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Effect of glass fiber and crystallinity on light transmission during laser transmission welding of thermoplastics

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ABSTRACT

In order to predict and optimize the contour laser transmission welding (LTW) process, it is important to understand how the laser energy behaves during transmission through the transparent part. In this study, transmission measurements were made on unreinforced and glass-fiber-reinforced amorphous and semi-crystalline thermoplastics at different thicknesses. Using the ratio of transmitted power to laser power, apparent absorption coefficients and apparent reflections were calculated. The results indicate that there is a linear relationship between the glass fiber volume fraction and the apparent absorption coefficient of reinforced polymers; similar effects were also observed for crystallinity. A simple model was developed to estimate apparent absorption coefficient of reinforced polymers as a function of composition.

The apparent reflection increased with crystallinity due to increased back scattering. However, for glass-fiber-reinforced polymers, the apparent reflection displayed a more complex behavior.

1. Introduction

Laser transmission welding (LTW) is used to join laser-transparent and laser-absorbent plastic parts [1]. The laser energy must first pass through the so-called transparent part in which there is interaction between the laser energy and the different solid phases such as reinforcements and amorphous/crystalline polymer. At phase boundaries, the light can be reflected or refracted. This causes a portion of incident light to be deflected from its initial path. This is referred to as scattering. Scattering creates a longer laser path length, and thus leads to increased absorption. It can also allow light to be reflected from the part due to so-called back scattering. In addition to energy losses due to absorption and reflection, scattering widens the beam cross-section causing an even lower power flux at the weld interface.

Laser light transmitted through the transparent part enters the absorbent part, where the light is absorbed at a much higher rate by laser-absorbing pigments (typically carbon black (CB)). The heat generated by absorption is then partially conducted to the transparent part, which leads to melting of the interface and ultimately diffusion of the molecular chains. A bond is formed between the two components upon cooling.

A number of techniques are used to deliver laser energy to the assembly [2–6]. These include irradiating the entire weld seam simultaneously (simultaneous welding), irradiating the seam multiple times at high speed (quasi-simultaneous welding), or irradiating the seam once at a relatively low speed (contour welding).

Regardless of the process, successful LTW requires a range of power fluxes to reach the interface to allow welding to occur. Too low a flux will not heat the polymer to a sufficiently high temperature to allow melting and diffusion. Too high a flux may lead to excessive temperatures and cause polymer degradation. Therefore, it is crucial to understand the transmission characteristics of the transparent part (such as transmission and reflection) in order to be able to predict and optimize LTW welding process conditions.

There are several methods to assess the transmission and reflection characteristics of polymers. Table 1 summarizes the related research using methods including spectroscopy [7–12], power meters [12–16] and infrared thermal imaging [17]. Spectroscopic methods use a spectrophotometer with one or more integrating spheres and allow transmission and reflection data to be obtained over a wide range of light wavelengths. Power meters combined with a laser source can be used to measure total transmission. Kagan [12] found that power meter methods provide higher fractional transmission data than spectroscopic methods. This is attributed to experimental energy losses in spectroscopic systems. Similar work by Azhikannickal [16] found that the specimen must be placed within 2 mm of the sensor surface in order to capture all transmitted

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Table 1
Literature survey of methods to characterize the optical properties of thermoplastics.

Authors	Methods	Polymers	Measured parameters	Results
Wang et al. [7,8]	Spectroscopy	Polypropylene (PP), polycarbonate (PC), polyamide 6 (PA) and glass fiber reinforced Polyamide 6.	Transmission	Specimen thickness exhibited strong effect on scattering and absorbance. Scattering was also observed to increase with increasing glass fiber content in PA6.
Aden et al. [9]	Spectroscopy	Polycarbonate (PC) with different additives	Transmission reflection	A four-flux model of radiation transport in the diffusive approximation was applied to obtain scattering and absorption coefficient. The additives had a significant influence on the scattering coefficient.
Geiger et al. [10]	Spectroscopy	Polypropylene (PP), polyamide (PA6) and polyoxymethylene (POM)	Transmission reflection	Absorption coefficient dependent on the material temperature was calculated by the Bouguer–Lambert Law. Compared with amorphous thermoplastics, in which no significant change of absorption coefficient with temperature was observed, semi-crystalline thermoplastics showed a distinct decrease of absorption coefficient in the melting range due to the semi-crystalline structure.
Coelho et al. [11]	Power meter and Spectroscopy	Polyethylene (PE) and polypropylene (PP) films (between 10 and 800 μm)	Transmission reflection	A linear relation between natural log of transmission and specimen thickness was observed. The slope of this curve is the attenuation coefficient. The reflectance was approximately constant for the thickness between 10 and 800 μm.
Kagan et al. [12]	Spectroscopy and power meter	Nylon 6 materials with short glass fiber or other fillers	Transmission	For nylon 6 plastics the laser energy transmission decreased monotonically with increasing fiber-glass content. Compared with power detector based method, the method of spectroscopy provided a lower transmittance since a large fraction of the transmitted light did not reach the detector.
Rhew et al. [13]	Power meter	Polycarbonate (PC) and High density polyethylene (HDPE)	Transmission reflection	For both materials, reflectance did not depend on thickness, but increased with increasing laser incidence angle.
Dosser et al. [14]	Power meter	Polyetheretherketone (PEEK) and polycarbonate (PC)	Transmission	Attenuation coefficient was calculated by Bouguer–Lambert Law. There existed a linear relation between natural log transmission and specimen thickness, and the slope was attenuation coefficient. PEEK has a much higher attenuation coefficient due to the semi-crystalline structure than amorphous PC.
Chen et al. [15]	Power meter	Polyamide 6 (PA6), glass fiber reinforced polyamide 6 (PA6GF) and polycarbonate (PC)	Transmission	A linear relationship between the measured natural log of the polymer transmittance and the part thickness for the light-scattering and non-scattering polymers PA6, PA6GF and PC was observed.
Azhikannickal et al. [16]	Power meter	Polyamide 6 (PA6) and polycarbonate (PC) reinforced with 10% glass fiber	Transmission	For a given thickness, the transmission decreases as the laser angle of incidence increases. At any given laser incidence angle, the transmission decreases as the thickness increases.
Azhikannickal et al. [17]	Thermal imaging technique	Polyamide 6 (PA6)	Reflection distribution of reflected laser light	Thermal imaging technique showed agreements between the estimated total power and the actual laser input power, and between the estimated power distribution and that determined experimentally via a knife edge based beam profiling technique.

light. Infrared (IR) thermal imaging measures the temperature at the laser entrance and exit surfaces of the laser-transparent part. The temperature data can be used to calculate the power flux. In addition to transmission, IR techniques can be used to examine the distribution of reflected light [17].

The influence of specimen thickness and glass fiber content on transmission and reflection has been investigated using these three experimental techniques [10,11,14,15]. It was found that the laser energy transmission decreased monotonically with increasing glass fiber content in polymers. There existed a linear relation between the natural log of transmission and specimen thickness. The Bouguer–Lambert Law has been used by several authors [9–11,14] to calculate optical properties such as absorption or attenuation coefficients. Due to the relatively low laser intensities, nonlinear optical phenomena can be neglected.

In general, the Bouguer–Lambert law is used to describe the laser power intensity in non-scattering or single-scattering polymers. Chen et al. [15] were able to model thickness-independent and thickness-dependent transmission losses in non-scattering, single-scattering or even multi-scattering materials by using the following equation which has a form similar to that of the Bouguer–Lambert law (Fig. 1):

$$T = \frac{P_{out}}{P_L} = (1 - R_1)e^{-A_1 D} \tag{1}$$

where T is the fractional transmission, P_{out} is the total laser power output after passing through the polymer specimen of thickness D; P_L is the incident laser power; R_1 is a parameter that accounts for *thickness-independent losses* due to reflection from the upper and lower surfaces as well as back scattering from bulk material underneath the incident surface. For cases where there is negligible bulk reflection such as in amorphous polymers, R_1 can be estimated using the Fresnel equation [19] for specular reflection from the top and bottom surfaces:

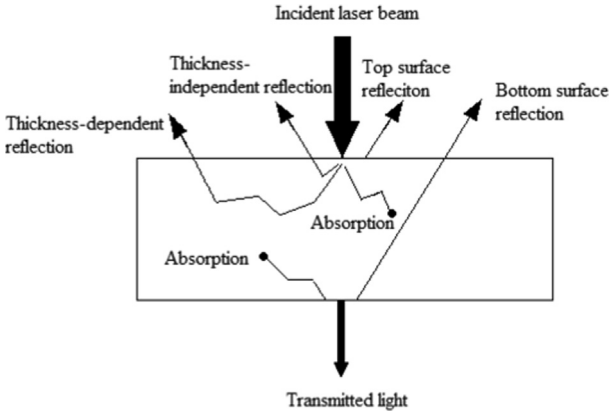

Fig. 1. Reflection, absorption and transmission of light through a laser-transparent thermoplastic.

$$R_1 \cong 2\left(\frac{n_1 - n_0}{n_1 + n_0}\right)^2 \tag{2}$$

where n_1 and n_0 are the indices of refraction of polymer and air. The coefficient 2 in the above equation is an approximation that accounts