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Laser–PMMA Interaction and Mechanical Stresses

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The polymethylmetacrylate samples were exposed to laser beams of various types of lasers. The modifications of the surfaces of the samples were analyzed by light microscopy and scanning electron microscopy. Numerical approach to thermal distribution for specified power ranges of selected lasers was obtained. The results of polymethylmetacrylate drilling and cutting performed by laser and non-laser means were compared by photoelastic methods.

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1. Introduction

Polymethylmetacrylate (PMMA) is a promising applicative material for many fields, due to its optical characteristics. The area of application is very wide, concerning objects used in everyday life: CDs, toys, boxes, device housings, glass replacement, but also in vehicle industry, civil engineering and architecture, as well as in medicine and electronics. Stress and strain characterizing of other materials can be done via PMMA — very useful for laser-material interaction [1–5].

After exposing PMMA samples to beams of several types of lasers, damages have been examined by optical microscopy and scanning electron microscopy (SEM). The analysis of the thermal distribution for specified power ranges of selected lasers has been performed numerically. The results of drilling performed by lasers and conventional devices were compared by photoelastic methods [2].

Various processes occur during the laser–material interaction. Some of them, like melting, evaporating and disintegration, cause damages. The observation of

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samples shows that it had been possible to obtain information on the processes and to provide experimental facts which were useful for modeling.

2. Mechanisms of interaction and damage

The level on which a material modification is considered as damage depends on the material characteristics, laser wavelength, the energy and the shape of pulse, both temporal and spatial. The analysis of interaction is complete when all the phenomena occurring in the material are observed and the data of ejected material is recorded. The experiments with the control of both the ejected materials and the processes in the bulk are very complex.

Particular procedures are used to determine the damage threshold, which depends on the administrative regulations, on the purpose of the component application (medical, industrial) and is specific for each country [6–10].

3. Disintegration of polymers

Transparent and opaque (non-transparent) materials differ in effects of disintegration. Experimental data [7] are useful in analyzing such effects in transparent amorphous and crystal materials. For simplest investigations, a Q-switch laser with regulated output power, lenses for beam focusing, a camera and investigated specimens are sufficient. Special care should be taken to aberrations of the optical system and elements, and particularly to new classes of aberrations connected to high-power laser systems. Two mechanisms are recognized: formation of rounded pores and formation of almost flat cracks (fissures). It seems that the type of disintegration in investigated power range depends only on the focal length of a lens; pores appear with greater focal length. The zone of disintegration has a conical form with several dots as centers of scattering. Polystyrene and PMMA have similar behavior during the laser beam interaction. Of special interest is to

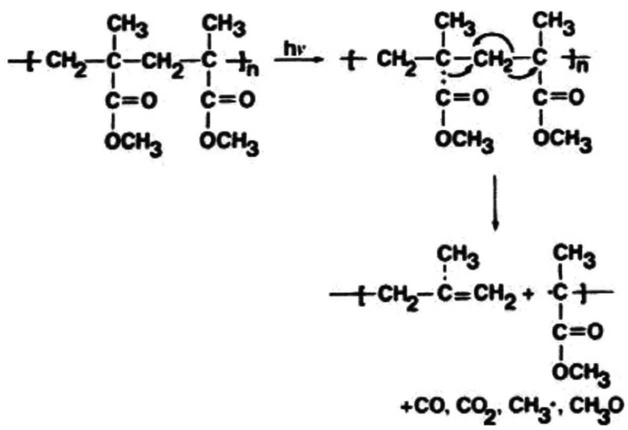

Fig. 1. Some possible chain scissions of PMMA resist.

observe the statistics of cracks formation [7, 9]. It is common [7] to investigate the interaction with: low power (1–10 MW) and long focal length (50–100 mm); high power (50–100 MW) and long focal length (50–100 mm); high power and short focal length (< 50 mm).

The influence of optical inhomogeneity and impurities to the threshold and character of disintegration is important. Both the kinetics of disintegration and the measurements of stress open new fields of investigation. Optical techniques for measurements, like photoelasticity, holography and optical tomography, were developed a long time ago. The potential role of newly developed ps and fs laser spectroscopies increases. The schematic of a polymer photodestruction is presented in Fig. 1 and could be the object for analysis in photochemistries.

4. Experiment

Samples are produced by various manufacturers under the commercial name "klirit". Some of the samples are manufactured by ICN Galenika (Belgrade), and they are very similar to "plexiglas" (Roehm), "lucite" (DuPont), "vedril" (Montecatini) and "organic glass" (Russian manufacturers). Several samples were designed for photoelasticity measurements as models for various loadings in constructions in civil engineering, architecture, electrical engineering, mechanical engineering; the others were designed as mechanical parts of a cellular neural network and as non-imaging concentrators [2, 5].

The nature of some samples is as follows. A solid thermoplastic is obtained from methylesther of methacrylic acid (monomer), the synthesis of which is generated by hydrocyanic acid and acetone. The monomer is featured by long chain, polymerized structures composing high molecular compounds. Klirit is cast-produced through so-called wet-dry product with minimum of monomer leftover, meaning final stability to all its physical and chemical properties.

5. PMMA and anisotropy — mechanical stresses

Besides the natural anisotropy of raw materials, the anisotropy could be artificially induced by various processes (electro-, magneto- and acoustooptical, magnetostriction, piezoelectrics...) among which the laser interaction is of special interest [11]. These processes can provoke three groups of changes of material characteristics which modulate the laser beam propagating through the material: long-lasting (inelastic), short-lasting (elastic), and intermediate case. These are the roots of optical modulation, optical memories, etc. Photoelasticity of compound crystal and amorphous materials is linked to other specific linear and nonlinear effects. Liaisons are established by tensor calculus. Tensor rank depends on the selected scheme of stress and on the class of crystal symmetry. For simpler cases, constants of isotropic material response (ε, μ, σ) are expressed with scalar variables before the appearance of mechanical loadings. It is not uncommon that residual stresses appear in the material as a consequence of mechanical or other (laser, plasma, ultrasound, etc.) processing.

6. Results and analyses

There were two groups of samples, one mechanically processed (cutting), and the other processed (cutting and drilling) by laser beams (CO_2, Nd^{3+}:YAG). After processing, some of the samples have been exposed to ruby laser beams.

In Fig. 2a, the microscopic view of the PMMA drilling is presented. The cutting operation was performed by CO_2 laser (50 W, on-time 10 ms, repetition 100 Hz). In order to observe the distribution of stresses, some samples have been mechanically loaded. Photoelasticity analysis (Fig. 2b), as one of the standard methods, presents the characteristic distribution of stresses, which could be further modeled. The stresses are generated by laser processing (cutting and drilling). However, stresses generated by the exposition to ruby laser are not visible in Fig. 2b, mainly due to the small dimensions of the damages.

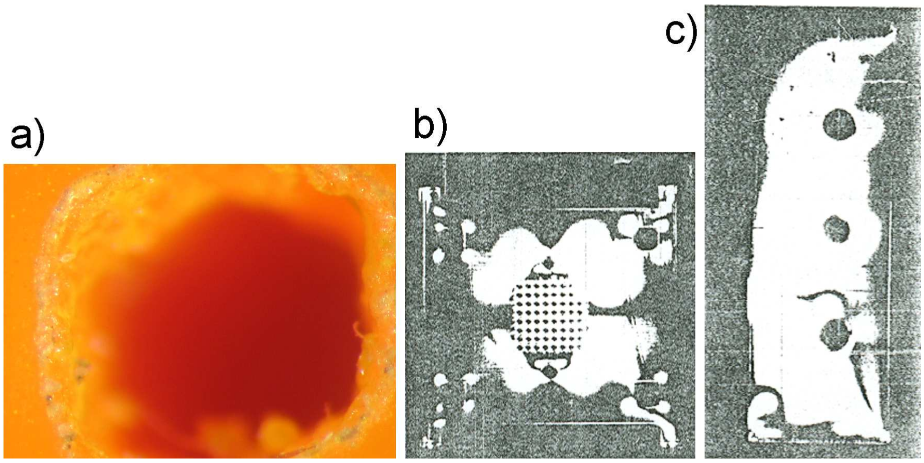

Fig. 2. Micrographs of PMMA specimens: (a) microscopic view of one laser-cut hole, (b) photoelasticity analysis of laser processed specimen, (c) photoelasticity analysis of mechanically processed specimen.

Residual stresses after processing are visible. The areas around laser induced holes are much smaller than other mechanically processed damages. Laser affected zone (LAZ) is less than heat affected zone (HAZ). The degree of material homogeneity can be derived from photoelasticity patterns by image processing.

Laser treatment of a PMMA sample has been simulated. The simulation was based on the assumption that all the energy of the beam penetrated the material. The temperature increase ΔT from ambient temperature was calculated in space laterally in respect of the direction of the beam propagation. It was also assumed that the PMMA sample was of half-infinite geometry and the beam

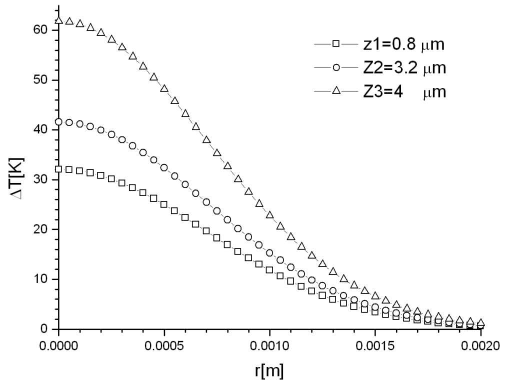

Fig. 3. Lateral temperature increase (from ambient temperature) induced by laser beams as a function of the distance from the beam axis, for 3 different longitudinal points ($z1$, $z2$, $z3$).

profile was of top-hat shape. The beam diameter was 1 mm (at the sample) and power was 500 W. The exposure time was 1 s. For PMMA constants [5] of specific heat, thermal conductivity and density, and assumed laser data, results of simulation by boundary element method (BEM) [12], the obtained lateral temperature distributions are presented in Fig. 3.

7. Conclusion

In the light of optical methods used for control and diagnosis, photoelasticity seems to be more practical, requiring fewer components. The consideration of damages approved the possibility to monitor the aging of the material. Holographic techniques ("interaction and polarization") give more data, but are more complex, as is in optical tomography. The applications of those techniques in civil engineering, machine tool industry, medicine, are well-developed and more and more implemented. This specially holds for dental and other prothetics where implants undergo strains of high degree.

Damages due to thermochemical changes of PMMA are more readily seen in bulk samples than in thin sheets because incompletely polymerized material carbonizes in small spots.

In this paper, the microstructures of damages induced by chosen lasers has been analyzed. The samples were exposed to atypical pulses in order to experimentally obtain the information on the interaction in selected power ranges. Photoelastic methods visually provided the first impression about the residual stresses occurring in the material after the processing, regardless of the techniques used conventional or unconventional. The divide between the conventional and unconventional techniques is much less clear nowadays.

Acknowledgments

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