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A laser tape placement process for selective reinforcement of steel with CF/PA6 composites: Effects of surface preparation and laser angle

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ABSTRACT

This paper investigates the manufacture of selectively reinforced hybrid metal/composite laminates in a laser tape placement process. Unidirectionally reinforced carbon fibre/PA6 composite tapes were applied to 2.0mm mild steel substrates. The effects of applying various surface treatments to the steel substrates were investigated including grit blasting and/or the addition of 60µm and 100µm PA6 film coatings. The effect of the laser angle was also studied. The substrate surface was characterised by profilometry, SEM and optical absorptance. The interfacial bond strength of the hybrid laminates was determined by ASTM D5868 lap shear tests. Placement onto PA6 coated substrates was successful with lap shear strengths as high as 30.7MPa achieved for grit blasted substrates coated with a 100µm PA6 film. 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, lightweight 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 [1–3], and offer significant weight saving potential [4–7]. Compared with conventional thermoset composites (e.g. with an epoxy resin), TPCs are remarkably tough and typically have specific impact energy absorption an order of magnitude higher [8]. TPCs are therefore expected to display even greater crash performance.

Direct bonding of thermoplastic polymers to metals without adhesives has been demonstrated with laser direct joining [9–14], however these processes require transparency of polymer at the wavelength of the laser radiation. Carbon fibre TPCs are strongly absorbing at typical laser wavelengths [15,16] and therefore laser direct joining is not feasible. Successful direct bonding of carbon fibre TPCs to metal substrates with no specialised surface preparation has been demonstrated in preliminary studies using laser heating [17–20] and friction welding [21–23] of the outer surface of the metal substrate. The bond interface is therefore heated via conduction through the thickness of the metal component. Such an approach has disadvantages of requiring access to both sides of the metallic part, and the inefficiency of heating the full thickness of the metal.

One possible avenue for rapid and flexible manufacture metal/TPC hybrids is to adapt the near infra-red (NIR) laser automated tape placement (ATP) process (Fig. 1). The composite substrate is replaced by a metallic substrate such as a stamped steel component. In this case, a multi-kilowatt NIR laser is considered due to its high productivity and reliability [24]. This would allow high performance composite structures to be manufactured rapidly in a low capital, out-of-autoclave work cell [24–27]. As it is an additive manufacturing process, ATP 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. The anisotropic nature of the reinforcement can increase the structural efficiency as the reinforcement can

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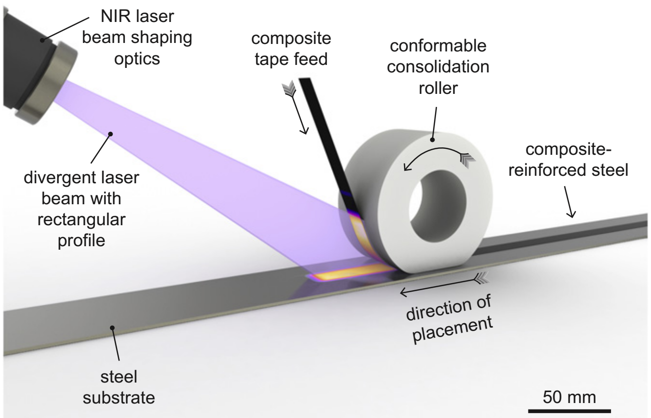

Fig. 1. A typical laser TPC-ATP manufacturing process adapted to manufacture steel/TPC hybrids.

be aligned with the load path. Another advantage is the reduction of the net thermally induced stress compared to bulk heating methods (autoclave, pressforming etc.) due to the shallow heat affected zone, resulting from a combination of the placement motion and local surface heating by the laser.

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 away from the consolidation zone. The NIR laser absorptance of the two materials is quite different — the relatively black carbon composite has high absorptance, while the steel has moderate absorptance.

This study focuses specifically on the application of unidirectionally reinforced carbon fibre/PA6 composite tapes to mild steel substrates, and how to achieve a good bond at the composite–metal interface. The effect of surface texturing, laser angle and the addition of 60 μ m 100 μ m PA6 films on the bond strength will be investigated. The substrate surface is characterised by profilometry, SEM and optical absorptance measurements. The quality of the hybrid bond (metal/TPC interface) will be characterised by means of ASTM D 5868 lap shear tests.

2. Experimental

2.1. Substrate surface preparation

The initial focus was to study the effect of surface treatments applied to the 2.0 mm bright mild steel (1.0161/S235JRG2C+C) substrates prior to placement of the CF/PA6 composite.

2.1.1. Surface texturing

The cold rolled (CR) surface of the steel as delivered is very clean and smooth. Roughening of the substrate surface should improve the bond at the interface as 1) the surface area for bonding is increased and 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 both the bond quality as well as the laser heating process. A subset of the samples was uniformly textured by abrasive grit blasting with size F36 (425 μ m to 600 μ m) corundum blasting media at an air pressure of 2.0 bar. Grit blasting (GB) was performed normal to the substrate at a distance of approximately 100 mm.

Table 1
Substrate surface preparation matrix.

	Surface Texture		PA 6 film	
Label	Cold Rolled	Grit Blasted	60μm	100μm
CR–D	●	–	–	–
CR–P60	●	–	●	–
GB–D	–	●	–	–
GB–P60	–	●	●	–
GB–P100	–	●	–	●

2.1.2. PA6 film lamination

The TPC prepreg has only a limited quantity of neat polymer available at the surface for wetting of a substrate surface texture. Addition of a neat polymer film to the substrate surface could therefore increase the wet-out of the surface texture leading to higher bond quality. Two PA6 films (*Folien Gmbh Monheim, Germany*) 60 μ m and 100 μ m in thickness were applied to a subset of the steel substrates by vacuum lamination on a flat heated tool. The textured substrates were grit blasted approximately 1 h prior to lamination. The PA6 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 PA6 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 at the polymer–metal interface.

The surface preparation combinations considered in this study are summarised in Table 1.

2.2. Laser ATP system

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 infrared (LWIR) sensor array. The laser power and angle is regulated by a control system to maintain equal surface temperatures on the tape and substrate at a user-set value. Referring to Fig. 2, it can be seen that the distribution of the laser radiation is dependent on (1) the angle of the placement head, α, which is programmed in the robot movement and (2) the laser bias angle, β, the angle of the laser optics relative to the default position, which is automatically adjusted by

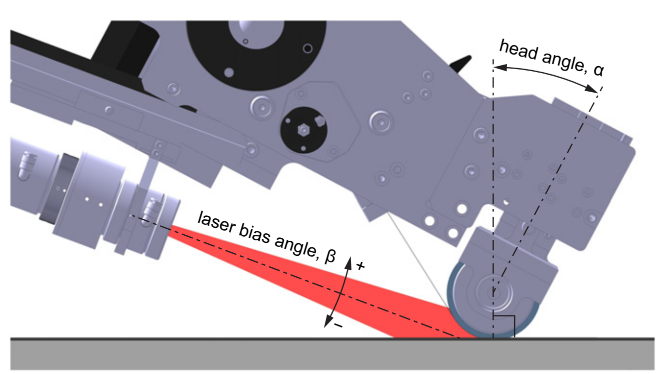

Fig. 2. A diagram showing the head angle (α) and laser bias angle (β).