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Thermal imaging technique to characterize laser light reflection from thermoplastics

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ABSTRACT

Characterization of laser light reflection during the laser transmission welding (LTW)[3] of thermoplastics is especially important for applications in which non-zero laser incidence angles are used. At higher laser incidence angles, reflection increases and has the potential to burn surrounding features of the part to be welded. This study presents and validates a technique for laser reflection measurement. Reflected energy is absorbed by a black plastic plate (containing carbon black, which is the absorber of the reflected energy). The surface temperature of the plate is measured by an infrared (IR) camera. The distribution of reflected power required to generate this temperature profile is estimated using a simple heat transfer model. The technique was validated by irradiating the black plate by the laser directly, while observing the time-varying temperature distribution of the plate by the IR camera. In this case, good agreement was observed between the estimated total power and the actual laser input power. Good agreement also existed between the estimated power distribution and that determined experimentally via a knife edge based beam profiling technique. The thermal imaging technique was subsequently used to measure the magnitude and distribution of laser light reflection from unreinforced nylon 6.

1. Introduction

Laser transmission welding (LTW) is increasingly becoming an attractive process for joining thermoplastic parts. LTW involves joining a laser-transparent and a laser-absorbent part together. A laser beam passes through the laser-transparent part and is absorbed by the laser-absorbent part near the interface between the two parts. The laser energy absorbed by the laser-absorbent part is transferred back to the laser-transparent part by heat conduction. Both parts become molten and a solid joint is formed by diffusion of the polymer molecules. The primary advantage of LTW compared to other welding processes is the precise and controllable energy deposition resulting in localized melting over a small region within the contact zone of the two parts. The process produces a weld seam of high optical quality. It also provides flexibility for a high degree of automation due to the various beam delivery options available. Laser transmission welding is being used for the joining of plastic housings and containers [1–3]. It is also being examined for its use in the medical device industry [4].

When laser light strikes the transparent part, all of this light is not transmitted to the laser- absorbent part. Reflection at the surface of the transparent part and back reflection due to scattering of the light through the bulk (of the transparent part) attenuate the light reaching the interface between the two parts. In addition, absorption of some of the light as it travels through the transparent part also decreases the amount of energy available for creating a weld at the interface. Semi-crystalline polymers tend to scatter light to a larger extent than amorphous polymers due to the co-existence of the amorphous and crystalline phases. Furthermore, if reinforcing agents such as glass fibers are incorporated into the transparent material, significantly more scattering takes place as observed by Kagan et al. [5]. This increased scattering may also result in greater back reflection.

The law of reflection neglects any surface roughness associated with the incident surface. The Fresnel relation can be used to determine the magnitude of this specular reflected light. For rough surfaces, the reflected light from the surface will be diffuse in nature and may emerge from the transparent part along various directions. For the specific case of laser welding, laser light may also be back-reflected from the bulk transparent

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[3] Abbreviations: LTW—laser transmission welding, CB—carbon black, IR—infrared, NPFD—normalized power flux distribution

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material. The magnitude and distribution of reflected light will depend on the laser angle of incidence, the optical properties and thickness of the transparent part, its surface quality as well as the magnitude of the incident laser power [6,7].

A variety of industrial applications may involve the laser striking the transparent part at a non-zero angle of incidence due to the geometry of the part. The joining of tubes to plates in the manufacture of plastic heat exchangers is one example. Welding space restrictions may be another reason for use of a non-zero laser incidence angle. The Fresnel equation can be used to predict the specular surface reflection as a function of angle of incidence and shows that it increases with angle. This indicates that reflection characterization, both magnitude and distribution becomes more important at non-zero laser incidence angles where reflected energy has the potential to unnecessarily heat and/or damage features of a part in the vicinity of the area to be welded.

Rhew et. al [8] used a power meter attached to a circular rotating rail to measure the transmission and reflection of laser light striking polycarbonate and high density polyethylene as a function of incidence angle and material thickness. The position of the power meter was changed with rotation of the optical rail to measure the transmittance and specular reflectance at various incident angles. It was found that for both materials, reflectance did not depend on thickness, but did increase with increasing laser incidence angle. The effect of laser incidence angle on the power distribution of the reflected light was not reported.

A few studies have focussed on the characterization of the magnitude and distribution of reflected power. A device designed to integrate the total light reflection from a surface was reported by Mehmetli et al. [9]. The device was used to measure the reflection from a CO_2 laser beam striking an aluminum alloy. The system consisted of a semicircular arc, pivoted at its ends, allowing it to sweep through the surface of a hemisphere. An infrared detector, which could be positioned at incremental locations along the arc, allowed the detector to reach any position on the surface of the hemisphere for subsequent reflection measurements. Van de Ven and Erdman [7] used a similar technique to simultaneously measure the light transmission and reflection from polyvinyl chloride having various surface finishes using a diode laser source. In this case, reflection measurements were taken at specified spatial increments by a photodiode that rotated around the sample along a semi-circle. The main drawback to this set of techniques is that they can involve somewhat more complicated set-ups.

Use of infrared (IR) thermography appears to be another potential option for characterizing reflected light. Haberstroh et al. [10] used an IR camera to examine the laser entrance and exit surfaces of various polyamide plate specimens exposed to a short laser pulse. The authors examined the temperature distribution of the areas heated by the laser as well as the dimensions of these areas. They used this data as a measure of the laser light scattering behavior of the polyamide material. Determination of the magnitude and/or distribution of laser power incident on the top surface or transmitted at the exit surface from the thermal images were not considered. Haferkamp et al. [11] utilized IR and visible light cameras to characterize various polymers suitable for use in the LTW process. A CCD camera was used to observe the exit surface of laser-transparent plates made from PBT and corresponding to thicknesses ranging from 0.5 to 2.0 mm. Using a 2 mm incoming beam spot size, a linear relationship was observed between the exiting beam radius and the material thickness.

Mayboudi [12] used thermal imaging observations during the welding of a transparent and absorbent part using a stationary laser beam. A laser power of 1 W was applied for 10 seconds at a distance of 3 mm from the front surface of the sample. The front surface, being viewed by the camera, was also coated with soot particles allowing energy from the stationary laser beam to be absorbed at this surface. The resulting temperature rise was captured by the infrared camera. The power flux at this surface was extracted from the temperature distribution (assuming the body to be a semi-infinite solid) and used as an indication of how the laser beam was scattered over this surface.

Currently, there are no studies using infrared thermal imaging for characterizing the magnitude and distribution of reflected light. The present study extends the work of Mayboudi. Carbon black filled thermoplastic plates (in this case nylon 6) were used as “absorbers” of reflected laser energy. Due to the high carbon black content of the plates, the reflected energy was assumed to be absorbed very close to the surface after which it would be conducted through the thickness. Based on these heat transfer characteristics, the plate was modeled as a semi-infinite solid. The temperature rise on the surface of the plate due to the reflected energy was be captured by an infrared camera. The thermal imaging data combined with the semi-infinite solid model was used to calculate the magnitude and distribution of reflected power. In order to validate this technique, a series of experiments in which a carbon black plate was exposed to a direct laser beam were conducted. The thermal imaging data from these tests along with the semi-infinite solid model were used to estimate the magnitude and distribution of the input laser beam power. This data was then compared to the input laser power and the experimentally determined power distribution of the beam. The validated technique enabled its use in reflection characterization of unreinforced nylon 6.

2. Technique validation

2.1. Experimental set-up, materials and equipment

A nylon 6 plate containing carbon black (further referred to as the CB plate) was exposed to a stationary laser beam with the laser incidence angle being 50°. A non-zero laser incidence angle was required to view the area of the CB plate exposed to the laser beam with the IR camera, while maintaining the camera perpendicular to the viewing area. Due to the relatively high CB level, it was assumed that the laser power reaching the surface of the CB plate would be absorbed very close to its surface and result in a temperature rise over the exposed area [13]. The temperature distribution was measured via an IR camera positioned normal to the CB plate at a distance of approximately 6.6 cm (Fig. 1). This distance resulted in optimal focus of the viewing area.

The CB plates used were made from unreinforced nylon 6 (provided by DSM) with 0.2% and 0.05% by mass carbon black, which acted as the laser-absorbent. The materials were injection molded on a 55-ton Engel injection molder into square plaques with dimensions $100\,mm \times 100\,mm$ and with a thickness of 3.2 mm. The same sized plates were also molded from unreinforced nylon 6 (provided by DSM) for the reflection experiments outlined in Section 3.0. The laser used in this study was a Rofin Sinar 160 W continuous-wave diode laser having a nominal focal spot size of $1.4 \times 0.7\,mm$ and a wavelength of 940 nm [14]. Powers were varied from 1.3 to 2.9 W and the working distances were varied from 82.5 mm to 98.5 mm. The working distance is defined as the distance between the CB plate and the laser lens (Fig. 1).

A Thermovision A40 IR camera from FLIR SYSTEMS was used to obtain the temperature distribution across the surface of the CB plate as it was heated by the laser beam. The camera had a spectral range of 7.5 μm to 13 μm and images were captured at a