Optics and Lasers in Engineering 72 (2015) 1–11

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Optical characterisation and modelling for oblique near-infrared laser heating of carbon fibre reinforced thermoplastic composites

C.M. Stokes-Griffin *, P. Compston

Research School of Engineering, CECS, Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
27 February 2015
Accepted 21 March 2015
Available online 11 April 2015

Keywords:
Diode laser
Anisotropic scattering
Automated Tape Placement (ATP)
Carbon fibre
PEEK

ABSTRACT

The optical behaviour of a carbon fibre reinforced thermoplastic composite material is investigated for a near infrared laser heating process applied to automated composite tape placement. A nip point heating strategy in laser tape placement results in a shadow before the nip point on both the incoming tape and substrate. The moderate laser angle relative to the surface of the composite leads to reflections in the cavity formed by the tape and the substrate, reducing the shadow. An optical ray tracing model can provide valuable insight to the interaction of the laser with the composite, as well as detailed estimation of the irradiance distributions. This paper provides the foundations for such a model, describing an optical characterisation process and formulation of appropriate models to capture the composite surface and laser source behaviour. A micro-half-cylinder surface treatment was shown to give a good approximation of the anisotropic scattering behaviour of the composite. Angular dependent reflectance was described well by Fresnel equations. An approximation of the laser beam profile and propagation is also presented.

1. Introduction

Carbon fibre reinforced polymer (CFRP) materials offer outstanding specific stiffness, strength and fatigue life. Modern applications of CFRPs are increasing and include sporting goods, bicycle frames, commercial aerospace (Boeing 787, Airbus A350) as well as lightweighting in automotive (BMW i3, i8). The manufacture of CFRP structures has been traditionally limited to low production volumes for two primary reasons (1) time and labour intensive manual lay-up process and (2) the use of thermosetting polymers (e.g. epoxy resins) that require long autoclave cure cycles (hours in length) to maximise quality and performance. Technologies such as automated tape placement (ATP) can minimise the lay-up time and manual labour requirements by utilising robotic heads to apply pre-impregnated composite tapes to tooling. The subsequent cure process remains a bottleneck. Cycle times are in the order of hours in energy-intensive and expensive autoclaves.

Thermoplastic (TP) matrix CFRPs are emerging as an alternative to thermosetting matrix CFRPs in ATP as they have potential to be rapidly processed in situ as they do not cure, rather they can be melted and bonded rapidly in situ. A typical TP-ATP setup using a nip point heating configuration is shown in Fig. 1. Unidirectional thermoplastic pre-impregnated carbon fibre tape is fed from a placement head onto the workpiece. A heat source, in this case a laser, is used to heat the surfaces of the tape and the substrate as they approach the nip point, the location where the two surfaces are brought together under the consolidation roller. The melted surfaces conform to one another under the pressure of the consolidation roller, forming a bond. This bonding process can occur in less than 1 s and no cure step is required. Components are manufactured in an additive fashion by the subsequent placement of many layers of tape. The bond strength development process [1,2] as well as other physical processes such as residual stress development [3], void dynamics [4–7], crystallinity [8,9], and degradation [8,10] are all strongly linked with the specific temperature history.

Heat sources traditionally utilised for TP-ATP include hot gas torches, direct flames and carbon dioxide lasers. The convective mode of heat transfer for hot gas torches and direct flames limit the surface heat flux, restricting the maximum placement rate. Inherently slow response of these sources further imposes limits on temperature control system performance [11]. Carbon dioxide lasers ($\lambda = 10.6\ \mu m$) with beam powers of 65–80 W were investigated for thermoplastic filament winding [12–16]. Round spot outputs were converted into lines (typically 2 mm wide) using ZeSe lenses [11,12,14–17] or galvanometer scanning [13]. The narrow line width causes high sensitivity to laser position [17] and poor bonding due to short dwell times [15,16].

In more recent times, near infra-red (NIR) diode lasers have been adapted due to high efficiency, near instantaneous response and the ability to deliver higher heat fluxes [18]. The shorter wavelength (λ=800–1000 nm) allows delivery of the beam to the

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

http://dx.doi.org/10.1016/j.optlaseng.2015.03.016
0143-8166/

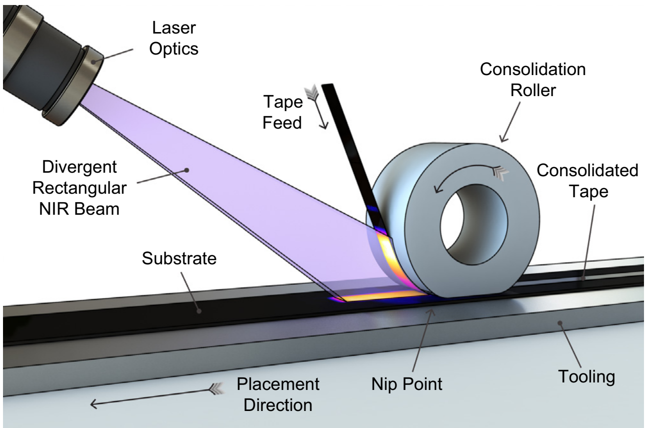

Fig. 1. Laser-assisted ATP process showing typical laser beam propagation with visualisation of the predicted irradiance. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

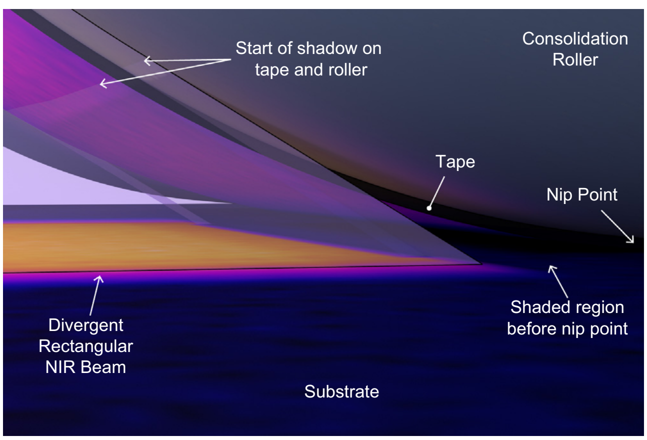

Fig. 2. Close up of the nip-point region showing the shadow cast by the tape. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

placement head via a light cable. Large homogeneous rectangular spots (45 mm × 16 mm in this application) can be produced by compact optical modules, resulting in uniform, progressive heating across the length and width of the tape, increasing the dwell time and therefore bond quality.

Previous work on thermal modelling of laser TP-ATP has typically assumed the simplification of the laser to a uniform heat flux applied as a boundary condition to the surfaces of the tape and the substrate [8,10,16,19–21], and the presence of a shadow not considered. For ATP using a nip point heating strategy, the laser is aimed into a wedge shaped cavity formed by the feed tape and the substrate (Fig. 1). The NIR radiation strikes the surfaces of the tape and the substrate at an oblique angle, resulting in potentially significant levels of reflection. One practical limitation of a nip point heating strategy is the laser optics need to be located above the plane of placement to provide adequate clearance from the work piece. As a result, the laser beam does not directly irradiate the substrate and the tape immediately before the nip point, potentially creating a shaded region [22] as illustrated in Fig. 2. Previous studies indicate that due to the rapid speed of the process, such a shadow would result in a significant temperature drop, adversely affecting the bond quality [23,22]. However, the oblique angle of the laser could lead to significant reflections that would result in some unknown degree indirect irradiation of the shaded areas. It is therefore of interest to model the interaction of the NIR radiation in the cavity to predict what level of shading exists and what affect it would have on the temperature history.

Grove [24] modelled a carbon dioxide laser ATP process with simple ray tracing calculations in 2D for a collimated laser source in the form of a 1 mm wide line. Specular reflection was assumed with a fixed value, based on the average value from reflectance measurements which varied inconsistently with angle of incidence and position, ranging from 0.14 to 0.42. Details of the measurement wavelength or apparatus were not given. Another study [16] modelled a CO_2 laser filament winding process. It was found that the model required one fifth of the power that was used in the experiments. An explanation for this difference was the reflected energy being scattered out of the nip point region, therefore the authors suggested a 3D optical model is necessary.

Grouve [23] investigated NIR laser-assisted TP-ATP for welding Carbon/PPS unidirectional tapes to pre-manufactured woven laminates. Experimental measurements demonstrated anisotropic scattering behaviour from the composite. The angular dependent reflectance was measured with a photometer and a $\lambda = 980$ nm laser pointer. It appears that only the specular component of the reflectance was measured based on the description of the measurement technique. A curve fit of the angular dependent reflectance measurements to Fresnels equation determined the effective refractive index to be $n = 1.8$. A 2D ray tracing model of the laser ATP process was constructed. Specular reflection was assumed with the angular dependence determined using Fresnel equations. The laser source was approximated as perfectly collimated with a top-hat beam profile. Model validations were performed with an infrared camera. Predictions agreed well for the tape, however the substrate temperatures were significantly overestimated. The discrepancies were attributed to the 2D simplification of the optical model and also the assumed thermal properties.

A well formulated 3D optical model can provide valuable insight into the laser's interaction with the cavity between the tape and the substrate, as well as detailed estimation of the irradiance distributions. Such distributions can then be subsequently applied to a thermal model, allowing the influence of a shadow on the temperature profile to be understood, and accurate prediction of the temperature history. The first step in formulating such a model is optical characterisation of the composite material and laser source, which is described in this paper. Models for approximating the composite behaviour in terms of scattering and reflected power will be formulated. The laser beam profile and propagation will be measured and approximated. The results of this work are intended to provide building blocks for the development of a complete 3D ray tracing model of the near infrared laser tape placement process.

2. Optical property characterisation

It is necessary to first understand the optical behaviour of the composite prior to formulating the optical model. As the configuration of the laser tape placement system forms a wedge shaped cavity between the substrate and the tape, the scattering distribution of the reflected radiation is also important, as will be shown later. The properties need to be determined at the wavelengths of the laser source, which emits at $\lambda = 940$ nm and 980 nm. The TP-CFRP considered in this study is a polyetheretherketone (PEEK) matrix reinforced with high strength carbon fibres (AS4), which has properties on par with a conventional high performance thermoset CFRPs. PEEK has outstanding qualities in terms of strength, toughness and temperature stability as well as creep and chemical resistance. Unidirectional reinforcement fibres occupy 55% of the composite by volume, are continuous in length and highly aligned.