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Through-transmission laser welding of polymers – temperature field modeling and infrared investigation

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Abstract

The purpose of the present study is to estimate the weldability of a polymeric material couple according to their thermal and optical properties. A first model based on Mie theory and Monte Carlo method describes the laser beam behavior in semi-transparent media and makes it possible to approximate the laser power distribution at the interface of the two materials. A second model based on finite element method permits the temperature field estimation into both parts to be welded. The results are validated by infrared thermography.

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Keywords: Laser welding; Light scattering; Polymer; Finite element; Heat transfer

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1. Introduction

Through-transmission laser welding of polymers requires an optically transparent part at the laser wavelength and an absorbing one and a preferential deposition of energy in the interfacial zone. The bonding between the two components occurs by the interpenetration of the molecular chains in this area. Since this phenomenon is very active in a "fluid" state of matter, the temperature at interface has to be between the temperature of solid–liquid transition and the initial temperature of degradation of the thermoplastic materials [1].

Compared to the conventional welding techniques, the efficiency of laser welding is strongly dependent on the optical properties of the two materials to be welded (reflectance, transmittance and absorbance). In the near IR spectrum, most of the thermoplastics polymers have low reflectivity (about 4%) and they are quite transparent. Their transparency plays a decisive role. For the first component it conditions the energy that arrives at the interface. In the most cases, from economical, technological or esthetical reasons, in their matrix additives are introduced which can strongly influence laser propagation. It is thus very important to quantify the influence of these heterogeneities on beam attenuation. For the second component this transparency has to be drastically reduced by adding absorbers in their matrix.

The goal in our study is to asses 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

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properties of the bulk materials of which the heterogeneities and the medium are made and 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 a hybrid code, developed by the CORIA laboratory and slightly modified to fit in with the exact experimental conditions, was used. The code combines the accuracy advantages of Mie theory and Monte Carlo simulation in a hypothesis of an incoherent scattering and permits to quantify the beam attenuation through the semi-transparent component.

The principle and the main steps of this model are presented in detail in a previous work [2] together with its experimental validation. However, for having a general idea we point out in the numerical modeling section, some aspects of the algorithm.

2. Laser-semi-transparent polymer interaction

2.1. Experimental study

Ones of the most important features in through-transmission laser welding are the amount of the transmitted energy through the semi-transparent component and the laser beam profile at the interface. In order to determine them, an experimental bench was conceived (Fig. 1). The laser source is a diode laser with 808 nm wavelength and a maximum delivered power of 15 W. The optical components are used to obtain a circular collimated beam with a trapeze shaped intensity profile. The semi-transparent sample is fixed into laser beam path and the transmitted beam profile is obtained by means of a linear light intensity to voltage converter with an active area of 0.26 mm^2 connected to a data acquisition system. For a complete characterization of the beam, two micrometric tables (Tables X and Y) are used to allow the sensor motion on two orthogonal directions.

The samples used for investigations were prepared by charging an amorphous matrix of PMMA with 5.5 μm diameter silica particles provided by DEGUSSA, at a 2.38% concentration. The PMMA slab thickness is 3 mm.

To quantify the attenuation and the dispersion of the beam obtained at the exit of the scattering medium a trapeze shaped profile was used to fit the experimental ones. As criterion for comparison between the incident and the transmitted beam, one considers the on axis intensities and the two characteristic radii (r_1, r_2 with r'_1, r'_2, Fig. 2).

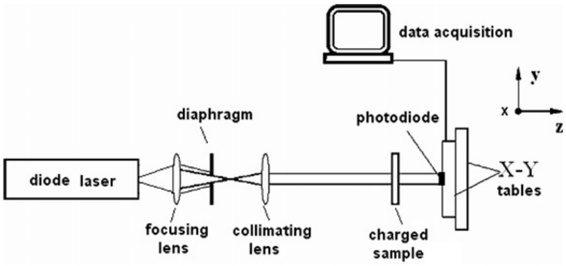

Fig. 1. Experimental set-up for measuring the transmitted beam through the scattering medium.

Since the complex refractive index of the fused silica at 800 nm is $n = 1.432\text{–}3 \times 10^{-5}i$ and the refractive index of PMMA is 1.49, the medium can be considered as a weak scattering one. The transmitted beam keeps the same trapeze shaped profile (Fig. 2) with a decrease of the on axis intensity with 17.6% from the incident one. The beam “broadening” is not very accentuated; the ratios between the characteristic radii (transmitted/incident) have values around 1 ($r'_1/r_1 = 1.05$ and $r'_2/r_2 = 0.9$).

2.2. Numerical model

From the theoretical point of view, the propagation of a radiation in a scattering medium can be described, in general, by the Mie theory [3,4] which provides the scattering parameters for one spherical particle. Among the most important are the scattering cross-section C_{sca} and the phase function $p(\theta)$. From the normalized phase function, which describes the probability density function for the azimuthal and longitudinal angles, is obtained the scattering direction for the traveling photons. The scattering cross-section gives the probability of photon scattering per unit path-length. If it is multiplied by the particles concentration n, we obtain the scattering coefficient $k_{\text{sca}} = n \cdot C_{\text{sca}}$, the mean free path $l_{\text{sca}} = \frac{1}{n \cdot C_{\text{sca}}}$ (the average distance traveled by the photon between two successive scattering events) and the optical depth of the medium $\tau = n \cdot C_{\text{sca}} \cdot L$ (where L is the geometrical thickness of the medium).

Thus, knowing these parameters, it can be established the scattering characteristics for a particular medium, with a known geometry and particles concentration.

After obtaining the scattering parameters mentioned above from Mie theory, we apply the Monte Carlo method widely used in multiple scattering topic, in which the trajectories of numerous light rays (commonly called “photons”) are simulated probabilistically through the considered medium until they hit a predefined detecting area.

In order to reproduce the experimental conditions, the considered medium for numerical simulations, is plane parallel, infinite in x- and y-directions, and 3 mm thickness in direction z, not absorbent, containing spherical particles randomly distributed, and illuminated by a trapeze shaped laser beam in normal incidence. The numerical calculations were made for an incident beam with the characteristics radii $r_1 = 3.11$ mm and $r_2 = 1.64$ mm (Fig. 3). Similar to the measurements, the same fitting was used for the laser profiles. Fig. 3 shows that the transmitted beam keeps the same trapeze shaped profile as the incident one with a decrease of the on axis intensity with 21.8% from the incident one and values for ratios between the transmitted and incident characteristic radii also around 1 ($r'_1/r_1 = 1.07$ and $r'_2/r_2 = 0.8$).

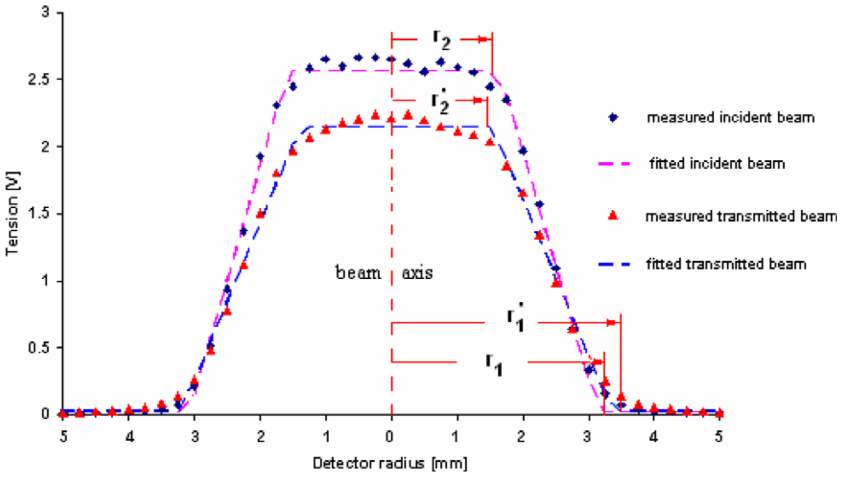

Fig. 2. The measurements for the incident and the transmitted laser beam profile through the slab and their approximations.

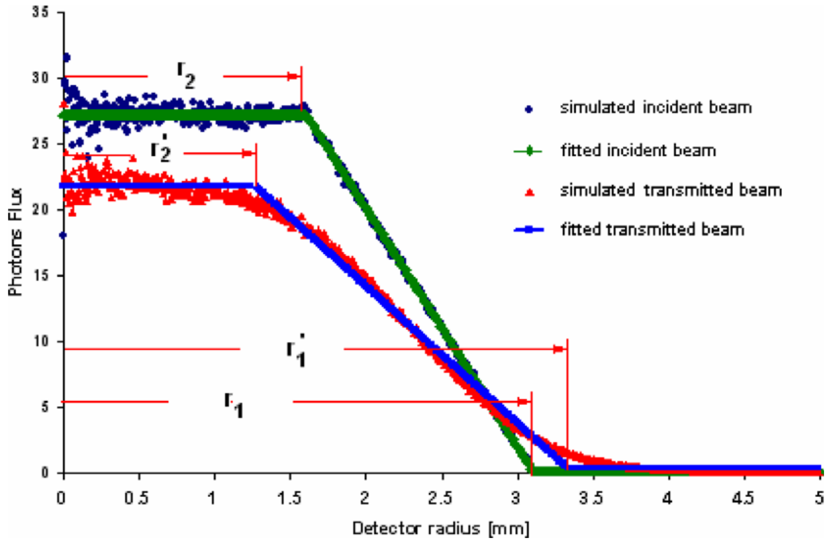

Fig. 3. The simulated profiles of light intensity distribution for the incident and the transmitted laser beam through the slab and their approximations.

3. Laser-absorbent polymer interaction

3.1. Numerical model

Since the first component do not absorbs the radiation, in order to obtain the necessary temperature at the interface and to assure an even distribution of the thermal field into the two parts to be welded, the second component must present a high absorption coefficient. For low absorption coefficients, the laser beam penetrates further into the absorbing part, which will lead to a temperature profile with a maximum into a layer much beneath the joining surface rather than near it.

Within the framework of the present study one considers a strong absorption in the second component and a heat transfer through conduction between the two parts.

In order to define the thermal source within the absorbent component, one starts from the incident trapeze shaped beam for which the power density can be written as:

$$p = \begin{cases} p_{\mathrm{i}} & r < r_1 \\ p_{\mathrm{i}} \cdot \left(1 - \frac{r - r_1}{r_2 - r_1}\right) & r_1 < r < r_2 \,, \\ 0 & r > r_2 \end{cases} \tag{1}$$

where p_{i} is the power density in the beam axis and r_1, r_2 are the incident beam characteristics radii.

The total power is given by:

$$P = \int_0^{r_1} 2 \cdot \pi \cdot r \cdot p_{\mathrm{i}} \cdot \mathrm{d}r + \int_{r_1}^{r_2} 2 \cdot \pi \cdot r \cdot p_{\mathrm{i}} \cdot \left(1 - \frac{r - r_1}{r_2 - r_1}\right) \cdot \mathrm{d}r. \tag{2}$$

The power density on the axis for the incident beam becomes:

$$p_{\mathrm{i}} = \frac{3 \cdot P}{\pi \cdot (r_1^2 + r_2^2 + r_1 \cdot r_2)}. \tag{3}$$

From the optical model of diffusion, one obtains an entering and an outgoing equivalent intensities (I_{i}, I_{o}), correlated with the number of “launched” and “received” photons and their declared energies. The power density at the exit of the scattering medium can be written as:

$$p_{\mathrm{o}} = p_{\mathrm{i}} \cdot \frac{I_{\mathrm{o}}}{I_{\mathrm{i}}}, \tag{4}$$

where p_{o} is the power density of the outgoing beam in the axis.

For a weak scattering medium, the transmitted laser beam has also a trapeze shaped profile so the same formula (1) can be used to describe its power density.

Considering the above formulas the power distribution at interface is

$$p_{01}(r) = \begin{cases} \frac{3 \cdot P}{\pi \cdot (r_1^2 + r_2^2 + r_1 \cdot r_2)} \cdot \frac{I_{\mathrm{o}}}{I_{\mathrm{i}}} & r < r'_1 \\ \frac{3 \cdot P}{\pi \cdot (r_1^2 + r_2^2 + r_1 \cdot r_2)} \cdot \frac{I_{\mathrm{o}}}{I_{\mathrm{i}}} \cdot \left(1 - \frac{r - r'_1}{r'_2 - r'_1}\right) & r'_1 < r < r'_2 \\ 0 & r > r'_2 \end{cases}, \tag{5}$$

where r'_1 and r'_2 are the characteristics radii of the outgoing beam.

The heat source becomes

$$q_v(r,z) = \begin{cases} 0 & z < d_1 \\ p_{01}(r) \cdot \alpha \cdot \mathrm{e}^{-\alpha \cdot (z - d_1)} & z > d_1 \end{cases}, \tag{6}$$

where d_1 is the thickness of the semi-transparent component.

It is considered that the laser beam is absorbed in a very thin layer, the beam ray remaining constant on this thickness and equal to the outgoing ray from the scattering medium and a linear behavior of the material so the Beer–Lambert law can describe the beam intensity reduction due to absorption.

The field of temperature in the two components to be assembled is determined by the resolution of the general heat conductivity equation:

$$\vec{\nabla}[\lambda(T)\vec{\nabla}T] + q_v = \rho \cdot c(T) \cdot \frac{\partial T}{\partial t}, \tag{7}$$

where $\lambda(T)$ is the thermal conductivity, ρ the density, and $c(T)$ the specific heat capacity.

The above model is employed in a finite element based code (COMSOL). For shortening the computing time, we consider a reduced 2D axial symmetric model. The network division was chosen at 0.2 mm on the axis of symmetry and the element grow rate at 1.1. The time stepping is 0.05 s and the total calculation time is set to be longer than the duration of the irradiation which allows us to compare the simulated and measured results during both phases: heating and cooling. For the heat transfer between the two elements and the surrounding medium one uses a global heat transfer coefficient, and the boundary condition can be written as:

$$-\lambda(T) \cdot \vec{\nabla}T \cdot \vec{n} = h_{\mathrm{global}} \cdot (T_\infty - T), \tag{8}$$

where $\vec{n}$ is the normal vector of the surface, h_{global}, global heat transfer coefficient (essentially on a convective form) and T_∞, surrounding medium temperature.

3.2. Thermography measurements

To validate the developed numerical model, one chooses as temperature measurement technique the infrared thermography. Being a contact-free measurement technique it is often used as a method to control the welding process [5,6]. The experimental device is based on the previous described bench and includes an IR camera (Fig. 4) placed successively in the positions (1) and (2) for the measurements of the thermal fields on the two sides of the polymer slab. The camera is a FLIR ThermaCam S60 with a detection wavelength between 7.5 and 13 μm, a resolution of 320 × 240 pixels and an acquisition frequency of 50 Hz. As absorbing component black carbon filled ABS-PC alloy sheets of 2 mm thickness was used. Its emissivity was determined by comparing the indication of the IR camera and the known temperature at which the plate was preheated. The found value was 0.98.

Due to the optical components used in the beam path, the maximum delivered power is 0.4 W so the measurements are made in the interval 0.2–0.4 W. The beam profile is described in the first part of this paper.

We present two examples of the experimental results (Fig. 5) together with the calculated ones for two different laser powers (0.27 and 0.39 W). Both simulated and measured temperature evolutions are presented for the center of the laser spot on the two sides of the polymer slab.

The accuracy of the numerical results depends on a good knowledge of the materials thermo-physical properties (reflectivity R, absorptivity α, density ρ, scattering coefficient k, thermal conductivity λ, specific heat capacity c, glass transition T_{g}) and their variation with temperatures. For the ABS-PC alloy, the specific heat capacity c was determined by differential scanning calorimetry using sapphire as standard material (Fig. 6) over a temperature range of 20–290 °C. Its evolution is approximated in the

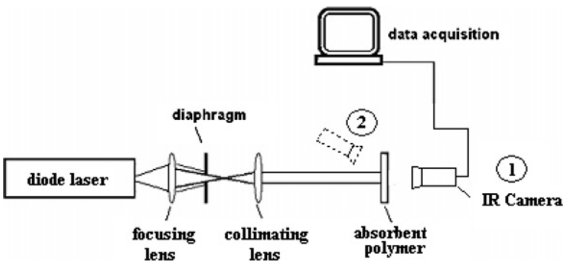

Fig. 4. experimental bench for IR measurements.

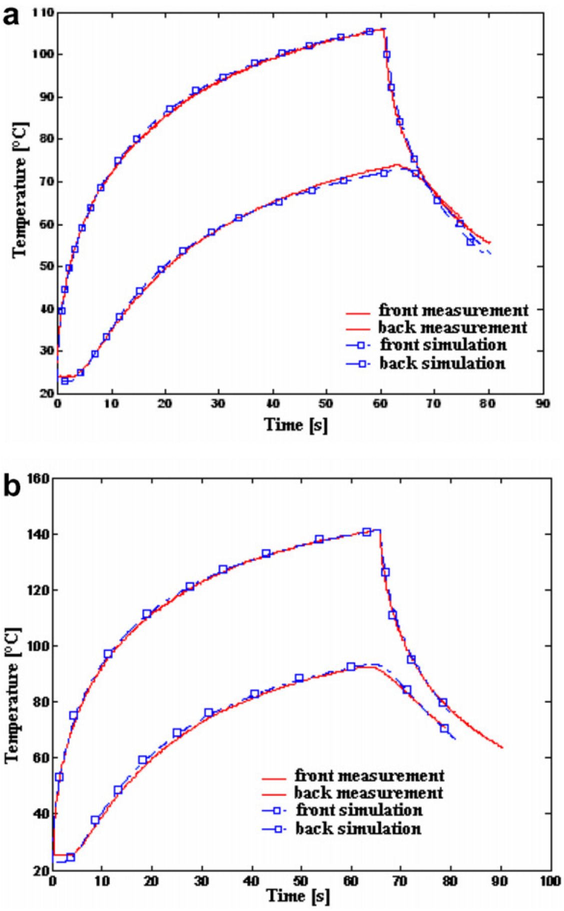

Fig. 5. Temperature–time evolution in the center of the laser spot for a laser power of 0.27 W (a) and 0.39 W (b).

finite element code with a linear form $c = 7.8027 \cdot T + 894.51$.

The thermal conductivity λ evolution with temperature is obtained from measurement made by National Physical Laboratory, UK [7] and extrapolated to 1 bar using the following exponential expression:

$$\lambda = 0.299 \cdot (\exp(1.67 \cdot 10^{-3} \cdot (T - 523.15))) \cdot (\exp(1.84 \cdot 10^{-6} \cdot T \cdot (0.1 - 80))), \qquad (9)$$

where T is the temperature (K).

The reflectivity was calculated considering the values of the refractive indexes of the polymer and air which gives a value of 4.

Due to the presence of the black carbon in the matrix of the polymer, the absorption coefficient α is rather difficult to determine, the polymer being completely opaque to laser radiation. The thermogravimetry analysis indicates 11% residues for ABS-PC alloy, so one assumes a high value for this characteristic. In order to achieve the desired level of agreement with the experimental results, the absorption coefficient is considered the only degree of freedom. A good adjustment of the experimental curves (Fig. 5) is obtained for a value of 19.5 mm^{-1}, which, according to the Beer–Lambert law, gives a total absorption of the laser radiation in 0.25 mm.

Using this value, the simulated temperature profile follows the experimental one for all the IR measurements at different laser powers.

4. Application to temperature field estimation for a couple of plates

Subsequent to this "calibration", experimental measurements were made on a typical setup for through-transmission laser welding of polymers using the silica charged PMMA sample as semi-transparent component and ABS-PC as the absorbing one.

The infrared images were recorded on the backside of the absorbing part (Fig. 7).

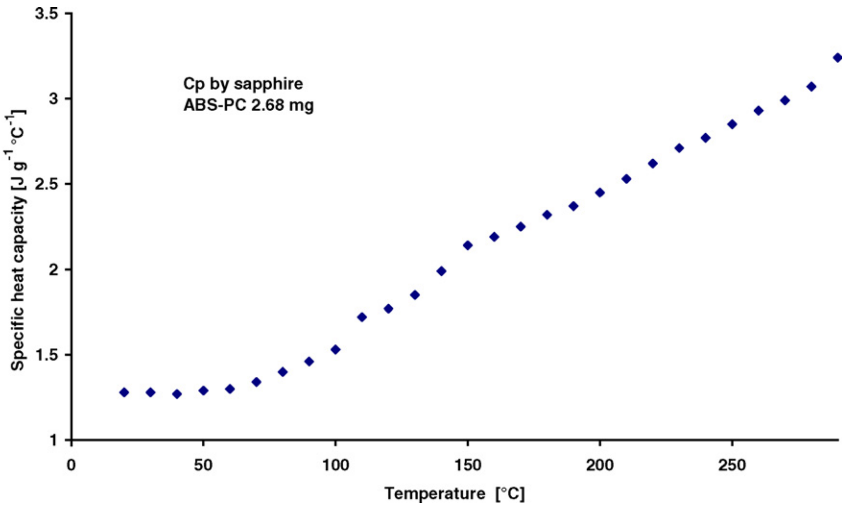

Fig. 6. Specific heat capacity evolution with temperature for ABS-PC alloy.

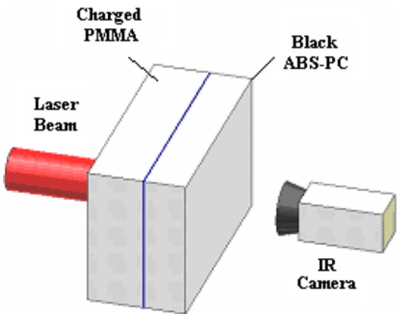

Fig. 7. Schematic set-up for through-transmission laser welding.

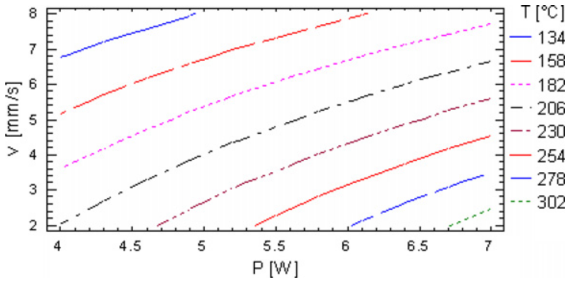

Fig. 9. Contours of estimated response surface for the temperature at the interface of the PMMA and ABS-PC couple.

The maximum temperature evolution is presented in Fig. 8 along with the calculated one, resulted from the combination of the two models presented above.

The calculated profile for the temperature evolution is influenced by the 5.5% error obtained from the optical model for the semi-transparent component so we record a small difference between the two profiles which it can be considered as negligibly.

Considering the fine agreement between the experimentally and calculated data we can state that the combination of the two presented models permit the determination of the thermal field in the whole volume of the two parts to be welded.

Exemplifying for the case presented above, by carrying out simulations for two values of the laser beam speed (2 and 8 mm s^{-1}) and two values of the laser power (4 and 7 W), the necessary linear energy can be estimated. Knowing that the PMMA has a glass transition temperature around 105 °C and the ABS-PC alloy has two glass transition temperatures: one at 105 °C and the other at 145 °C, one can choose a linear energy ($E_l = P/v$ [J m^{-1}]) that assures a temperature at interface greater than 145 °C and smaller than the degradation temperature of the polymers (Fig. 9).

The possibility of estimating the temperature distribution into the irradiated materials offers two considerable advantages: assessment of the laser parameters which can assure the appropriate temperature at the interface and the possibility to calculate the residual stresses and distortion resulting from the heat input during the welding.

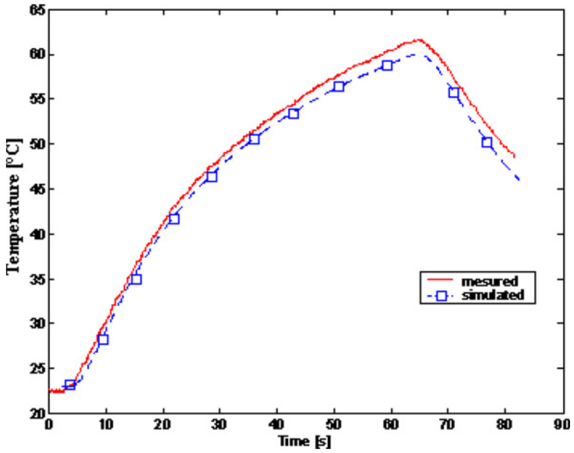

Fig. 8. Temperature–time evolution in the center of the laser spot for a PMMA-ABS/PC couple for a laser power of 0.39 W.

5. Conclusion

Using a hybrid code, which combines the Mie theory and the Monte Carlo method, we can quantify the scattering phenomena in semi-transparent polymers in absence of absorption. The numerical computations allow us to obtain the profile of the laser beam distribution both inside and at the exit of the slab. The result can be used to define the heat source profile and its magnitude at the interface, required for further numerical simulations of the welding process using finite element method, in order to predict materials weldability.

It will permit an efficient prediction of the weld quality for a range of laser speeds and powers on different plastics thus reducing the experimental time and concentrating the efforts in optimizing the process.

Experimentally measurements made on PMMA samples charged with silica particles, used as semi-transparent material, and ABS-PC alloy sheets used as absorbent part, confirmed our modeling results.

Further investigations of the laser beam behavior in polymers with an absorbing matrix or charged with absorbing particles are necessary in order to cover all types of thermoplastics materials used in through-transmission laser welding.

Acknowledgement

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