Composites Part A 111 (2018) 42–53

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Manufacture of steel–CF/PA6 hybrids in a laser tape placement process: Effect of first-ply placement rate on thermal history and lap shear strength

C.M. Stokes-Griffin[a,*], A. Kollmannsberger[b], S. Ehard[b], P. Compston[a], K. Drechsler[b]

[a] ARC Training Centre for Automated Manufacture of Advanced Composites, Research School of Engineering, Australian National University, Canberra, ACT 2601, Australia

[b] Chair of Carbon Composites, Department of Mechanical Engineering, Technical University of Munich, Boltzmannstrasse 15, D-85748 Garching, Germany

ARTICLE INFO

Keywords:
A. Hybrid
A. Polymer-matrix composites (PMCs)
C. Finite element analysis (FEA)
E. Tape placement

ABSTRACT

This paper investigates the manufacture of selectively reinforced metal/composite hybrids in a laser-assisted automated tape placement process. Carbon-fibre/PA6 composite tapes were applied to PA6-coated steel substrates. The bonding of the first-ply to the substrate is critical to the success of the hybrid; the effect of first-ply placement rate was investigated for speeds of 25 mm/s, 50 mm/s, 100 mm/s. The interfacial bond strength of the hybrid laminates was determined by ASTM D3165 lap shear tests. A 3D finite element thermal model was formulated to elucidate the thermal behaviour for increasing first-ply placement rate. A method for increasing model efficiency was shown to significantly decrease the computational difficulty while maintaining solution accuracy. Raising the first-ply placement rate from 25 mm/s to 100 mm/s resulted in a fourfold increase in lap shear strength with a maximum value of 22 MPa. The greater strength at higher speeds is attributed to improved synchronisation of the temperature and consolidation pressure history.

1. Introduction

In more recent times there has been increased application of carbon fibre composites to light-weighting of structures, particularly in the aerospace and automotive sectors [1,2]. Hybrid structures with combinations of dissimilar metals and composites can provide a more optimal balance of cost, manufacturability and performance. Sheet metal/carbon fibre epoxy reinforced structures have been demonstrated to have good crash performance for automotive structures [3–5], and offer significant weight saving potential [6–9]. Selective reinforcement of critical safety structures with small amounts of strategically placed high value reinforcement has been demonstrated in the BMW 7 series [10,11], with carbon fibre reinforcements applied to reduced gauge steel pillars, resulting in decreased weight, while simultaneously increasing crash performance and chassis stiffness with the flow on improvements to vehicle dynamics from a lower centre of mass. Similar synergy exists in the Aston Martin DB11 which features composite components bonded to aluminium base structure [12].

At this point in time, the application of structural composites in automotive has been limited to flagship models and exotics due to a combination of cost and limited productivity. Many of the currently employed manufacturing processes rely on thermoset-based resin systems, requiring time for the polymer to cure (polymerise) during the manufacturing process of both the composite and the adhesive bond. Thermoplastic composite (TPC) materials are supplied in a polymerised state; processing simply requires melting and re-solidification thus the cure cycle is avoided, and the bonding process can occur much faster-typically less than one second in a tape placement process. This also opens the possibility of rapidly bonding (akin to hot-melt adhesives) the composite directly to a metallic substrate without an intermediate adhesive. 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 [13] as well as greater prospects for recycling and repair. The use of TPCs is therefore expected to provide improved production rates, crash performance and end of life credentials for mass-produced vehicles. However, a suitable manufacturing process for application of TPC selective reinforcements is needed that would ideally meet the following requirements:

(1) a short cycle time.
(2) production flexibility, with minimal design constraints and capital investment for new component variations.
(3) limited or no surface preparation requirements.

Selective reinforcement of metallic components with laser tape placement of TPC materials opens the possibility of manufacturing

* Corresponding author.
E-mail address: chris.stokes-griffin@anu.edu.au (C.M. Stokes-Griffin).

https://doi.org/10.1016/j.compositesa.2018.05.007
Received 22 December 2017; Received in revised form 4 May 2018; Accepted 8 May 2018
1359-835X/

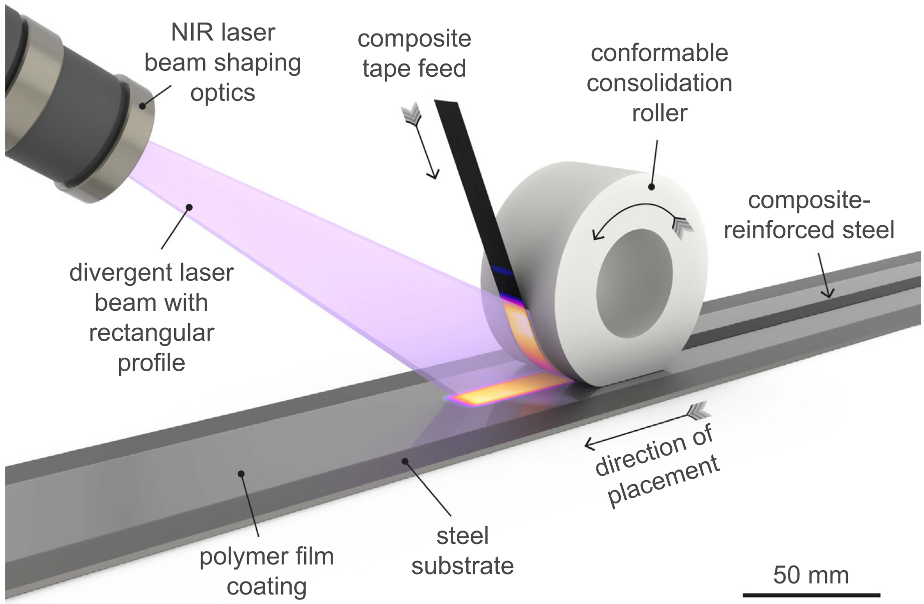

Fig. 1. A typical laser TPC-ATP manufacturing process adapted to manufacture steel/TPC hybrids. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

high-value, light-weight hybrid structures in a rapid, flexible and efficient process, and meets requirements (1) and (2). Fig. 1 demonstrates this concept applied to a near infra-red (NIR) laser automated tape placement (ATP) process. A placement head dispenses TPC material, typically in the form of a unidirectional prepreg tape. A multi-kilowatt NIR laser heats the surfaces of the tape and steel substrate. The molten surface of the tape contacts the substrate at the nip point, followed by consolidation and cooling under the consolidation roller. This concept was recently demonstrated for placement onto steel substrates and was shown to be particularly successful for reinforcement of substrates with a grit blasted and PA6 coated surface pretreatment [14] with lap shear strengths exceeding 30 MPa. It should be noted that the bonding mechanism between a polymer film coating and a composite tape is by polymer fusion bonding. Texturing (by means of grit blasting) of a cold-rolled steel surface was found to increase the laser absorptance by 60% and the surface area by 139%. However, successful bonding required additional, non-viable for production surface preparation and therefore unable to meet requirement (3).

The strength of the interface is key to the success of a load-bearing metal-composite hybrid. Achieving a quality bond is challenging due to the great differences in physical and chemical characteristics. Differences in thermal expansion lead to residual stress and the thermal diffusivity differs by orders of magnitude creating unique challenges when processing. A variety of approaches for joining the interface have been reported including discreet joining methods such as spot welding by friction stirring [15] or resistance welding [16,17] and clinching [18]; these methods are rapid however load transfer is poor due to stress concentrations and they are not compatible with additive manufacturing processes like ATP. Macro-mechanical methods such as arrays of pin-like reinforcements result in a high quality interface and can be manufactured by CMT [19,20], additive manufacturing [21,22], electron beam sculpting [23–25] or drilled and inserted [26]; however they do not meet requirement (3) as they are considered to be significant surface preparation. The interface can also be enhanced by surface treatment methods such as laser ablation [27], grit blasting [14,28–30], chemical modification [16,31], electrochemical treatment [32] and pickling [29].

The hot-rolled steels used in automotive structural panels are often supplied with a pickled surface finish. It is likely that the pickled texture has both higher surface area and laser absorptance compared with the previously investigated cold-rolled steel that has a relatively smooth surface [14]. Furthermore, acidic pickling treatments have been shown to enhance bonding of aluminium/CF-PA66 joints [29]. It is therefore of interest to study whether good bonding can be achieved with a pickled surface finish without additional texturing, satisfying requirement (3).

Thermoplastic fusion bonding involves two main processes- intimate contact development and autohesion. Intimate contact development is the flattening of asperities at the bond interface, the rate of which depends on the applied pressure and the viscosity of the polymer which is highly temperature dependent. For the regions in intimate contact, the polymer molecules may diffuse and entangle cross the bond interface developing strength in a process known as autohesion or healing. The rate of molecular diffusion is highly temperature dependent, and depends directly on the molecular weight and molecular structure [33]. The majority of literature in the field of TPC-ATP has investigated composites with a PEEK matrix. PEEK has a relatively high melt viscosity and low rates of molecular diffusion, narrowing the process window. Despite this, high relative interlaminar strengths have been reported for TPC-ATP of CF/PEEK at placement rates of up to 400 mm/s [34–38]. Polymers commonly used in automotive applications such as PA6 have significantly lower melt viscosities allowing for rapid intimate contact development [39].

Previous work found the attachment of the first ply of a CF/PA6 to a steel substrate to be the most challenging and critical aspect of the TPC-ATP selective reinforcement process [14]. Relatively low first-ply placement rates of 25 mm/s were employed and all failures were observed at the hybrid interface or within the first ply. After application of the first ply to the metallic substrate the process is relatively straightforward as it is regular TPC-ATP where high interlaminar strength can be achieved at placement rates of 400 mm/s [38]. The attachment of the first ply is the most critical step to the success of the reinforcement. Previous work employed relatively low first-ply placement rates of 25 mm/s [14]. In the interests of increasing productivity, the effects of increasing the first-ply (TPC to substrate) placement rate will be studied. During the process, it is only possible to view the temperature history on the surface of the composite or in the composite at discreet locations with embedded thermocouples. The temperature field through the thickness of the substrate and tape cannot be measured practically. To elucidate how the process responds to increasing