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Review

Femtosecond laser ablation profile near an interface: Analysis based on the correlation with superficial properties of individual materials

Gustavo Nicolodelli*, Cristina Kurachi, Vanderlei Salvador Bagnato

Instituto de Física de São Carlos, University of São Paulo, Grupo de Óptica, Av. Trabalhador Sancarlense 400, P.O. Box 369, CEP 13560-970, São Carlos, SP, Brazil

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A B S T R A C T

Femtosecond laser ablation of materials is turning to be an important tool for micromachining as well as for selective removal of biological tissues. In a great number of applications, laser ablation has to process through interfaces separating media of different properties. The investigation of the ablation behavior within materials and passing through interfaces is the main aim of this study. Especially, the analysis of the discontinuity in the ablation profile close to interfaces between distinct materials can reveal some of the phenomena involved in the formation of an ablated microcavity geometry. We have used a method that correlates the ablation cross sectional area with the local laser intensity. The effective intensity ablation properties were obtained from surface ablation data of distinct materials. The application of this method allows the prediction of the occurrence of a size discontinuity in the ablation geometry at the interface of distinct media, a fact which becomes important when planning applications in different media.

Contents

1. Introduction

Ablation promoted by an ultrashort laser pulse operating in the femtosecond regime is a new and relevant field for material processing. Not only metals [1–3] and ceramic materials [4,5] have been targets for ablation investigations, but also many materials of biological interest have been the subjects of investigation in this field [6–9].

For hard dental treatment using lasers, an attractive field of study is the selective laser interaction with materials and tissues. Examples of laser applications are the selective removal of restorative dental materials or of dental caries requiring a cavity preparation while preserving healthy tissues [6,10].

Ultrashort lasers have been used in micromachining and ultraprecise surgery because the intense laser light from an ultrashort pulse laser can induce nonlinear processes such as multiphoton absorption. These high power densities can promote plasma-induced ablation [11]. In this way, when using a femtosecond laser, there is high energy intensity during an extremely short time, achieving a clearly defined removal of material. Due to the short pulse width lower than the solid thermal diffusion time, an ablation without the occurrence of thermal damages in the adjacent areas is obtained. Another important aspect is that the laser pulse is significantly shorter than the time it takes for electrons to transfers their energy to the lattice via electron–phonon coupling [12]. Thermal ablation occurs when the laser pulse width is longer than the electron-lattice relaxation time [13]. In this way, femtosecond laser ablation results in a micromachining of high band-gap materials that can be achieved with a minimum of thermal and mechanical defects. As a consequence, ultrashort laser pulses have been considered important in surgical procedures that demand precise ablation without heating of tissues. There are, however, many issues to be addressed regarding the dynamics of propagation of ablated volumes within the materials.

Conventionally, most of the existing studies of hard material ablation are limited to the surface analysis of the irradiated areas

* Corresponding author. Tel.: +55 16 3373 9810; fax: +55 16 3373 9811.
E-mail address: nicolodelli@ursa.ifsc.usp.br (G. Nicolodelli).

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[1,4–6]. The spatial progression of ablation within the bulk material has not been fully investigated, even though this information is relevant for many situations (for example, in dentistry and surgery). The dynamics of a progressing ablation can impose certain limitation on a certain application. Biological organs and tissues, e.g. tooth and bone, present interfaces separating regions with different characteristics, which can respond differently to the laser–material interaction.

This paper investigates the behavior of ablation across a surface of two materials and proposes an alternative method to evaluate the progression of ablation, especially near an interface between two distinct media. We have used a method that correlates ablation properties of the materials at the free surface and within the bulk of the material. The application of this method allows the prediction of the occurrence of a size discontinuity of the ablation geometry at the interface of distinct media. To our knowledge the analysis of the phenomena of ablation at the interface between two distinct materials like e.g. in hard dental tissues has not yet been investigated. This lack of studies motivated our research. In this study, the method is applied to understand the variations on the ablation geometry that occurs at the interface of restorative dental materials, but, it can, in principle, be applied to any interface involving distinct materials, or even in multilayer assembly of materials. We start presenting the used methodology and materials followed by the presentation of the results combined with discussion. In the final remarks the impact of the work is analyzed.

2. Materials and methods

A Ti:Sapphire femtosecond (Libra-S, Coherent, Palo Alto, CA, USA) Q-switched and mode-locked laser, emitting pulses of approximately 70 fs, at 801 nm, and operating at a constant pulse repetition rate of 1 kHz was used in this study. Pulse duration of 70 fs was measured using a 2nd-order autocorrelator (Coherent-SSA^{TM}). The beam was steered with highly reflective coated dielectric mirrors and passed through a 20 cm focal length lens before reaching the target sample. The experimental optical setup resulted in a Gaussian laser beam of a waist (ω_0) of around 17 μm at the focal point.

We have performed the experiments using samples of commercial dental restorative resin Z-250 (3 M/USA), (resin A), and a manipulated resin composed of Bis-GMA (weight 60%), TEGDMA (weight 30%) and UDMA (weight 10%), with camphorquinone and amine, (resin B). The resin samples were inserted in metal molds with cylindrical format and a diameter of 8 mm by 1 mm and 2 mm height. The polymerization was performed using a blue LED (MM Optics, São Carlos, Brazil) under 40 s of photoactivation for the Resin A and 20 s for the Resin B (following the manufacturer's instructions).

We have prepared individual samples of resins as well as a composed sample having 1 mm of resin A and 1 mm of resin B.

The dental resins samples were irradiated at different average power levels (on the range 0–1 W) and exposure times (10–15 s), at the focused position as indicated in Fig. 1.

In the first experiment, for each resin (A and B), we investigated the superficial ablated diameter as a function of the incident intensity and fixed exposure time of 15 s. In the second experiment, a sample composed of the two resins was polymerized, resulting in a double-layered material with an interface between the two parts. After irradiation, the samples were longitudinally rubbed with sandpaper to allow the observation of the ablated region and its progress through the material. An optical microscope was used for the determination of the diameter and depth along the created microcavity. As a result, the profile of the ablated microcavity was determined. This corresponds to the progression of the laser ablation along the material depth, i.e., within the material along the direction of light propagation. Digital images of micro-cavities were obtained using a CCD camera attached to the optical microscope. For each of the ablated position we associate the diameter with an intensity, and the analysis performed as each z-position was a free surface using the data from a previous experiment. The intensity obtained in this way is called "effective intensity". The profile of this "effective intensity" can be obtained from the surface, passing through the interface.

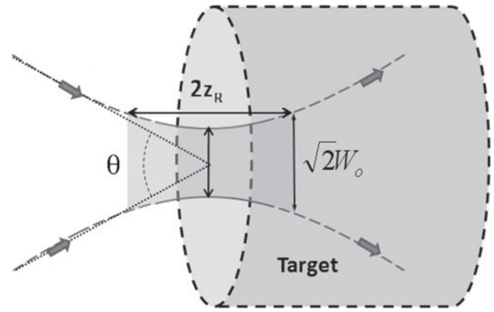

Fig. 1. Representative diagram of a sample placed at Gaussian focused beam.

3. Results and discussion

A typical expected profile for an ablated cavity is a cone geometry [10]. The diameter decreases with the z position (depth), and this geometry depends on the characteristics of the laser–material interaction. The ablation profile obtained at the double-layered material is shown in Fig. 2. An abrupt variation of diameter at the interface can be observed in Fig. 2a and the detail in Fig. 2b. The variation of the diameter as a function of depth is presented in Fig. 3.

In order to analyze the abrupt diameter variation near the interface between two materials, it is convenient to introduce a method to predict the geometry of ablation, correlating the ablation and the basic properties of laser–material interaction, as described in below. A first point to be considered is the fact that the focused Gaussian beam at the surface may be defocusing within the material, resulting in lower intensities as the ablation progresses. This can certainly decrease the ablation diameter.

We start by considering the Gaussian beam intensity profile, $I_{(r,z)} = I_0 e^{-2r^2/\omega^2(z)}$, where I is the intensity at each position, I_0 is the central beam intensity, r is the transversal radial coordinate and z is the coordinate along the propagation direction. $\omega(z)$ is the beam Gaussian waist, $\omega(z)$ varies along the propagation direction and is given by a well-known expression [14]. In terms of incident power (P_0), $I(r,z)$ can be written as, $I_{(r,z)} = (2P_0/\pi\omega^2(z))e^{-2r^2/\omega^2(z)}$, with ω_0 = 0.017 mm (determined by the scanning knife-edge method for the Gaussian beam [15]) and z_R = 1.1 mm (Rayleigh length). These values fully characterize the laser beam profile used in our experiment, and hence the intensity along the z-position in the absence of interaction with the sample.

The beam divergence and its correlation with the ablation profile can be evaluated. For a fixed exposure time there is a minimum intensity for the ablation (threshold intensity, I_{th}) below which no ablation is observed and above which ablation occurs. In this sense, the minimum intensity to result in material ablation can be determined assuming $I_{th} = I(r = R, z)$, where R is the radius of the beam for each position. Removing I_{th}, from this equation we obtain, presuming that the laser beam is not affected, the beam radius, expressed in terms of the Gaussian beam characteristics.

It is clear that the observed geometry of Fig. 2 employing a Gaussian beam cannot be explained merely based on a possible

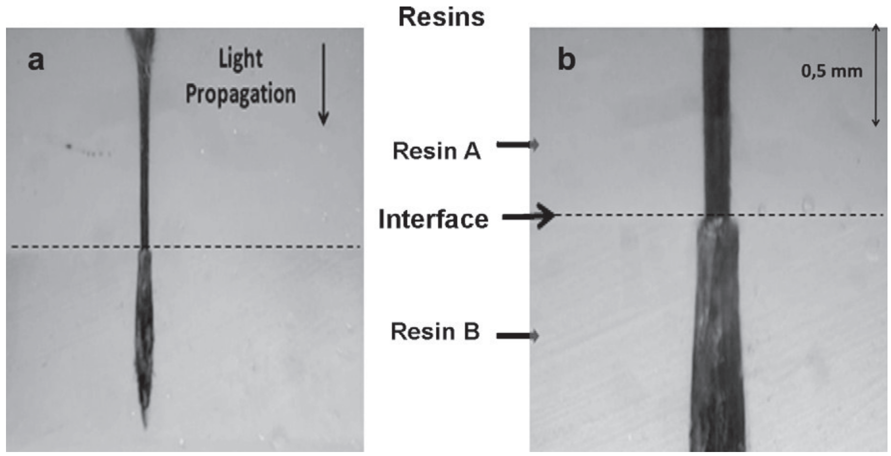

Fig. 2. A micrograph of the ablation profile of the sample at resin A/resin B interface.

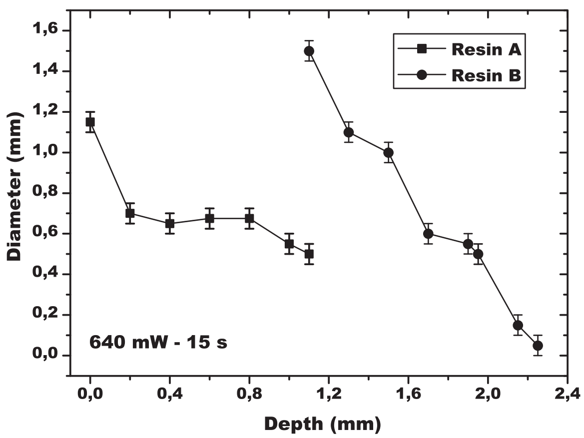

Fig. 3. Ablated diameter as a function of depth for one sample composed of two different resins after 640 mW average power and 15 s exposure time irradiation.

divergence of the beam (Fig. 1). We will now consider the effective intensity analysis as previously discussed.

To apply this method, first the correlation between the diameters of the ablated free surface region, this is obtained when the laser is focused. The results of this measurement for two different resins are shown in Fig. 4.

The plot of Fig. 4 shows the results of the ablated microcavity, correlating the Gaussian laser peak intensity (I_0) with the ablated superficial diameter. For distances $z \le z_R$, which is the case at the surface, we can assume that $\omega(z) \approx \omega_0$. We associate each position of the ablation depth with a "local intensity" that caused the diameter of ablation as observed at the surface. The final result is a plot of "effective intensity" versus depth.

The observation of the diameter discontinuity, indicated in Fig. 3, corresponds to the real interface between two materials. The discontinuity of the diameter is observed around $z = 1.1$ mm, where the resin A/resin B interface is located. Based on the experimental data of the ablation profile of the microcavity and the laser intensity at $z = 0$ position (Fig. 3), the effective intensity for each z-position can be determined.

Fig. 5 shows the "effective intensity" as a function of depth for the composed sample resin A/resin B. The plots show the decrease of the effective intensity along the ablation depth, as a result of the ablation progression. The "effective intensity" (Fig. 5) goes basically smoothly through the interface. The variation on the diameter of the ablated region as a function of the cavity depth comes essentially from a mechanism causing an effective intensity attenuation, as a consequence of a series of complex effects. Mechanisms like the ablation products shielding the further action of the consecutive pulses of the incident beam, and many others are all summarized through the use of an effective intensity.

The resins used in this study are not transparent at $\lambda = 801$ nm. In fact, we have measured the attenuation coefficient $\alpha = 15\ \mathrm{cm}^{-1}$ (resin A) and $\alpha = 2\ \mathrm{cm}^{-1}$ (resin B). If the materials were transparent, we should relymainly on a two photon mechanism of interac-

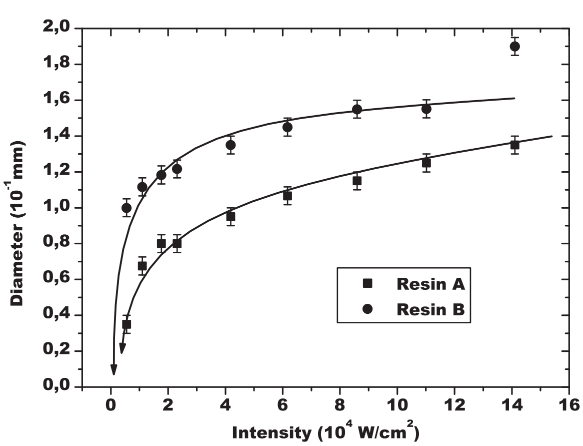

Fig. 4. Superficial ablated diameter as a function of intensity for the resin A and resin B.

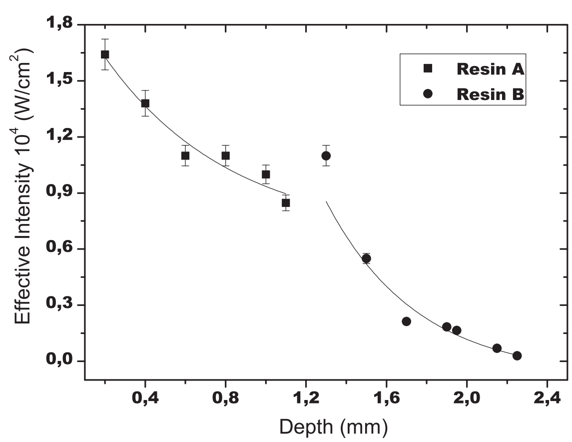

Fig. 5. "Effective" intensity as a function of depth for a sample composed of resin A/resin B interface.

tion, and a different analysis from "effective intensity" attenuation would be performed. It is clear that the mechanisms involved in the ablation process are very diverse in our case. The main aspect of our methodology is based on the fact that we do not need to refer to the actual mechanisms involved, since they all influence the effective intensity that can be extracted from surface ablation data.

The local effective intensity basically remains the same at the interface, but causes different effects in each material. This means that the variation of the geometry on the ablated material is fully determined by the variation of the ablation threshold of the materials. From Fig. 5, we furthermore observe that the effective decay of intensity along the penetration is specific for each material, characterizing the differences in the absorption coefficient for each.

When the light beam coming from one material enters into another material with different ablation properties, a series of interactions occurs at this interface. Moreover, the change of the refractive index in a Gaussian beam implies in the displacement of the focal plane in the direction of the incident beam (z), consequentially the beam waist in this position also changes, but this does not affect the effective intensity analysis.

We already observed that the ablation process shows an interesting behavior when it begins at the resin A surface, progresses within the material and reaches the resin B. A reason for this discontinuity of the diameter is the difference of the ablation threshold for the materials. When using information of Figs. 3 and 5 we observe that, in fact, the plot in Fig. 4 provides sufficient information allowing the prediction of the discontinuity of the ablation diameter that occurs at the interface of two different materials. The results are quite consistent with observations. More detailed studies of the process of ablation at interfaces between two materials are necessary, in order to better understand this phenomenon, and to support the application of femtosecond lasers in layered tissues/materials. Our work shows that an analysis based on the effective intensity may be quite useful.

4. Conclusion

This study demonstrates the validity of local effective intensity analysis and allows a quantification of the overall variation in ablation geometry that takes place at the interface of two different materials. Additionally, our data are sufficient to predict that a discontinuity in the ablation profile will occur at the interface between two material media: resin A and resin B, showing a sudden discontinuity of the ablated cavity diameter. This can be applied to understand ultrashort laser ablation in structural systems, e.g. hard dental tissues (enamel/dentin) and others. We would like to express acknowledgment to FAPESP and CNPq for their financial support.

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