untreated, mechanical abrasion with 800-grit sand paper and laser engraving with various scanning speeds, on the surface characteristics, mechanical response and failure behaviour of CFRP single lap joints (SLJs) were investigated.

The results indicate that the surface treatment has a significant influence on the surface condition and the adhesive bonding performance of the joints. Mechanical abrasion with Sandpaper 800 reduced surface roughness and produced a more uniform surface than the untreated condition but its effect on wettability and lap shear strength was still limited. On the other hand, laser surface treatment allowed more controlled surface modification and led to higher mechanical performance.

The mean stress-strain curves showed better mechanical behaviour for all laser-treated specimens compared to the untreated and the Sandpaper 800 condition, which means that the interfacial load transfer capability is improved. The maximum lap shear strength in terms of quantity was obtained at a scanning speed of 50 mm/sec with a value of 12.530 ± 1.230 MPa, which is more than 45% higher than that of the untreated and Sandpaper 800 specimens. Laser 50 showed the best performance of all the conditions studied, although Laser 100 and Laser 200 also had higher lap shear strength than the conventional treatments.

The combination of the results of surface roughness, contact angle and lap shear strength leads to the conclusion that the bonding performance cannot be described by one single parameter. The optimum condition was not the lowest roughness or the lowest contact angle but a balanced surface state achieved by controlled laser modification. This indicates that surface morphology, surface energy and interfacial bonding are the dominant factors controlling the joint strength.

These results also verify that the improved performance of the CFRP single lap joint is not only related to wettability. Although the contact angle was not significantly decreased after the laser treatment, the specimens treated with laser still showed higher lap shear strength and more substrate dominated failure characteristics. This suggests that interfacial and morphological effects such as controlled surface roughness, laser-induced surface texture and mechanical interlocking dominated wettability improvement in improving the joint strength.

The main scientific contribution of this study is the identification of the laser scanning speed as a key processing parameter controlling the balance between the surface morphology and the bonding performance. Among the investigated conditions, the laser 50 mm/s resulted

in the most favorable surface state and the highest lap shear strength. Therefore, laser engraving at an optimum scanning speed can be considered as a reliable and reproducible alternative to traditional mechanical abrasion for enhancement of the adhesive bonding in CFRP structures. In future work, detailed fracture surface analysis and long-term durability evaluation under environmental exposure, including seawater immersion and hygrothermal ageing, should be performed to further evaluate the applicability of this method in aerospace and marine-related structures.

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6. Contributorship Statement

The authors have made substantial contributions to the conception and design of the study. The data analysis was performed by the authors, who also interpreted the results and discussed the findings. The authors read and approved the final manuscript.

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