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Improvement of the spatial resolution of prototypes using infrared laser stereolithography on thermosensitive resins

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Abstract

In this paper, the use of infrared laser radiation to achieve localized curing in thermosensitive materials, is presented. In stereolithography, the objective is to cure a localized region in a material by precisely confining the laser energy to the area that is to be cured. In the experiment, a CO_2 laser beam at 10.6 μm (infrared radiation) was focused onto a sample with a composition of epoxy resin, diethylene triamine (curing agent) and silica powder (filler). Using a differential scanning calorimeter (DSC) we were able to determine reaction rates as a function of temperature as well as the enthalpy involved in the phase transition and activation energy of the curing process. This paper presents a numerical model for the two-dimensional curing problem with infrared radiation laser by using a Finite Element Technique in Ansys program. The solution of the heat equation simulating this process was in general agreement with our previous observations of the stereolithographic results. Results and discussion about prototypes of different geometries and sizes were performed and presented as well as discussion about width and depth of the layer cured in the prototype construction.

Keywords: Polymer; Stereolithography; Localized curing; Infrared radiation; CO_2 laser

1. Introduction

High power lasers have been used for material processing applications for a wide variety of materials. It is also well known that stereolithography is a powerful technique for producing three-dimensional models or prototypes with any desired geometry, using an ultraviolet laser source in a conventional process applied to organic compounds. Traditionally the process of development and fabrication of models (parts) allow the construction of three-dimensional parts, curing photopolymers upon exposure to ultraviolet light. The traditional and efficient process in this spectral region is carried out at about 0.352 μm [1,2]. Ultraviolet photons (UV), when absorbed by organic molecules give rise to electronic excitation in the first instance. The electronically excited organic molecules depend on various parameters, as well as the chemical structure of the molecule, the wavelength of the photons, and the medium in which the excitation is carried out. The study of organic photochemistry has been carried out for many years, covering a vast field [3].

The infrared laser (IR) photon excitation, which lead to vibrational and rotational excitation was not observed to have interesting effects until the advent of lasers. Particularly, the interaction of the infrared laser with organic materials lead to a thermal process in which controls of the depth of heating, pulse energy, exposition of heating time, and other thermal parameters, are the principal features to be considered in laser application studies. Laser application to thermosensitive materials, such as resins, has been considered an important field, since it allows new ways of manufacturing prototypes. The application of infrared laser (CO_2) to cure thermosensitive materials may provide a innovative and cost-effective means of manufacturing industrial prototypes [4,5].

A numerical method based on finite element is applied to simulate the heat transfer on the sample in order to compare with our previous observations of the stereolithography results.

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The software, of generic application, Ansys, is used in this work to solve localized curing process. Ansys is a program based on Finite Elements Method used, initially, to treat mechanical problems, and this work explores its application in the thermal area.

Important tests have been carried to check laser scan head performance using different laser parameters. Results showed that the laser parameters and the stoichiometric combination of the sample compounds play an important role in the curing process as well as the type of silica powder involved. The differential scanning calorimetry (DSC), to obtain the activation energy of the curing reaction as a function of temperature and to study the rate sample behavior such as temperature change, was discussed.

2. Physical model for the localized curing process

A simple physical model has been worked out aiming at the exact characterization of every physical phenomenon that can occur in the process of localized curing. The model describes the energy flow deposited by the laser in terms of the control of the operational parameters and the behavior of the resin, aiming at localized curing (Fig. 1). Initially, in order to obtain the power associated to the laser beam, the dwell time of the beam in the sample was determined. The localized curing in the beginning of our experiment was achieved by scanning a continuous wave (cw) CO_2 laser repeatedly over a circular trajectory on the sample's surface with scan speed v. By dividing the beam diameter 2ω by the scan speed, one obtains the dwell time:

$$t_d = \frac{2\omega}{v} \tag{1}$$

concerning the time of interaction laser/resin at a surface point. As the resin is highly absorptive at the CO_2 laser wavelength (10.6 μm), it is assumed that, during dwell time, nearly all the beam energy goes into the inner part of the sample at a distance from the surface equivalent to the absorption depth δ. The absorption depth was determined by measuring the transmittance of a non-cured sample, which presented a thickness of 80 μm at the CO_2 laser wavelength. The value found was 40 μm. It is assumed that energy E was absorbed in the small cylindrical volume V during the dwell time, the volume being defined as:

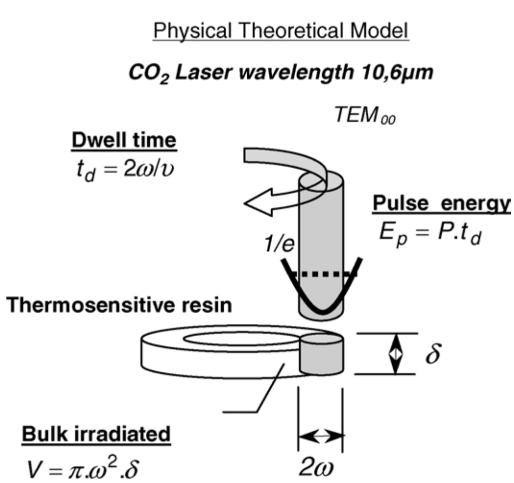

Fig. 1. Simple model of the heat flow in laser-induced localized curing.

$$V = x\,\omega^2\delta \tag{2}$$

The energy released in V is the product of the laser power by dwell time:

$$E = Pt_d \tag{3}$$

The approach of (2) is reasonable in this experiment because the sample absorbs at very small depths. Energy absorption in materials is quite critical with regard to the depths they reach. In materials that do not absorb energy strongly, the absorption depth may exceed the focus depth of the beam. As a consequence, the confinement of energy at the surface of the model is not maintained. By mean energy E, it is possible to determine the variation of temperature, which is proportional to the deposited energy with regard to the thermal capacity C_P and mass m of the material contained in volume V, according to the following equation:

$$E_p = C_p m \Delta T \tag{4}$$

the mass of the heated volume may be calculated by using the mass density of the sample $\rho = 2.799\ \text{cm}^{-1}$. If it is assumed that nearly all the energy deposited by the laser beam is absorbed every moment the laser passes at a point on the surface of the sample, it follows that the irradiated volume will undergo a temperature increase that is determined by the expression:

$$\Delta T = \frac{E_p}{mC_p} = \frac{Pt_d}{x\omega^2\delta\rho C_p} \tag{5}$$

3. Temperature calculation on surface of polymer

In order to model the heat flow in laser-induced curing, we used a finite-element approach to solve the time-dependent heat equation [6]. The thermal analysis was developed applying a program Ansys [7].

The time-dependent heat equation is:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \{v\}^T\{L\}T\right) + \{L\}^T\{q\} = \ddot{q} \tag{6}$$

where ρ is the mass density, c_p the heat capacity, T the temperature, t the time, $\{L\} = \left(\frac{\partial}{\partial X}, \frac{\partial}{\partial Y}, \frac{\partial}{\partial Z}\right)$ = operator vector, $\{v\} = (V_x, V_y, V_z)$ the velocity vector to transport of heat, $\{q\}$ the heat flow vector and $\ddot{q}$ is the heat generated by laser.

The heat generated by laser source with Gaussian distribution, is given by:

$$\ddot{q} = \frac{P}{\pi\omega^2\delta} \tag{7}$$

where P is the laser power, ω the radius laser beam and δ is the absorption depth.

The numerical simulation was developed under a set of initial and boundary conditions, listed below: