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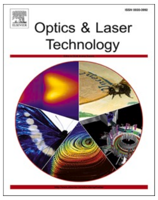

Resin absorption and transmittance in CFRPs during CO_2 laser surface preparation: Insights into matrix removal mechanisms

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ABSTRACT

Recent studies have explored CO_2 laser surface treatment to enhance the adhesion of Carbon Fibre Reinforced Polymer (CFRP) composites. This paper investigates the absorptivity of epoxy resin at 10.6 μm to better understand and optimise laser-based surface preparation for improved bonding performance. Epoxy resin samples (15–110 μm thick) were exposed to unfocused CO_2 laser beam (wavelength 10.6 μm). Results indicate that a 15 μm resin layer transmits 55 % of the laser power, while transmission drops significantly to 5 % for an 86 μm thick resin layer. Calculations based on the Beer-Lambert law reveal an absorption coefficient of 0.0343 μm^{-1} and a penetration depth of approximately 29 μm, indicating that the thickness of the matrix outer layer can significantly influence the removal mechanism.

1. Introduction

CFRP composites, known for their exceptional strength-to-weight ratio, are particularly favoured in the aviation industry. However, joining CFRP elements poses challenges, as mechanical fasteners can create stress concentrations. Adhesive bonding offers a superior alternative, addressing the drawbacks of traditional fasteners and maximising the benefits of lightweight construction. However, surface preparation of adherends is crucial for removing contaminants and release agent residues to achieve strong and consistent bonds. Current industry methods, including mechanical abrading, peel ply, and chemical etching, have limitations [1,2].

Lasers, being contactless and wear-free, show significant potential for surface treatment. Research has investigated the effects of various continuous and pulsed lasers across different wavelengths [1–3], including the Continuous Wave (CW) CO_2 laser [4]. Joint strength is improved by removing part or all the initial (outer) matrix layer, which eliminates contaminants and exposes fresh material to the adhesive [1]. Previous studies emphasise the importance of fully exposing the underlying carbon fibres (CFs) for direct adhesive bonding by removing the outer layer of the CFRP matrix [2,4,5].

The wavelength of the laser is a crucial factor in understanding the matrix removal mechanism. It determines photon energy, which categorises the laser-material interaction into photothermal or photochemical processes. Short wavelengths in the UV range have high photon energy, breaking down polymer molecular bonds, while longer wavelengths in the IR range result in photothermal interactions. Additionally, the absorption coefficient, specific to each wavelength, influences a material's absorptivity and transmittance [2,3]. Laser intensity decays exponentially with the distance travelled through a material according to the Beer-Lambert law, the reduction in intensity with depth determined by the material absorption coefficient [6].

Some researchers have reported that, for Mid Infra-Red (MIR) lasers, e. g. CO_2 lasers at 10.6 μm, thermosetting epoxies show high absorption with almost no transmittance based on experimental studies using epoxy samples of 0.17 mm and 2 mm in thickness [7,8]. However, the outer layer matrix of CFRPs is significantly thinner, often less than 10 μm [9]. In another study, Kumar et al. [10] reported that a 6.5 μm thick epoxy paint sample transmitted significant amount of incident CO_2 laser power (10.6 μm). Similarly, Kim et al. [11], who studied the effect of curing agents on the optical characteristics of cured transparent glass-fibre-reinforced epoxy composites, and Fischer et al. [3], who investigated laser surface processing of CFRPs for adhesive bonding, both provided transmission spectra demonstrating that the epoxy resin permits some transmission of light at 10.6 μm. In terms of optical properties, these spectra are regarded as qualitative rather than quantitative. To the best

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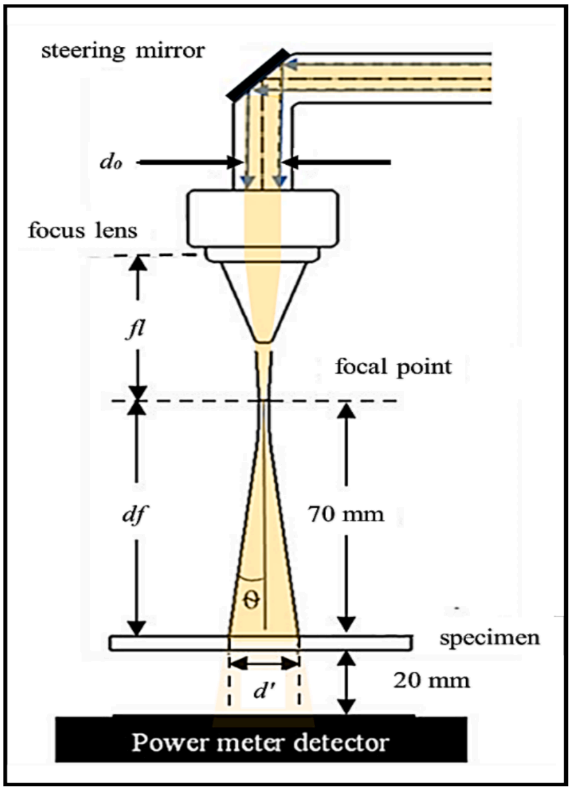

Fig. 1. Schematic diagram of the laser system and experimental setup.

of current knowledge, data on the absorption coefficient and penetration depth of thermosetting epoxies at 10.6 μm remains unavailable, highlighting a significant gap in research. Nevertheless, earlier studies on thermal stereolithography have explored the penetration depth of CO_2 lasers in non-cured epoxy resins [12,13]. This study aims to systematically measure the transmittance, absorption coefficient, and reflection of a representative thermosetting epoxy matrix when exposed to a CO_2 laser, providing a comprehensive understanding of the matrix removal mechanism.

2. Material and experimental methods

A 30 W Continuous Wave (CW) CO_2 laser was used to examine the transmittance of epoxy resin films. The laser source was a Lotus Laser Systems LL10600. According to the manufacturer specifications, it has a maximum power of 30 W, beam diameter of 3.5 mm and $M^2 < 1.2$. The beam was directed through a 40 mm focal length ZnSe focussing lens. The epoxy films were placed 70 mm below the focal point of this lens, Fig. 1.

As the distance from focus significantly exceeds the Rayleigh length (the distance from the waist of a laser beam to the point where the beam's cross-sectional area doubles), the beam diameter increases approximately linearly with the distance, it is diverging in a conical shape that contains approximately 86 % of power [14]. Using **Equation (1)**:

$$d' = \frac{d_0 \cdot df}{fl} \tag{1}$$

where (*df*) is the defocus distance, (d_0) is the beam diameter at the lens, (*fl*) is the focal length of the lens, an estimated spot size of the beam at the epoxy films (*d'*) is 6.1 mm. The power of the laser beam was measured using a power meter (OPHIR NOVA II) both with and without a sample, and it was recorded as 0.65 ± 0.02 W when no sample was present. The low power and large spot size used in the experiment ensured the resin film did not degrade.

IN2 resin, an ultra-low viscosity infusion thermoset epoxy (Easycomposites UK), formed films of 15 to 110 μm thickness. Resin moulding occurred between two toughened glass sheets with mirror finish, compressed with ratchet bar clamps. Aluminium sheets served as shims to control film thickness. Prior to resin application, the glass sheets were wiped with a lint-free cloth soaked in CR1 Easy-Lease, a volatile chemical release agent from Easycomposites UK, waiting for about 60 s to be evaporated. The resin films were cured at room temperature for seven days. For accuracy, the thicknesses of the produced epoxy films were measured using profilometry. This was achieved by measuring the thickness of a 5 mm x 5 mm piece from each sample, cut from a location near the laser-exposed region. Fig. 2 illustrates an epoxy film that was aimed to be 25 μm thick but measured 23.5 μm thick according to profilometry. This example is provided to represent the thickness measurements taken for all resin films in the study. Furthermore, multiple profilometry measurements confirmed that the thickness of the release agent layer was less than 0.1 μm and thus it was considered to have minimal impact.

The power transmitted from each resin film was recorded after laser scanning for 10 s. The power meter showed a stable reading after 1–2 s. Each resin film was exposed to the laser at three distinct but closely spaced positions. Readings from at least two repeated measurements were found to be matched, and these were then considered. To measure the thickness of the outer layer matrix resin of CFRPs, cross-section of

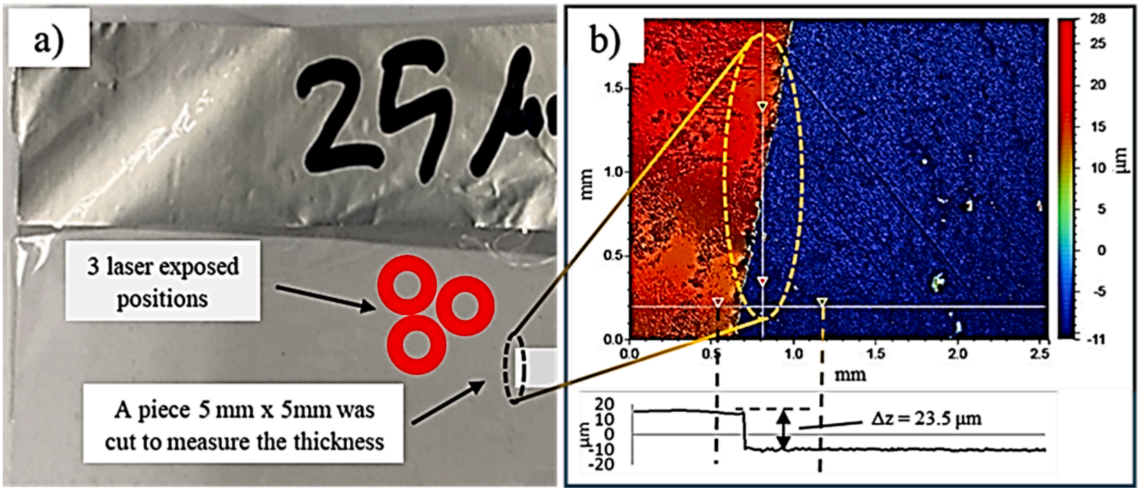

Fig. 2. (a) Macro photograph of an epoxy film, designed to be 25 μm thick; (b) Profilometry measurement of the same film, showing a thickness of 23.5 μm.

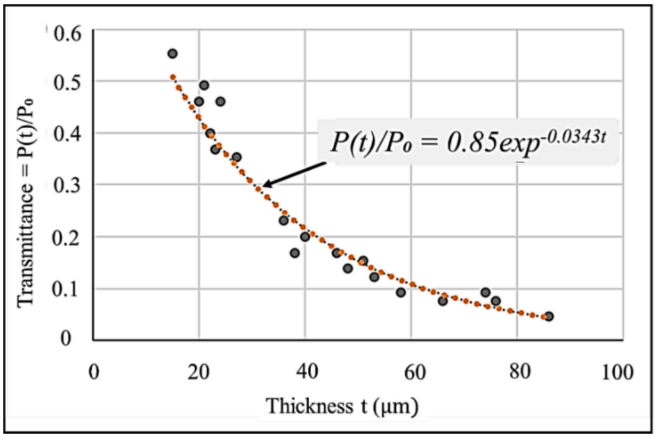

Fig. 3. Laser power transmittance ($P(t)/P_0$) through resin films of varying thickness (t).

different CFRP samples were examined using Scanning Electron Microscopy (SEM) (Inspect S model, Thermofisher). The samples were moulded within epoxy and polished to mirror finish before SEM assessment.

As the resin moulding process was conducted using glass sheets with a mirror finish, the produced resin films were considered to have the same surface finish as the glass sheets. Moreover, to simplify the calculation of the absorption coefficient in this study, the reflection from all resin films was assumed to be constant, no scattering, and the beam is attenuated exponentially mainly by absorption. These assumptions were made to focus on the primary goal of determining the absorption characteristics of the epoxy resin at a specific wavelength. The absorption coefficient (α) and the reflectivity (R) are determined by substituting the exponential trend of the measured transmittance data with Beer-Lambert law, which relates the amount of light absorbed by a medium to the distance the light travels through it, **Equation (2)**, [15].

$$\frac{P(t)}{P_0} = (1 - R)e^{(-\alpha t)} \tag{2}$$

3. Results and discussion

The results indicated a 15 μm film transmitted approximately 55 % of the laser power, whereas less than 5 % was transmitted through an 86 μm film. Fig. 3 shows the measured relationship between resin film thickness (t) and the normalised laser power transmittance ($P(t)/P_0$), where P_0 is the incident power and P(t) is the transmitted power.

The 110 μm resin film showed no transparency at the power used, so it was excluded from the plot. The data points closely fit an exponential decay equation $Y = 0.85e^{(-0.0343t)}$ representing the relationship between transmittance and film thickness. Based on this exponential fit of the

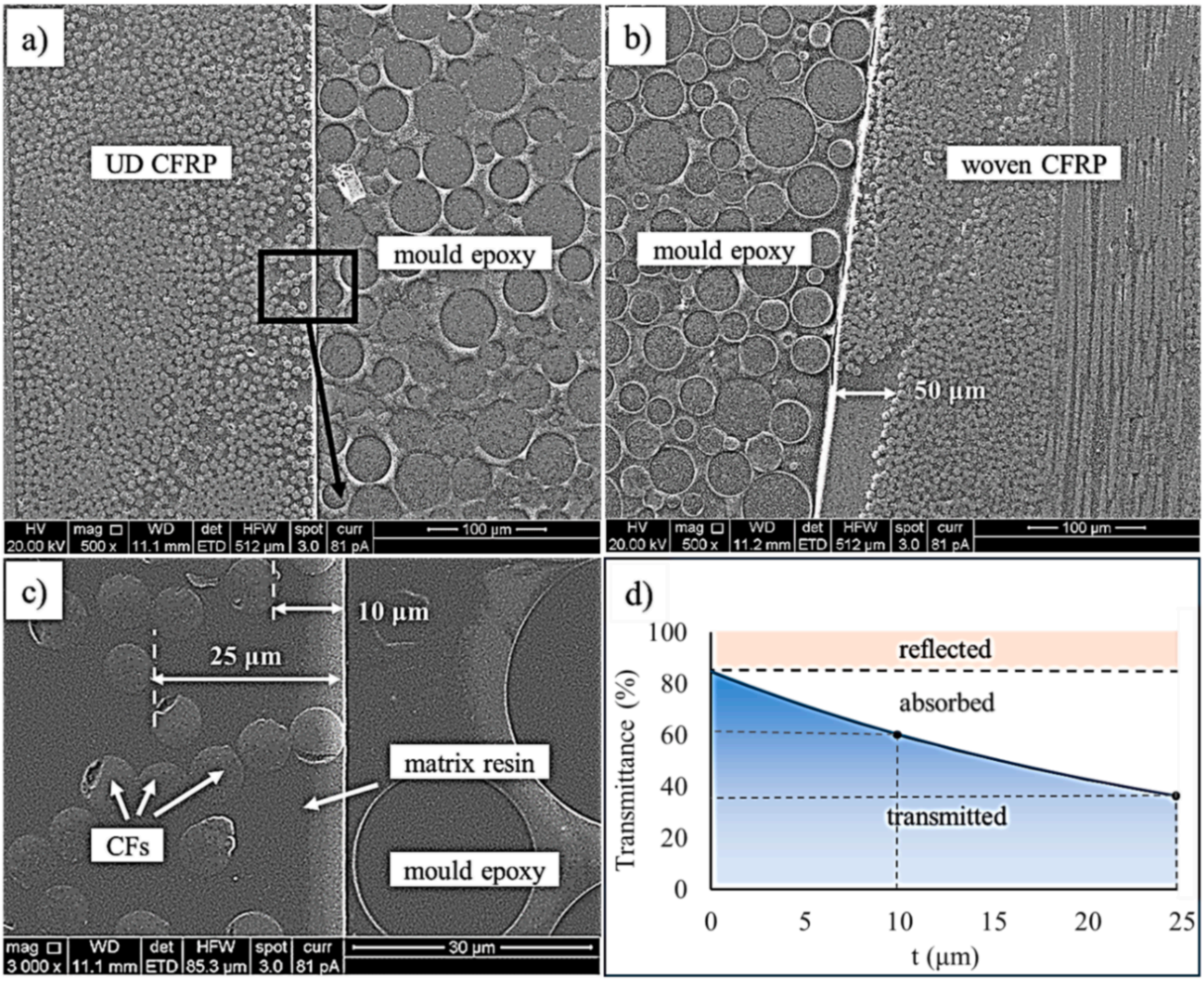

Fig. 4. SEM images of cross-section of CFRP composites show the matrix outer layer thickness in a) UD reinforced and b) woven reinforced CFRP. c) shows a high magnified image of a UD reinforced CFRP, and d) A plot illustrates absorbed, transmitted, and reflected percentages of CO_2 laser passing through resin film (0–25 μm thickness).

measured transmittance data, this work estimates the reflectivity of the film to be 15 % and the absorption coefficient (α) to be 0.0343 μm^{-1} at wavelength10.6 μm. This coefficient results in a penetration depth (1/α) of approximately 29 μm, which represents the depth at which the illumination intensity decreases to about one-third of the incident value [16]. SEM assessment of cross-sections of various CFRP materials revealed varied outer epoxy matrix layer thicknesses, dependent mostly on whether the reinforcement is unidirectional (UD) or woven. For UD reinforcement CFRPs, it ranged from 1 to 25 μm, with an estimated average of about 10 μm, Fig. 4 **(a)** and **(c)** [17]. This range is much wider for woven reinforced CFRPs Fig. 4**(b)**. Fig. 4 **(d)** illustrates the percentages of laser power absorbed, transmitted, and reflected as a function of resin film thickness ranging from 0 to 25 μm, in accordance with the Beer-Lambert law. For a 10 μm resin layer, which is the estimated average outer layer matrix of the tested UD CFRP material, about 60 % of the light intensity is transmitted through the matrix and absorbed by the underlaying CFs while only 25 % is absorbed by the matrix layer itself and the remainder (15 %) is reflected.

4. Conclusions

This experimental study presents and discusses briefly thermosetting resin transmittance to CO_2 laser. Findings reveal that a 15 μm epoxy layer transmits about 55 % light, while an 86 μm thickness allows only 5 % transmission. Employing the Beer-Lambert law equation facilitated calculating absorption coefficient (α) of 0.0343 μm^{-1} this indicated a penetration depth (δ) of about 29 μm. The latter falls within the range of typical matrix outer layer thicknesses in CFRPs. This finding suggests that, using a CW CO2 laser, the removal mechanism of the matrix outer layer is strongly influenced by its thickness (t). For thicker layers ($t > \delta$), the degradation predominantly occurs due to direct matrix absorption of the laser energy. In contrast, for thinner layers ($t < \delta$), the degradation may involve a combination of direct matrix absorption and heat conduction facilitated by the laser-irradiated fibres. Therefore, when using a CO_2 laser for surface treatment of CFRPs or other applications involving the removal or ablation of resin layers, such as paint stripping, it is essential to account for the thickness of the target layer to optimize the processing parameters. These findings offer valuable insights into the optical properties of thermoset epoxies and discussions on surface treatment of fibre reinforced polymers using CO_2 lasers. Additionally, they provide a solid foundation for future simulation studies aimed at further understanding degradation and the matrix removal mechanisms in CFRPs.

Acknowledging that the simplified assumptions of the constant reflection may not adequately account for the variability in reflection characteristics across different resin samples, which can introduce errors in the results if these variations are not considered.

CRediT authorship contribution statement

Ahmed Al-Mahdy: Writing – original draft, Methodology, Investigation, Formal analysis. **Tahsin Tecelli Öpöz:** Writing – review & editing, Supervision, Formal analysis. **Hiren R. Kotadia:** Writing – review & editing, Supervision, Formal analysis. **Juan Ignacio Ahuir-Torres:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Martin Charles Sharp:** Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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