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Laser beam scattering effects in non-absorbent inhomogenous polymers

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Abstract

In this paper a numerical model for laser beam scattering in the semi-transparent polymers is presented, using a Monte Carlo algorithm and the Mie theory. The algorithm correctly accounts for the independent multiply-scattered light. We describe the algorithm, present a number of important parameters that account in the welding process, and explicitly show how the algorithm can be used to estimate the laser beam intensity both inside the semi-transparent component and at the welding interface and the beam widening. For the model validation an experimental bench test has been realized and some results from two test cases are presented.

Keywords: Laser welding; Light scattering; Polymer; Mie theory; Monte Carlo

1. Introduction

As known, the thermoplastics laser welding is a modern and innovative technology with well-known general advantages of laser materials processing, as a non-contact, non-contaminant process, flexible, easy to control and automate. A better knowledge of the scattering phenomena and their importance in the polymers welding process are imperatively required due to the fast and continuous development in this area and to the large variety of thermoplastics family.

During the last decade, the research on this subject has recorded a great development, regarding new laser sources, new absorbers, increasing speed, mathematical modeling and industrial applications. Still the current level of laser welding technology is far from maturity and researchers and manufacturers alike are actively seeking new methods of understanding and optimizing the process.

In essence, through-transmission laser welding requires an optically transparent part and an absorbing one and a preferential deposition of energy in order to melt the material in the interfacial zone. The process efficiency is strongly dependent on the optical properties of the two parts to be welded (reflectance, transmittance and absorbance) so it is very important to quantify the influence of each of these on the beam attenuation.

Since the real polymeric materials contain a large variety of heterogeneities (mineral filler, additives, pigments…), the energy deposition at the welding interface may be dramatically reduced and subsequently affect the welding potential.

Generally, an electromagnetic wave traveling through a medium is attenuated by an extinction phenomenon, in which absorption and scattering effects can equally coexist or prevail to each other. In the present study, we will consider only non-absorbent inhomogeneous mediums in order to quantify the scattering effects.

The final goal in our study is to predict the thermoplastics weldability by determining the thermal field developed inside the components to be joined and the structure behavior under laser irradiation. The first task in pursuit of this goal is to quantify the beam attenuation in the semi-transparent polymers by making connection between the optical properties of the bulk materials of which the heterogeneities and the medium are made and

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the laser intensity spatial distribution into the medium. The second is to utilize these results for further numerical simulation of the welding process with a FEM-based code.

In order to accomplish the first task we used a hybrid code developed by the CORIA laboratory and slightly modified to fit in with the exact experimental conditions. The code combines the accuracy advantages of Mie theory and Monte Carlo simulation in a hypothesis of an incoherent scattering.

2. Theoretical consideration

2.1. Scattering theory

The exact analytical solution of Maxwell's equations for the scattering of an electromagnetic plane wave from a spherical, homogenous particle is given by Mie theory since 1908 [1]. During the last years, intensive efforts have been devoted to overcome the limitations of this theory and generalize it to different laser beams profiles and asymmetric shapes of scatters [2–4].

Considering the case of a single particle, the Mie theory provides the scattering parameters which offer us the first information on how efficient the particle will scatter the radiation, that is: scattering cross-section C_{sca}, absorption cross-section C_{abs} and phase function $p(\theta)$. Anisotropy factor g may then be deduced. We will briefly explain each of them, more detailed information can be found in [5,6].

The scattering cross-section gives the probability of photon scattering per unit path-length and multiplied by the particles concentration n is the reciprocal to the mean free path $l_{sca} = 1/n \cdot C_{sca}$ (the average distance traveled by the photon between two successive scattering events).

This parameter is a very important one in establishing if there is a simple or a multiple scattering regime. For a medium with a thickness $L \approx l_{sca}$ the photons will be scattered once, which simplifies the issue because there is a proportionality relationship between the scattered intensities (the scattered intensity by the medium is N times that scattered by a single particle).

For higher volume fractions, where $l_{sca} \ll L$, the scattering regime is a multiple one, and it is a more complex case especially when we deal with the dependent scattering regime. Dependent scattering denotes scattering process where the mechanism of particle–wave interaction itself is modified by the presence of neighboring particles [7]. Generally, assuming a random distribution of scatters can make considerable simplifications. This brings us to the incoherent scattering case but it is difficult to state precise general conditions under which this scattering criterion is satisfied.

In addition to these angle-independent quantities, Mie theory allows us to calculate the angular distribution of the scattered radiation in the far-field of the particle. The amount of the scattered radiation into a solid angle about a given direction is the differential cross-section $\mathrm{d}C_{sca}/\mathrm{d}\Omega$ and the angular distribution is usually expressed in terms of the angular distribution function $p(\cos\theta)$ known as the phase function in the light scattering literature:

$$p(\cos\theta) = \frac{1}{k^2 C_{sca}} \frac{\mathrm{d}C_{sca}}{\mathrm{d}\Omega}, \quad (1)$$

where $k = 2\pi/\lambda$ is the wave number, with λ the wavelength of light in the medium.

The anisotropy factor is an averaged cosine of the scattered angle and it can take values close to -1 for a backscattering, 1 for a forward scattering and 0 for an isotropic scattering (Fig. 1).

2.2. Monte Carlo algorithm

After obtaining the scattering parameters mentioned above from Mie theory, we apply the Monte Carlo method widely used in multiple scattering topic [8,9], in which the trajectories of light rays (commonly called "photons") are simulated probabilistically through the considered medium until they hit a predefined detecting area. We present a flowchart in Fig. 2 that illustrates the main steps in Monte Carlo technique.

2.2.1. Photon initialization

In this study, a plane–parallel medium, infinite in the x and y-directions, with a thickness L in the z-direction, containing random distributed, identically sized, non-absorbing spheres and illuminated by a Gaussian collimated beam in normal incidence is considered. Radius of the beam is assumed to be larger that the diameter of the particles.

When the photons are launched, their initial position (defined by radius r and angle ϕ) inside the beam section is chosen. Angle ϕ is equidistributed inside $[0, 2\pi]$ and radius

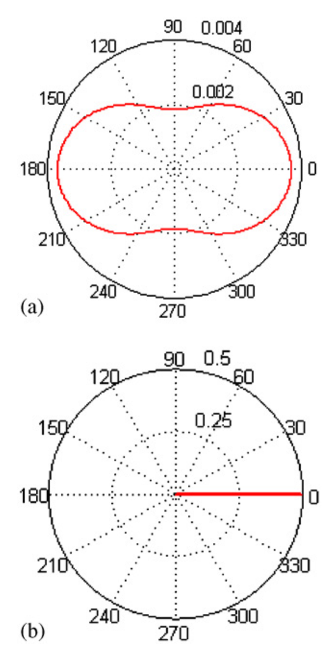

Fig. 1. Phase function for $g = 0.06$ (a), $g = 0.96$ (b).