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Photoacoustic study of curing time by UV laser radiation of a photoresin with different thickness

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ABSTRACT

This paper deals with the study of the cure of a resin in the presence of a UV laser radiation used as the excitation source, operated at $\lambda = 405$ nm, with an output power of 20 mW. The open photoacoustic cell (OPC) technique was used to study the curing of the resins as a function of time. The curing characteristic time values were $\tau = 10.43$, 20.99, 30.18, 45.84, 67.59 and 89.55 s for the resin thicknesses of 1000, 2000, 3000, 4000, 5000 and 6000 μm, respectively. A parabolic behavior of the resin thickness, as a function of the curing characteristic time, was obtained. UV–vis spectroscopy and infrared Fourier transform spectroscopy (FTIR) techniques were employed to characterize the resin in order to study the optical absorption and the chemical bonds, respectively. Our work has applications in the manufacture of 3D printing parts for applications, among others, in medicine.

1. Introduction

Prototyping and manufacturing, and also called layered manufacturing, 3D printing, refers to a group of technologies that enable quick fabrication of engineering components for prototyping applications. This advanced manufacturing technology, which combines laser technology, photo-chemistry and computer graphics, is capable of direct and rapid manufacture of complex three-dimensional objects from profiles created using CAD and digital images and other data. The technology emerged in 1987 with the introduction of first commercialized rapid prototyping (RP) machine called stereolithography apparatus (SLA) from 3D system. It has now been applied to the 3D printing, it is a process of making a three-dimensional solid object of virtually any shape from a digital model which is achieved by adding successive layers of material (liquid resins) in different shapes. The 3D printing technology is used for both prototyping and distributed manufacturing with applications in industrial design, automotive, aerospace, engineering, dental and medical, consumer products, business machines, art and many other fields [1–8].

In the last decade, the stereolithography technology, based on UV polymerization of a thin resin film are used for the realization of three-dimensional objects which are built without the use of molds. The objects are obtained polymerizing a low viscosity liquid resin section by section. The shape and the dimensions of the parts are directly transferred from a three-dimensional CAD system, where a laser beam (usually diode, Argon and He–Cd) was used to polymerize the different layers [9].

The objects, generated directly from their drawing, are typically used as prototypes or for the construction of molds. The kinetic behavior of the resin represents a key point for a full comprehension of the cure condition occurring in the small zone exposed to laser irradiation [10]. During curing of resins typically used in stereolithography, strong structural changes affecting the final properties of the materials occurred. The polymerization of a thermoset polymer generally involves the transformation of a viscous liquid monomer into a rubber (gelation), and then into a solid glass (vitrification), as a result of the chemical reactions between multifunctional active groups present in the system which develop a progressively denser polymeric network. A significant contraction, associated with the degree of reaction and temperature gradients, may be responsible for the buildup of residual stresses and distortion of the parts during cure.

The curing properties of resins have been subjects of great study for characterizing process in manufacturing of 3D parts [11].

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Considering the application of 3D stereolithography, recently a bionic ear via 3D printing of a cell-seeded hydrogel matrix in the anatomic geometry of a human ear was generated. It is long with an intertwined conducting polymer consisting of infused silver nanoparticle [12].

In this work the characterization of a resin, used as a basic material for a 3D printer, was studied by using the photoacoustic (PA) technique. The photoacoustic (PA) technique is well known for its investigation of thermal parameters of gases, liquids, thin film and powder materials [13–15]. PA technique is based on light absorption in which the energy of light is transferred to the species. The received energy causes the temperature of the sample and the surrounding gas to increase, which leads to thermal expansion. By modulation the light source using a mechanical chopper at a certain frequency, the thermal expansion is also modulated. This modulated thermal expansion causes an oscillatory motion of the gas layer which produces a sound wave proportional to the absorbed energy [16].

In this way, we will use the PA technique to monitoring different processes that change the structure, and consequently the curing process of the resin. In this study, the PA technique is applied to study the curing process of resins with different thickness as a function of time, to estimate the curing characteristic time in this process.

2. Experimental method

The study of the curing process of the resin was measured using the photoacoustic technique. Fig. 1 shows a schematic diagram of basics of the experimental setup of the open photoacoustic cell measurement. The photoacoustic setup comprised of a diode laser beam operating at UV that was used as the excitation source with an output power of 20 mW. The laser beam passes through a SR540 mechanical chopper which was modulated at variable frequencies. The laser beam was reflected from a mirror into the photoacoustic cell. The resin sample was placed inside a different thick steel ring of 3 mm inner diameter with a 0.0017 cm aluminum foil thick disk at the bottom. The entire sample holder was mounted on the open photoacoustic cell by the means of a thin layer of vacuum grease.

The sample's temperature increased due to the energy absorption from the aluminum foil. So, the generated heat diffused from the aluminum foil and propagated into the sample as well as the gas chamber. Following the periodic heating, an oscillation pressure also occurred within the photoacoustic cell. This cyclic pressure induced by light was sensed as acoustic waves by a microphone connected to the photoacoustic cell under the gas chamber. The microphone signal was collected and amplified by a low noise preamplifier and then processed by the lock-in amplifier (SR530). In this experiment the photoacoustic signal was recorded as a function of time with a fixed frequency of 17 Hz. Using a Lab View program, the data collected by the lock-in amplifier was analyzed to obtain the photoacoustic signal amplitude as a time function of the resin sample.

3. Theory

The theoretical model to analyze the experimental PA signal is based on the PA effect, whereby the sample's temperature was increased due to energy absorption from the aluminum foil. So, the generated heat diffused from the aluminum foil and propagated into the backing material (sample) as well as the gas chamber. Following the periodic heating, an oscillation pressure also occurred within the PA cell. This cyclic pressure induced by light was sensed as acoustic waves by the microphone connected to the PA cell under the gas chamber. To determine the change in pressure of gas in the PA cell, we assume the Rosencwaig–Gersho model for the production of the PA signal [17].

$$S \cong \frac{(1-i)}{2a_g}\left(\frac{\sqrt{2\alpha_b}}{\sqrt{\omega}}\frac{1}{k_b}\right)Y \qquad (1)$$

where $i=(-1)^{1/2}$, a_g is the thermal diffusion coefficient of the gas inside the PA chamber, $\omega=2\pi f$, f is the chopping frequency of the incident light beam, α_b and k_b are the thermal diffusivity and thermal conductivity of the base (backing material), respectively, and Y is a constant factor. In the PA chamber, the base corresponds to the material in front at the absorber of the chopped light. Another thermal property is the thermal effusivity, defined as $e=k/(a)^{1/2}$. The thermal effusivity essentially measures the thermal impedance of the sample, or the sample's ability to exchange heat with the environment [5]. Using the definition of the thermal effusivity, Eq. (1) can be rewritten as follows:

$$S \cong \frac{(1-i)}{2a_g}\left(\frac{\sqrt{2}}{\sqrt{\omega}}\frac{1}{e_b}\right)Y \qquad (2)$$

Eq. (2) means that, in thermal thin and optically opaque material, the PA signal is sensible to the thermal properties of the base.

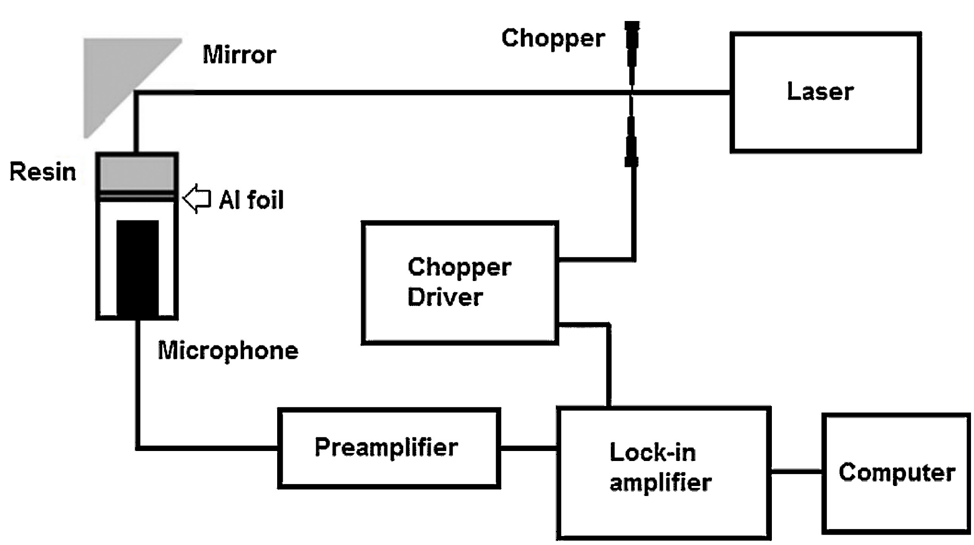

Fig. 1. Diagram of the open photoacoustic cell experimental setup.