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Effect of part thickness, glass fiber and crystallinity on light scattering during laser transmission welding of thermoplastics

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ABSTRACT

It is important to understand how laser energy scatters within the transparent component in order to predict and optimize the laser transmission welding process. This paper examines the influence of part thickness, glass fiber and crystallinity levels on the distribution of laser light after transmission through amorphous polycarbonate (PC) and semi-crystalline polymers such as polyamide 6 (PA6), polypropylene (PP), and polyethylene (PE). An experimental technique based on laser-scanned lines of progressively increasing power was used to assess the transmitted energy distribution. This distribution was characterized using a two-parameter model that captures scattered and un-scattered components of the laser beam. The results clearly show how the scattering is increased by increasing the numbers of interactions between laser light and phase boundaries either by increasing the particle concentration (i.e., glass fiber level and crystallinity) or increasing part thickness.

1. Introduction

Laser transmission welding (LTW) is a technique used to join laser-transparent and laser-absorbent thermoplastic components. In this process, the laser passes through a so-called transparent part in which some light is scattered and absorbed by amorphous and crystalline phases as well as pigments, reinforcements and fillers present in the material. The transmitted energy enters the laser-absorbent part where it is converted into heat by laser-absorbing materials (typically carbon black). This causes the polymer near the interface to melt and transfer some of the absorbed energy to the transparent part by thermal conduction. At the molten interface, molecular diffusion occurs and a weld forms upon cooling. Since the joining takes place at the interface between the two parts, it is important to know the total power transmitted through the transparent part and its distribution. Mathematically, the energy density distribution at position y along the weld interface ($\xi^*(y)$) can be described by:

$$\xi^*(y) = \frac{T\, P_L\, \Psi^*(y)}{V} \tag{1}$$

Referring to Fig. 1, P_L is the power from the laser and T is the fractional transmission of the laser light through the transparent part. V is the laser scan velocity in the x direction. $\Psi^*(y)$ is the transverse normalized power flux distribution (T-NPFD) of the transmitted beam introduced by Zak [1]. It accounts for the distribution of light in the original laser beam as well as any scattering that occurred during transmission. Knowing T and $\Psi^*(y)$ would allow those modeling the laser transmission welding process to calculate the energy flux at the weld interface in order to estimate temperature during this welding process. Too low a temperature will not cause the thermoplastic to melt and an excessively high temperature may result in material degradation.

Many laser welding studies have estimated T using spectrophotometers [2–6], power meters [5–10] and infrared thermal imaging [11]. The characterization of light scattering in the laser-transparent part to estimate the T-NPFD has received less attention. There are several methods to determine the distribution of transmitted energy. Becker and Potente [12] used a 1 mm diameter pinhole and a power meter to assess scattering in polypropylene. Haberstroh [13] and Haferkamp [14] used infrared and visible-light cameras to measure the transmitted beam dimensions. Although the camera-based technique provides fast results, no power flux distribution is obtained by using this method. Furthermore, no rational means of describing the transmitted power distribution as a function of the input laser beam has been proposed.

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2. Model development

A novel experimental technique to estimate the T-NPFD was proposed by Zak [1]. This laser-line scan (LLS) technique is shown schematically in Fig. 2. The laser-transparent and laser-absorbent (latter is referred to as the sensor polymer) parts are separated by thin shims (0.3 mm). A series of parallel high speed laser scans are made over the surface of the laser-transparent part. Each scan has a progressively higher power. At low powers, no mark is left on the sensor polymer surface; at a threshold power value of P_0, the sensor polymer will just start to melt and a very thin line is obtained on the sensor polymer surface. As the power is raised further, the width of lines on the surface of the sensor polymer increases as a greater fraction of the transmitted light beam has sufficient power flux to cause the sensor polymer surface to melt. The widths of the lines (w_k) are measured for each power setting P_k.

For a laser beam that is symmetric about $y=0$, the authors equate the energy density at P_0 when the sensor polymer just starts to melt (at a position approximated by $y=0$) with that at the edge of the molten polymer width ($y = w_k/2$) at power P_k to obtain:

$$\Psi^*(w_k/2) = P_0\Psi^*(0)/P_k \tag{2}$$

where $\Psi^*(w_k/2)$ is the T-NPFD of the transmitted laser beam at different values of y (corresponding to experimental values of $w_k/2$), and $\Psi^*(0)$ is a scaling factor determined by the requirement that the area under the $\Psi^*(y)$ versus y plot be equal to 1. The plot will normally have a peak with tails, similar to a Gaussian distribution.

Obtaining values of $\Psi^*(y)$ at high and low values of y is experimentally challenging using the LLS technique. Here, the ratio of P_0/P_k must approach zero. However, the maximum value of P_k is

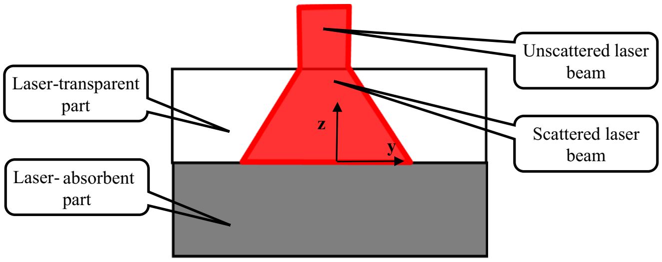

Fig. 1. Schematic cross-section of a laser beam traveling along the x-axis.

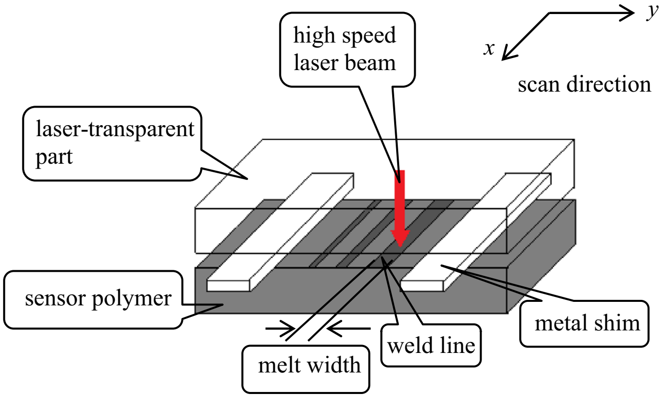

Fig. 2. Laser scanning on the laser absorbent specimen surface [1,15].

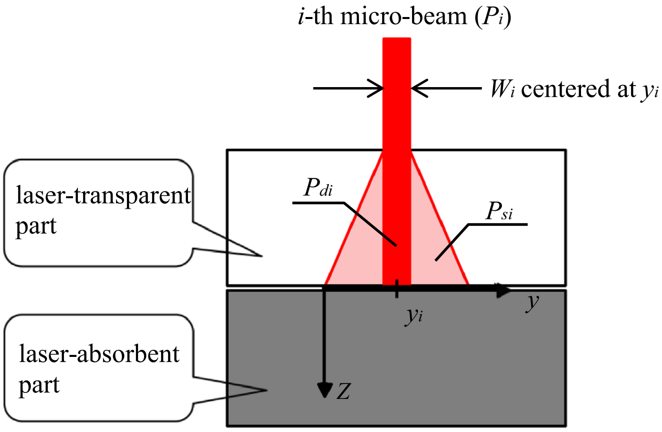

Fig. 3. Direct-scattered model of the ith laser micro-beam [15].