# BONDED HARD-PATCH COMPOSITE SCARF REPAIRS: INFLUENCE OF MACHINING TECHNIQUES AND SURFACE TREATMENT

P. M. Wales[1], C. O Brien[2], A. J. Conneely[2], G. M. O Connor[2], K. B. Katnam[3] and T. M. Young[1]

[1] Irish Centre for Composites Research (IComp), University of Limerick, Ireland
Emails: paul.wales@ul.ie and trevor.young@ul.ie
http://www.icomp.ie
[2] National Centre for Laser Applications (NCLA), School of Physics, NUI Galway, Ireland
Emails: cormac.obrien@nuigalway.ie, alan.conneely@nuigalway.ie, and gerard.oconnor@nuigalway.ie
http://www.ncla.ie
[3] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester,
Email: kali-babu.katnam@manchester.ac.uk
http://www.mace.manchester.ac.uk

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**Abstract**

Advanced composites are widely being used in the design of aircraft structures to reduce weight, improve fuel efficiency and consequently reduce emissions. However, when damaged in service, composite components (*e.g.* fuselage or wing skins) require robust repair methods to restore structural integrity (*i.e.* strength and stiffness) as well as aerodynamics. In this context, adhesively bonded composite scarf repairs can offer high joint efficiency and also aerodynamic surface finish. However, to produce reliable bonded scarf repairs, two fabrication steps are critical: (a) accurate machining to achieve designed patch geometry and (b) appropriate surface treatment prior to adhesive bonding. In this work, hard-patch scarf repairs (*i.e.* secondary bonding of a cured patch with a structural adhesive) were investigated for understanding the influence of different machining techniques and surface treatments on structural repair efficiency (*i.e.* tensile strength). The effect of (a) manual sanding, (b) manual sanding after CNC machining and (c) laser ablation after CNC machining were investigated and compared. Representative bonded scarf repairs (*i.e.* scarf joints) were produced by a hard-patch approach using carbon-fiber epoxy pre-preg laminates (HTA 6376 supplied by Hexcel) and a structural film adhesive (FM300-2 supplied by Cytec). Pre-cured parent and patch laminates were bonded in a hot drape former (an out-of-autoclave approach). Quasi-static tensile tests were performed on scarf joints with different surface treatments. Moreover, fractography studies were conducted using optical and scanning electron microscopy to investigate failure mechanisms. The joint strengths and failure mechanisms were compared and the key observations made were discussed.

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## 1. Introduction

Advanced composites are becoming increasingly popular in engineering structural applications (*e.g.* aerospace, automotive, marine and wind energy). For example, carbon-fiber epoxy composite materials are being used significantly in civil aircraft structures to reduce weight, enhance fuel efficiency and thereby reduce emissions. While advanced composites offer superior properties such as high strength-to-weight ratio, high stiffness-to-weight ratio, high fatigue life and corrosion resistance, the inherent brittle behaviour and susceptibility to impact damage are often acknowledged as the Achilles' heel of composite structures. When a large composite structural component is damaged in service, it is often very costly to replace and may require significant downtime. On the other hand, if the damage is not too extensive, then structural repairs can be performed as a cost-effective solution while reducing downtime. A structural composite repair by bonded scarf patches is the preferred technique for composite components with aerodynamics surfaces [1].

Using conventional repair techniques, the damaged region (which often contains local delamination, matrix-cracking, fibre-matrix debonding and fibre-breakage [2]) is first removed with a manual sander. The surface of the scarf cavity is then activated for bonding by increasing wettability and surface energy (*e.g.* by a combination of surface sanding and solvent wipes [3]). The conventional repair approach uses uncured pre-preg plies (matching the paprent layup) together with a film adhesive for fabricating a scarf patch. A vacuum bag with a heat blanket is often used to apply pressure and temperature to cure and consolidate the patch and the adhesive layer for *in situ* repairs. However, a manual scarfing technique often leads to inaccurate scarf geometries (prone to human error) and could also introduce additional damage if not appropriately used [4]. This challenge provides research opportunities for developing robust *in situ* repair processes. In this context, automated laser machining has the potential to provide the accuracy and reliability required to achieve designed scarf geometries [5, 6]. The application of robust laser scarfing processes could offer opportunities to develop repeatable, tailored scarf repairs and thus scope for restoring damaged primary structures with better consistency [7, 8, 9].

The aim of this experimental work was to investigate the applicability of laser ablation in scarf repairs to achieve better accuracy (*i.e.* in terms of scarf geometry) and repeatability (*i.e.* in terms of joint strength). In this regard, the carbon-fibre epoxy composite laminates were produced using pre-pregs and autoclave fabrication. The laminate edges were tapered (*i.e.* scarfed) by three machining techniques: (a) manual sanding, (b) manual sanding after CNC machining and (c) laser ablation after CNC machining. The objectives of the work conducted were to: (a) manufacture scarf joints by a hard-patch approach and out-of-autoclave curing; (b) compare the effects of different scarfing techniques (manual sanding, CNC machining followed by manual sanding, and CNC machining followed by laser ablation) on the tensile strength of scarf repairs; (c) conduct microscopy to identify surface damage and integrity prior to bonding and failure mechanisms after quasi-static fracture.

## 2. Materials and Manufacturing Methods

### 2.1 Pre-preg Laminates

Cross-ply composite laminates were manufactured using HTA 6376 (supplied by Hexcel) carbon-fibre epoxy pre-preg with a symmetric layup of $[0°/90°]_{8S}$. The laminates were cured at 7 bar pressure and 175°C for 2 hours in an autoclave (TC1000LHTHP system, manufactured by LBBC). The nominal thickness of the laminates was approximately 4.3 mm with a fibre volume fraction ($v_f$) of approximately 0.60 [10]. Composite laminates, with length 205 mm and width 175 mm, were cut with a wet composite cutting tool, rinsed and then dried for scarfing (see Section 3).

### 2.2 Structural Film Adhesive

An epoxy structural film adhesive FM 300-2 (supplied by Cytec) was used for secondary bonding of pre-cured tapered laminates and to produce scarf joints that represent the interface between a cured parent laminate and a cured patch laminate (*i.e.* resembling tapered scarf repairs using a hard-patch approach [2]) using a hot drape former, which is an out-of-autoclave approach (OOA) [10].The film adhesive was cured at 121°C with approximately 1 bar pressure for 90 minutes. A single layer of film adhesive was observed to have produced a bondline thickness of approximately 125 μm. A few layers of FM300-2 were used, depending on the type machining technique used and the surface finish (accuracy) obtained, for manufacturing scarf joints (see Section 3.4).

## 3. Scarf Joints: Laminate Machining

To produce bonded scarf joints, the laminates were machined to achieve a targeted constant scarf

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angle (*i.e.* thickness to tapered length ratio was 1:15 or 3.8° angle). For the laminates used, the nominal thickness was 4.3 mm and thus the tapered length was 62.8 mm (see Fig. 1). The targeted scarf angle was produced by using three methods: (a) manual sanding, (b) CNC machining, and (c) laser ablation after CNC machining.

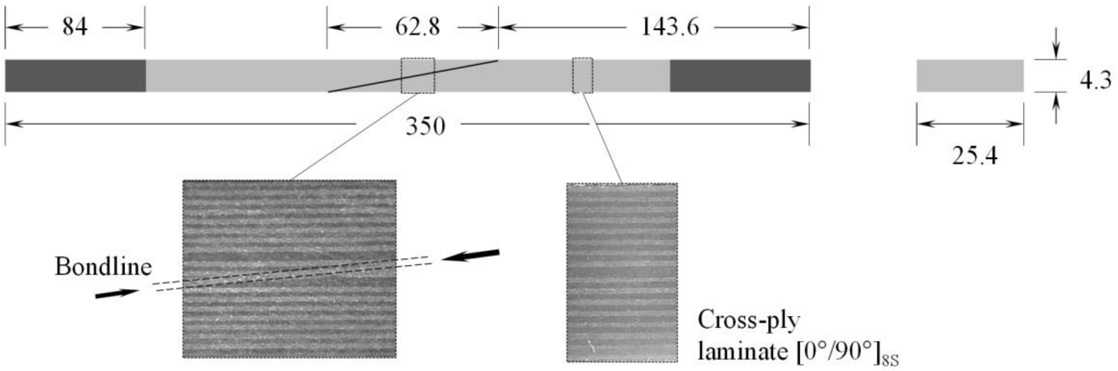


**Figure 1.** Composite scarf joint with nominal dimensions (in mm)

### 3.1 Manual Sanding

The laminates were tapered (by a certified aircraft repair technician to reproduce the current industry standards) to achieve the targeted scarf angle (*i.e.* 1:15 or 3.8°, approximately 62.8 mm in length, see Fig. 1) by using a circular sander. The surface was then finished with 320 grit sandpaper. The tapered laminate edge was examined for identifying surface damage and integrity using scanning electron microscopy (Joel JCM-5700). As shown in Fig.2 (a), fiber-breakage and partially damaged matrix regions were observed.

### 3.2 CNC Machining

In this case, the laminates were tapered by CNC machining to obtain the targeted scarf angle (*i.e.* 1:15 or 3.8°, approximately 62.8 mm in length, see Fig. 1). The machined laminates were then rinsed with water to remove coolant and dried with tissue paper. The machined surfaces were then examined for identifying surface damage and integrity (see Fig. 2(b)). Fiber-breakage and partially damage matrix characteritics were observed (similar to Fig. 2 (a), obtained for manually sanded laminates).

### 3.3 Laser Ablation

A combination of CNC machining and laser ablation was used to achieve the targeted scarf angle (*i.e.* 1:15 or 3.8°, approximately 62.8 mm in length, see Fig. 1). The CNC machining was used to remove the bulk of the tapered region. Subsequently the CNC machined laminates were laser ablated with an objective to improve the machining accuracy (*i.e.* uniform scarf angle along the length of the laminate) as well as modifying surface features. For laser ablation, a pico-second laser (1030 nm wavelength, 200 kHz repetition rate, 21.6 W power, and < 10 ps pulse duration) was used (Trumpf TruMicro 5050 system) to reduce the size of heat-affected-zone (HAZ).

In order to investigate the effect of laser ablation on scarf angle accuracy and sub-surface damage, the CNC machined surfaces were laser ablated: (a) with 1 cross hatched 0°/90° pass (1 pass) scanning along and across the tapered edge at a speed of 2.5 m/s, and (b) with 5 cross hatched passes 0°/90° (5 passes) at a speed of 2.5 m/s. The ablated surfaces were examined and the micrographs are shown in Fig. 2 (c) (for 1 pass) and Fig. 2 (d) (for 5 passes). In the case of 1 pass ablated surfaces, a hatched pattern was observed on the fibres and no visible surface damage was seen on the resin- rich surfaces. In the case of 5 passes ablated surfaces, the resin was completely ablated and only the fibres were exposed with a hatched pattern.

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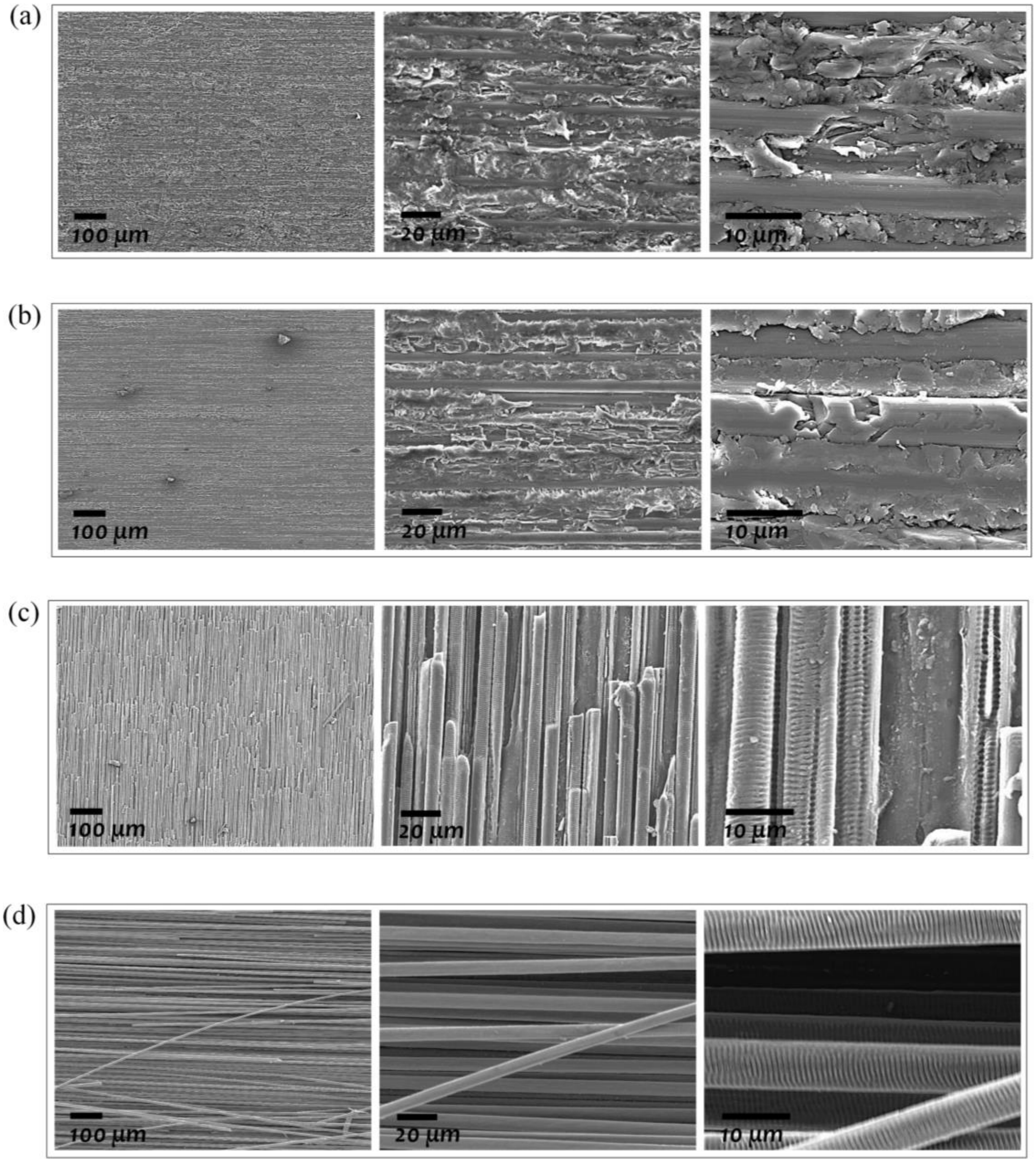


**Figure 2.** Scanning electron micrographs obtained from tapered surfaces: (a) manually sanded, (b) CNC machined, (c) laser ablated with 1 pass, and (d) laser ablated with 5 passes.

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### 3.4 Scarf Joints: Secondary Bonding

To investigate the effect of machining techniques on the strength of composite scarf repairs, bonded scarf joints were produced by using a hard-patch approach (*i.e.* secondary bonding of a cured patch with a film adhesive). A two-part aluminium mould and a hot-drape-former (HDF2 from Laminating Technology, UK) were used for producing bonded scarf joints [10]. The following steps were used for secondary bonding: (a) two tapered laminates with identical machining conditions (*i.e.* a pair of tapered edges either manually sanded, CNC machined or laser ablated) were taken, (b) then the tapered surfaces were prepared by using PF-QD solvent wipes (PT Technologies Europe), and (c) then layers of film adhesive (*i.e.* FM300-2) were positioned between the tapered edges. As the PF-QD solvent evaporates typically in < 3 minutes (as per the supplier), the prepared surfaces were allowed to dry for 10 minutes prior to applying the film adhesive. The adhesive was cured using the two-part mould under approximately 1 bar pressure and 121°C for 90 minutes. It is important to note that the manually sanded laminates were observed to have some geometric inaccuracies (*i.e.* non-uniform scarf angle along the tapered edges) and thus were bonded with 5 layers of film adhesive in order to accommodate the mis-matched surfaces (a maximum gap of 0.6 mm was measured at certain regions) and avoid bondline cavities (*i.e.* regions with no adhesive). However, in the case of CNC machined and laser ablated laminates, the tapered edges were observed to have uniform scarf angles along the length and thus were bonded with 2 layers of film adhesive. The bonded laminates were then cut with a diamond edged composite wet cutter to obtain test specimens (as shown in Fig. 1). After wet cutting the specimens were rinsed and dried with tissue paper and further at room temperature for 24 hours.

## 4. Quasi-Static Tensile Testing

Tensile tests were conducted on the scarf joints in accordance with ASTM Standard D3039/D3039M–08. The tests were performed with a 300 kN tensile test machine, and a cross-head displacement rate of 0.02 mm/s was used. The specimens were tested in tension to full failure. Using the hydraulic grips, a pressure of 150 bar was applied over a length of approximately 84 mm (see Fig. 1). The gauge length of the specimens was 182 mm (see Fig. 1). The type of specimens tested, number of specimens tested per each type, mean failure load and standard deviation are given in Table 1.

**Table 1:** A comparison of the tensile failure load of bonded scarf joints

| Scarf joint type | Specimens tested | Failure load (kN) | Standard deviation (kN) |
|---|---|---|---|
| Manual sanding (5 layers of FM 300-2) | 5 | 42.18 | 3.29 |
| CNC machining (2 layers of FM 300-2) | 5 | 41.86 | 2.23 |
| Laser ablation (1 pass and 2 layers of FM 300-2) | 5 | 36.36 | 1.75 |
| Laser ablation (5 passes and 2 layers of FM 300-2) | 5 | 42.31 | 2.05 |

As shown in Table 1, the mean failure load of manually sanded scarf joints was 42.18 kN, with a standard deviation of 3.29 kN. The CNC machined scarf joints failed at a mean load of 41.86 kN (close to that of manually sanded scarf joints). The standard deviation was 2.23 kN (considerably less than that of manually sanded scarf joints), suggesting the presence of uniform scarf angles along the width of the specimens tested. Moreover, the mean failure load of laser ablated (with 1 pass) scarf joints was 36.36 kN and the standard deviation was 1.75, indicating the interface strength was relatively poor but consistent (indicating the effect of uniform scarf angles). However, the mean failure load of laser ablated (with 5 passes) scarf joints was 42.31 kN and the standard deviation was 2.05 kN. This suggests that these joints provided high strength and importantly with a low standard deviation, indicating the positive effect of uniform scarf angles. It is important to note that the laser ablated surfaces (with 5 passes) were wiped by using PF-QD solvent wipes prior to bonding. The resin deprived surface fibres, see the micrographs shown in Fig. 2(d), were removed during the surface preparation and thus helped expose a layer of material prior to bonding as shown in Fig. 3.

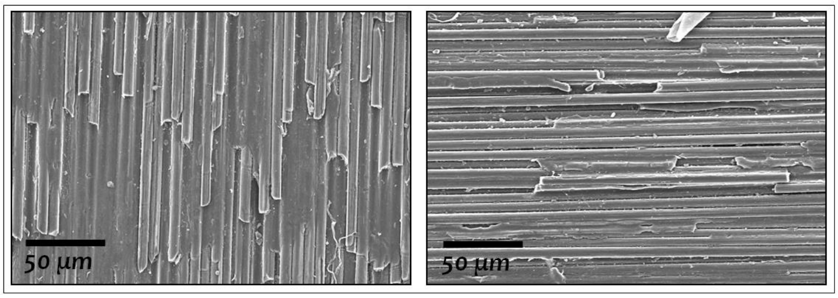


**Figure 3.** Micrographs obtained from tapered surface (both 0 and 90 fibre directions) that was laser ablated with 5 passes. (see Fig. 2(d)) and then wiped with PF-QD solvent wipes prior to bonding.

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## 5. Fractography

### 5.1 Adhesive Bondline

The cross-sectional view of a representative bonded scarf joint is shown in Fig. 1. The cross-sectional examination of different joint types manufactured revealed that the bonding process employed (see Section 3.4) produced no visible voids in the joint bondlines (*i.e.* within the FM 300-2 layer).

### 5.2 Fracture Surfaces

The fracture surfaces of the joints tested are shown in Fig. 4. The failure surfaces revealed a ply-by-ply step pattern, and the typical failure mode was either near the laminae-adhesive interface or cohesive (with patches of adhesive left on either side) along the bondline for all the joints tested. But no visible failure in the composite laminates was observed.

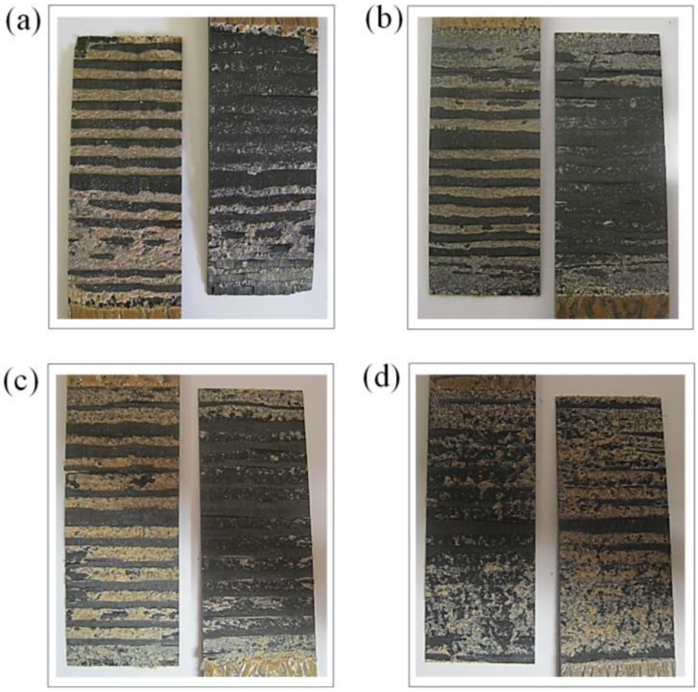


**Figure 4.** Fracture surfaces obtained from the scarf joints tested: (a) manually sanded, (b) CNC machined, (c) laser ablated with 1 pass, and (d) laser ablated with 5 passes.

### 5.3 Failure Mechanisms

The fracture surfaces of the scarf joints were examined to identify the failure mechanisms near the bondline of the parent-patch interface at different magnifications (see Fig. 5). The micrographs were obtained from regions that are near the bondline edge (where typically high normal and shear stresses are expected). The micrographs suggest that the crack path in all the cases tested was in the composite laminae that were next to the adhesive layer. The failure patterns further suggest that the fracture mode in the case of manually sanded and CNC machined scarf joints (see Fig. 5 (a) and (b), show river markings in the matrix rich region next to the debonded fibre edges, indicating mode-I dominant mechanisms. In the case of laser ablated (with 1 pass) scarf joints, the micrographs show hackle pattern (see Fig. 5 (c)) in the matrix rich region next to the debonded fibre edges, indicating mode-II dominant mechanisms. Moreover, when compared to Fig. 5 (a), (b) and (c), the fibre impressions in Fig. 5(c) are wider, suggesting a larger fibre-matrix interface crack running around the fibres. However, in all the cases, the fibre impressions indicate debonding of fibres from the matrix.

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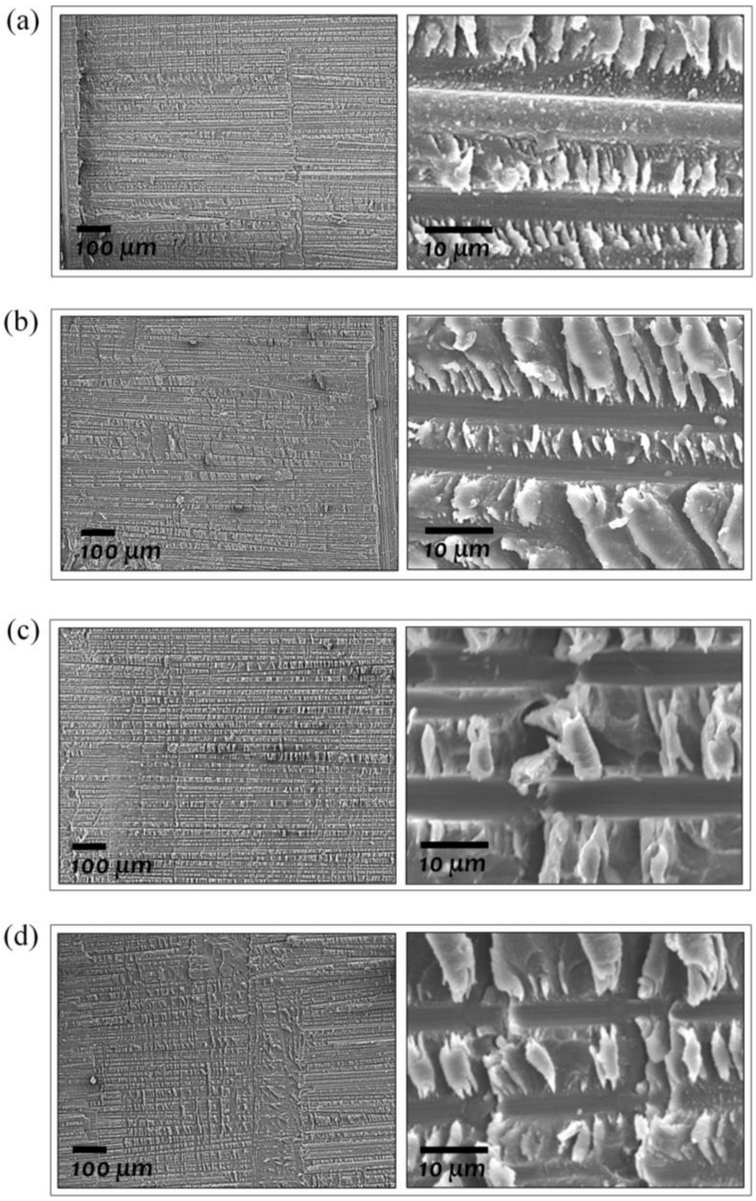


**Figure 5.** Micrographs obtained from fracture surfaces: (a) manually sanded, (b) CNC machined, (c) laser ablated with 1 pass, and (d) laser ablated with 5 passes.

## 6. Conclusions

In summary, bonded scarf joints were produced by a hard-patch approach together with an out-of-autoclave method. The effects of machining and surface preparation conditions (*i.e.* manual sanding, CNC machining followed by manual sanding, and CNC machining followed by laser ablation) on the tensile strength of scarf joints were investigated. The machined surfaces (prior to bonding) and failure surfaces (after failure tests) were investigated to identify surface features and failure mechanisms.

Based on the observations made, the following conclusions are drawn for the material systems tested:

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- Manual sanding produced non-uniform scarf angles, and therefore required additional adhesive to fill the surface mis-match and avoid bondline cavities. Although manually sanded scarf joints provided high strength, the standard deviation observed was relatively high when compared to that of the other joints (see Table 1, for CNC machining and laser ablation).
- The strength of CNC machined scarf joints was similar to that of manually sanded joints. But the standard deviation was reduced as uniform scarf angles produced (see Table 1).
- Laser ablation together with CNC machining produced uniform scarf angles and also improved joint strength and reduced stranded deviation. This could be employed to reduce machining time to achieve targeted scarf angles. However, laser ablated surfaces without sub-surface matrix ablation (see Table 1 for 1 pass condition) reduced the joint strength considerably—suggesting the presence of sub-surface matrix damage.
- Laser ablation with sub-surface matrix ablation and then followed by a solvent wipe improved the joint strength and also reduced the standard deviation (see Table 1 for 5 passes). It was observed that laser ablated surfaces with sub-surface matrix ablation exposed near-surface fibres. When the exposed fibres were removed prior to bonding, the joints provided highest strength and lowest standard deviation compared to that of the other joints (see Table 1).
- The failure surfaces and micrographs revealed that the crack path in all the joints was in the laminae near the adhesive bondline.

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