SELECTIVE REINFORCEMENT OF STEEL WITH CF/PA 6 COMPOSITES IN A LASER TAPE PLACEMENT PROCESS: EFFECT OF SURFACE PREPARATION AND LASER ANGLE ON INTERFACIAL BOND STRENGTH

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Abstract

This paper investigates the possibility of manufacturing hybrid metal/composite laminates in a laser tape placement process. Unidirectionally reinforced carbon fibre/PA 6 composite tapes were applied to 2.0 mm mild steel substrates. The effect of two surface treatments to the steel substrates were investigated 1) grit blast and 2) application of a 60 µm PA 6 film. The effect of laser bias angle was also studied. The interfacial bond strength of the hybrid laminates was determined by means of lap shear tests following the ASTM D 5868 standard. Direct placement onto steel was unsuccessful due to the high laser reflectivity, however placement onto PA 6 coated substrates was successful due to increased laser absorptance. The lap shear strengths as high as 29.5 MPa were achieved for grit blasted and PA 6 coated substrates. The process was found to have a low sensitivity to laser bias angle.

1. Introduction

The application of laser tape placement of thermoplastic composite (TPC) materials to the selective reinforcement of metallic components opens the possibility of manufacturing high-value, light-weight hybrid structures in a flexible and efficient process. The main differentiation between thermoplastic and traditional thermoset composites is thermoplastic polymers do not contain cross-links, allowing them to be melted and therefore laminates are made by consolidation with the polymer in the molten state. Furthermore, thermoplastic prepregs are already in their polymerised state prior to processing, therefore unlike a thermoset, no cure cycle is required. Processing with the polymer in the molten state allows the possibility of rapid melt bonding of thermoplastic composites to dissimilar materials such as metals.

Hybrid sheet metal/carbon fibre epoxy reinforced structures have been demonstrated to have good crash performance for automotive structures [1–4], and offer significant weight saving potential. Compared with conventional thermoset composites (e.g. epoxy), TPCs are remarkably tough and typically have specific impact energy absorption an order of magnitude higher [5]. TPCs are therefore expected to display even greater crash performance. The welding process can be performed in situ during automated tape placement (TP-ATP) (Fig. 1), allowing high performance composite structures to be manufactured rapidly in a low capital, out-of-autoclave work cell [6–9]. As it is an additive manufacturing process, it

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can be used to selectively reinforce components to increase strength and/or stiffness. Advantages include flexibility of the process- different geometries and thicknesses are easily tailored and the anisotropic nature of the reinforcement makes it structurally efficient in that the reinforcement acts purely along the load path.

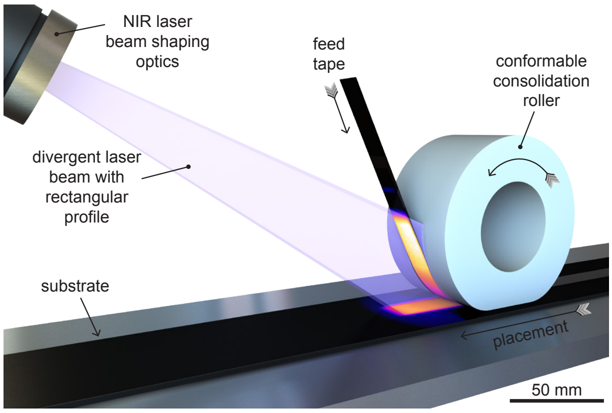

Figure 1. A typical laser TP-ATP manufacturing process.

Successful direct bonding of TPCs to metal substrates with no specialised surface preparation has recently been demonstrated in preliminary studies using processes that lend to high production rates such as laser heating and friction welding [10–17]. However, no studies in published literature have reported direct bonding of thermoplastics to metals with TP-ATP.

While such a process is quite attractive, it is accompanied by a number of challenges. The thermal diffusivity of the steel is two orders of magnitude greater than that of the composite making it very effective at dissipating heat in the consolidation zone. The laser absorption of the two materials is quite different- the black carbon composite has high absorptance, while the steel has a relatively low absorptance and therefore high reflectance. The process control system for the laser tape placement system adjusts the laser power and bias angle based on long wave infrared measurements of the substrate and tape surfaces. For typical surface finishes, the steel has a very low emissivity making this method of control unsuitable for adjusting the laser bias angle.

This study focuses specifically on the application of unidirectionally reinforced carbon fibre/PA 6 composite tapes to mild steel substrates, and how a good bond can be achieved. The effect of various surface preparations and laser angle on the bond strength will be investigated. The bond strength will be characterised by means of ASTM D 5868 lap shear tests.

2. Experimental

The initial focus was to study the effect of surface treatments applied to the 2.0 mm mild steel (1.0161 / S235JRG2C+C) substrates prior to placement of the CF/PA 6 composite. Roughening of the substrate surface should improve the bond at the interface as 1) the surface area for bonding is increased 2) there is a greater degree of mechanical interlocking; the optical properties are also affected with a greater degree of scattering of incident light as well as variation in the absorptance. It is therefore expected that the surface roughness will have a measurable impact on the laser heating process. A subset of the samples were uniformly abraded by grit blasting. The addition of a neat PA 6 film was also investigated as an adhesive layer.

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2.1. PA 6 film lamination

A 60 µm neat PA 6 film (*Folien GmbH Monheim*) was applied to a subset of the steel substrates by vacuum lamination on a flat heated tool. The PA 6 film was placed on the heated tool, separated by a polyimide release film. The substrates were first cleaned with acetone and subsequently placed face down on the PA 6 film. A second release film, breather and vacuum bag were added and an insulating blanket placed on top. Vacuum was applied and the tool heated to 270 °C over a ~90 min period and then allowed to cool naturally, resulting in a dwell time above the melting point of at least 5 min.

2.2. Laser tape placement cell

Placement trials were performed using a tape placement system from AFPT GmbH. Heat is supplied by means of a near infra-red diode laser. In typical usage, a control system monitors the apparent temperature of the surfaces of the tape and substrate prior to the nip point by non-contact measurements with a long wave infra-red (LWIR) sensor array. The laser power and bias angle is regulated to maintain equal surface temperatures on the tape and substrate at a user-set value. The configuration of the placement head for the experimental trials is summarised in Table 1.

Table 1. Placement head configuration

Roller material	Silicone
Roller diameter	60 mm
Roller pressure	3.0 bar
Head angle	28°
Laser optics	40 mm × 20 mm

2.2.1. Placement of initial layers

A fully impregnated 0.15 mm × 12 mm CF/PA 6 unidirectional prepreg tape (*Celanese Celstran*) was placed onto the substrates at a rate of 25 mm/s. Initial trials revealed that the steel substrates have a mirror-like appearance and have very low emissivity compared with the composite tape, therefore making regular LWIR process control not possible as the laser bias angle adjustment no longer has a reliable measure of substrate temperature. To overcome this, the laser bias angle was fixed. Starting from a fixed bias angle of 0° (laser equally on tape and substrate), placement trials of a single tape were performed with increasing bias towards the substrate in −0.5° increments until the greatest qualitative strength was achieved by manually peeling the tape from the substrate. In all cases, the laser power was regulated by the control system so as to maintain a temperature of 250 °C on the surface of the CF/PA 6 tape.

After determination of the best laser angle, two parallel strips (30 mm apart) were placed lengthwise onto a fresh substrate (Fig. 2). The length and width of the substrates was 600 mm and 70 mm respectively. The substrates that were both abraded and had a PA 6 film applied showed very high adhesion for the first layer over multiple laser angles. For this subset of substrates, the effect of the laser angle was investigated for −3.0°, −3.5° and −4.0° laser bias angles.

2.2.2. Placement of further layers

Placement of further layers was straightforward as the tape and substrate surfaces are the same material. An additional 14 plies were placed at a rate of 100 mm/s utilising automatic power and laser bias angle

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control, resulting in a $[0°]_{15}$ laminate approximately 2.0 mm thick applied to a steel substrate. The temperature control target was 250 °C for all layers, which corresponds with good consolidation for CF/PA 6 based on previous experience.

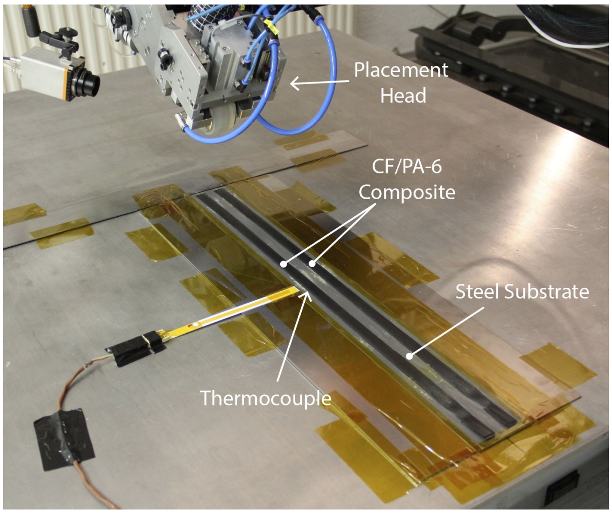

Figure 2. Two parallel strips of CF/PA 6 applied to a steel substrate.

2.3. Lap shear mechanical tests

The ASTM D 5868 standard was followed in this work and is suitable for assessment of FRP-Metal bonds. Samples were supported in a purpose built fixture and cut using a 2 mm tungsten carbide slot drill (with coolant) in a conventional milling machine. A total of six lap shear samples were cut, three from each central section of the two strips, corresponding with the region where the process had stabilised. Following the geometric ratios of the standard, the lap shear samples had a 10 mm × 10 mm lap region and an adherand length of 40 mm, resulting in a total sample length of 70 mm. Samples were mounted in an *Instron* universal testing machine (Fig. 3) with 4 mm support pins and tested with a crosshead speed of 13 mm/min.

3. Results and Discussion

3.1. Effect of surface preparation

Placement of the initial layers onto the steel substrates with no surface treatment was unsuccessful, with no adhesion of the composite tape to the steel for any laser angle. The relatively smooth flat surface was observed to reflect the laser radiation onto the tape in a mostly specular fashion. Increasing the laser bias angle towards the substrate has minimal effect on changing the heating bias as the majority of the radiation is reflected onto the incoming tape. Even with the laser spot aimed entirely on the substrate, the substrate is only slightly warm to touch immediately following placement despite the tape reaching the process temperature of 250 °C due to heating by reflected radiation. It is thought that the molten surface of the tape would be quenched on contact with the cold steel, preventing any significant bond development.

The rough texture of the grit blasted substrates results in scattering of the incident laser radiation, therefore less of the reflected radiation will strike the surface of the tape, in turn allowing greater laser powers to be utilised compared with the non-abraded samples. At the highest bias angle (−5.0°), the laser spot

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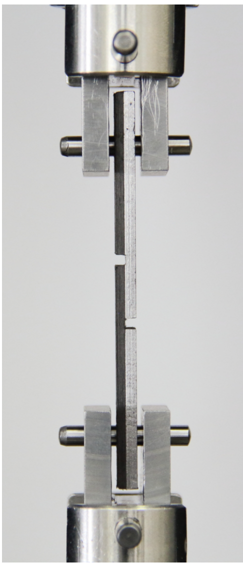

Figure 3. A lap shear sample loaded for testing

was still incident on the tape. The angle of the placement head was therefore increased to 40° so as the laser spot was only incident on the substrate to maximise the heat input into the steel. The tape was therefore only heated by diffuse reflections from the laser on the substrate. A large number of trials were performed to achieve the best bonding of the initial ply to the substrate. The bonding improved with increasing placement rate, however the 4 kW power limit of the laser was reached for placement at 100 mm/s. Placement of subsequent layers onto the grit blasted substrate was initially successful, however delamination at the steel-composite interface occurred after application of the 11th ply.

Both the natural and abraded samples with the PA 6 film applied had a markedly darker appearances suggesting greater absorptance. For both types of coated substrates, a laser bias angle of −3.5° resulted in the best qualitative initial ply attachment. Placement of a further 14 plies was successful in both cases.

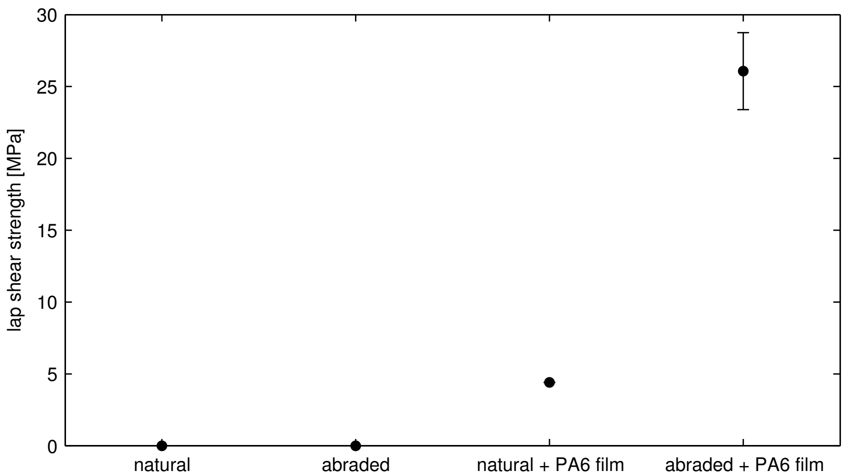

Figure 4. The effect of various surface treatments on lap shear strength.

The lap shear results for all combinations of surface treatments are presented in Fig. 4. No samples could be cut for the substrates that had no PA 6 film applied, therefore the lap shear strength was zero.

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The majority of the samples prepared from the substrate with the natural finish combined with a PA 6 coating failed between the steel-PA 6 interface during cutting. This was attributed to the low apparent peel strength of the PA 6 to the non-abraded substrate. Only one lap shear sample was successfully tested in this case. Adhesive failure was observed between the steel and PA 6 film, which implies superior strength for the PA 6 film to composite bond formed during placement. All of the abraded substrates with PA 6 film applied were cut and tested successfully. Cohesive failure was predominantly observed in the composite, indicating excellent bonding of the PA 6 film to both the composite and the steel substrate. Mixed failure was observed for some samples with small regions of adhesive failure between the steel and PA 6 film in combination with cohesive failure in the composites. It is clear from the results that the combination of surface roughness and a nylon film provides superior lap shear strength, with an average strength of 26 MPa. It is thought that this combination provides the best strength as 1) the surface roughness increases the strength of the PA 6 – steel interface 2) heating is improved as the PA 6 film increases the laser absorptance of the substrate 3) the PA 6 in the film and composite bond rapidly 4) the PA 6 film can act as a compliant interlayer to mitigate stresses caused by the mismatch in thermal expansion between the composite and steel.

3.2. Effect of laser bias angle

The lap shear strengths for different laser bias angles are presented in Fig. 5. It can be seen that placement onto grit blasted, PA 6 coated substrates has a low sensitivity to laser angle, indicating a relatively robust manufacturing process. Lower scatter is observed when increasing the laser bias angle, corresponding with greater heat input into the substrate. This effect is attributed to greater bond development from longer dwell times above the melting point due to increased substrate temperatures which would decrease the cooling rate in the consolidation zone. A laser bias angle of $-4.0°$ resulted in the highest lap shear strength of 29.5 MPa, in agreement with closely related CF/PA 66 to aluminium ultrasonically welded joints [18].

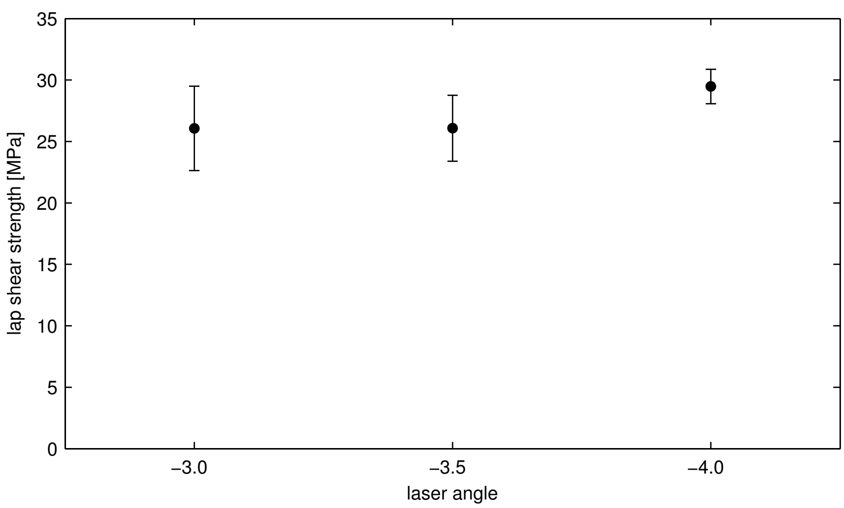

Figure 5. Effect of laser angle for grit blasted substrates with a PA 6 film applied

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4. Conclusion

This work investigated the application of unidirectionally reinforced carbon fibre/PA 6 composite tapes onto mild steel substrates using a laser tape placement system. Two surface preparations were investigated on 2.0 mm mild steel substrates- 1) Grit blast and 2) 60 μm PA 6 film. The interfacial bond strength of the hybrid laminates was determined by means of lap shear tests following the ASTM D 5868 standard. The key findings are summarised below:

- Placement of initial layers required use of fixed laser angle as the substrate temperature cannot be determined with the LWIR sensor due to the relatively low emissivity of the steel.
- Placement onto untreated steel was unsuccessful due to the high reflectivity which resulted in overheating of the feed tape by the reflected laser radiation.
- Grit blasting the steel greatly reduced the specular reflection onto the tape, however the absorptance of the steel is still relatively low therefore high laser power is required. While initial layers bonded, the samples failed during placement of further layers due to thermal stresses.
- Application of a PA 6 film enabled successful placement of CF/PA 6 onto steel. The PA 6 film increased the laser absorption enabling the substrate to be heated sufficiently. The CF/PA 6 composite also rapidly bonds to the PA 6 film.
- On the non-abraded samples adhesive failure was observed between the steel and PA 6 film, which implies superior strength for the PA 6 film to composite bond formed during placement.
- Cohesive failure was predominantly observed in the composite for the grit blasted and PA 6 coated substrates, indicating excellent bonding to the substrate. The process was found to have a low sensitivity to laser bias angle and relatively high lap shear strengths of 29.5 MPa could be achieved.

Further work includes investigation of the optical properties and thermal behaviour of the PA 6 coated steel substrate to elucidate the reasons for superior lap shear strength.

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