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Review Article

Laser Micromachining of Glass, Silicon, and Ceramics

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A brief review is focused on laser micromachining of materials. Micromachining of materials is highly widespread method used in many industries, including semiconductors, electronic, medical, and automotive industries, communication, and aerospace. This method is a promising tool for material processing with micron and submicron resolution. In this paper micromachining of glass, silicon, and ceramics is considered. Interaction of these materials with laser radiation and recent research held on laser material treatment is provided.

1. Introduction

Miniaturization is an important trend in many modern technologies. Micromachining of materials with micron resolution at high speed is a widespread technology used in nearly all industries. This method can be found in manufacturing high-tech microproducts for biotechnological, microelectronics, telecommunication, MEMS, and medical applications. After absorption of radiation the material is removed by the process of laser ablation. Laser ablation usually relies on strong absorption of laser photons; thus the laser wavelength has to be appropriate unlike ultrafast lasers which are used. Ultrafast lasers cause ablation as a result of multiphoton absorption at high peak intensities, so that even materials transparent to the laser wavelength can be machined [1].

Many types of lasers are supposed to be used for micromachining materials. These include microsecond carbon dioxide lasers at wavelengths between 9.3 μm and 11 μm, nanosecond and femtosecond solid-state lasers at wavelengths between 1030 nm and 1064 nm (e.g., Nd: YAG and Ti: Saphir) with the possibility of higher harmonic generation in visible (515 nm–535 nm) and ultraviolet (UV) spectrum (342 nm–355 nm and 257 nm–266 nm), then copper vapor lasers, diode lasers, and excimer lasers emitting at UV region (157 nm–353 nm) [2].

Main process parameters in the laser-material interaction involve laser pulse duration. Consequently it significantly affects the quality of the produced microfeature and the material removal rate. Thermal relaxation time τ plays critical role during ablation. Thermal relaxation time is related to dissipation of heat during pulse irradiation and is expressed as

$$\tau = \frac{d^2}{\kappa}, \tag{1}$$

where d is absorption depth and κ is thermal diffusivity. Thus, high absorption coefficient α and low thermal diffusivity κ ensure easy initiation of ablation [1].

Ablation of material can be facilitated by using short pulses (shorter than τ, generally 10 ps) as the laser energy is confined in a thin layer. For longer pulses, absorbed energy will be dissipated in the surrounding material by thermal processes. Absorption of long laser pulse also causes melting and substantial sputter evaporation of the material. These phenomena can contaminate surrounding area, produce microcracks, and remove material over dimensions much larger than the laser spot. Other adverse effects include damage to adjacent structures, delamination, formation of recast material, and formation of large heat affected zone (HAZ). Thus, efficient ablation of the material necessitates the use of ultrafast lasers. Ultrashort pulses produce very high peak intensity ($>10^{15}$ W·cm^{-2}) and deliver energy before thermal diffusion occurs. High efficiency and precision of the process are achieved without significant thermal degradation (melting, spatter, recrystallization, etc.) to the surrounding region. When such intense bursts of energy collide with the surface of any material, strong electromagnetic field of the focused laser pulse rips the electrons out of their atoms. Exposed material becomes ionized and thin plasma is created which results in material removal with extremely precise edges. The electrons are lighter and more energetic than the ions so they come off the material first, later followed by the ions. As the ions all have positive charge, they repel each other as they expand away from the material. Consequently, there are no droplets condensing onto the surrounding material [3].

2. Effect of Laser Pulse Duration

The interaction of laser radiation with matter was studied systematically. During the interaction absorbed laser energy is basically transferred to the electrons of machined material. The electrons reach thermal equilibrium in about 100 fs. After a certain period of time the electrons transmit their energy to the surrounding atoms or ions. This time interval is called electron-phonon relaxation time (τ) for materials with crystal structure and depends on the properties of the crystal lattice. Typical electron-phonon relaxation times differ from 0.5 ps to 50 ps. Thermal equilibrium between the electrons and the lattice is set in after a multiple of τ. Thus, no heat is transferred to the lattice for laser pulse durations shorter than τ. Therefore a melt phase or thermal damage in the material should not be present. Unfortunately situation in practice is different. As the lattice is heated up the evaporation takes place and persists for several nanoseconds. The material stays in molten state for tens of nanoseconds. So, even for ultrashort pulses, thermal processes last for time period in order of nanoseconds. Hence, the melt layer is never zero, but it reaches a thickness of several submicrons [1, 4].

3. Laser Micromachining of Glass

Glass is suitable for many micro- and nanotechnology applications. Glass materials are characterized by attractive properties, such as inertness and other thermomechanical properties. Nowadays huge attention is being paid to glass machining because glass-based microstructures are found in disciplines such as biomedicine, biochemistry, lab-on-chip devices, sensors, and MEMS devices. Micro lenses and optical waveguides are key components for optical communication. In almost all cases, it is necessary to avoid damage and microcracking around laser machined site and femtosecond lasers have proven to be excellent sources for such precise machining work.

Generally, infrared (IR) laser radiation is not absorbed very well in variety of glass materials. It means that the band gap of the material is bigger than the photon energy and linear single photon absorption process cannot take place. If the material is exposed to high intensity femtosecond laser pulses the probability of nonlinear absorption mechanisms increases. For example, Li et al., 2008, fabricated microchannels and microchambers in silica glass and Darvishi et al., 2011, realized microchannels both in soda-lime and borosilicate glass using fs laser pulses [5, 6].

During micromachining, interaction of glass with laser beam is the most important part. Two types of phenomena can be observed when the beam is incident to glass, thermal expansion, and crystallization. Surface ablation occurs during both of these phenomena but during crystallization new phase is formed. To produce micro lenses for optical parts, the following conditions have to be kept: (1) no crystallization, because crystallization reduces the transmittance of glass and changes refractive index and (2) no contamination and cracking of the treated area. At this point glass has to satisfy high thermal stability and solidity [7].

To form the well-known waveguide structures it is desirable to focus the laser beam deeper under the glass surface. Then the local multiphoton interaction of laser pulses modifies refractive properties of glass creating waveguide structure. Laser fluence has to be greater than the surface damage threshold. This observation illustrates a significant difference of surface and internal laser-material interaction. In the material surface, the ionization stimulates avalanche processes and the resulting plasma plume either takes away material or causes a local breakdown with a following ejection of droplets. Internal multiphoton ionization most likely causes local photochemical reactions with a modified refractive index as a result [8].

Very thin glass sheets (with a thickness < 1 mm) are difficult to machine by conventional methods. These glass sheets are able to machine *in situ* with high quality, without damage and the formation of microcracks mainly by using ultrafast lasers [9, 10]. This method is confirmed by Yashkir and Liu, 2006, who presented ultrafast laser micromachining of 175 μm thick glass sheet using a Ti: Saphir laser. They demonstrated ultrafast microdrilling with HAZ limited to less than 1 μm and no presence of microcracks [8].

Methods using a laser with short wavelength or short pulse, glass with high absorptivity, and the addition of absorbents all have been proposed for the laser machining of glass without cracking. Laser radiation is absorbed at the interface of glass and the absorbent material and only a part of glass in contact with the absorbent is ablated. Mitsuishi et al., 2008, studied a method for machining a 3D microchannel in silica glass using a UV nanosecond pulsed laser and the slurry as absorbent. The machining specifications while using three different nanopowder materials, CeO_2, TiO_2, and ZnO, were investigated. Authors observed glass melting as a result of the heat transfer from absorbent particles, which were attached to the surface and assured strong laser absorption [11]. Kim et al., 2009, treated soda-lime and borosilicate glass doped with cobalt oxide as absorbent. Cobalt ions ensured that glass could be processed by laser. The irradiation area was smooth and no microcracks were present. The ablation height could be controlled by setting laser energy. Finally, type of glass used in this study was useful for the fabrication of microoptics parts [7].

One of the most promising indirect processing methods is the laser-induced back-side wet etching (LIBWE). During this method, transparent targets are in contact with liquid thin layers, which absorb and transform pulse energy resulting in etching. LIBWE is an effective method for crack-free etching of transparent materials such as glass achieving high precision and near-optical quality surfaces. Traditionally, LIBWE is performed using UV laser sources. However, Cheng et al., 2006, described the use of an economic Q-switched 532 nm green laser in microfabrication of soda-lime glass substrates. Using a common organic dye (Rose Bengal) as the photoetchant, crack-free microstructures with a minimum feature size of 18 μm were obtained [12]. Yen et al., 2010, used visible LIBWE with gallium and eutectic indium/gallium as absorbers, for crack-free microfabrication of soda-lime and quartz glass [13]. Ultraviolet surface microstructuring of silica glass plates by LIBWE was performed upon irradiation from solid state UV laser (266 nm) by Niino et al., 2006. They reported a well-defined micropattern formation without debris and microcrack around the etched area. Zimmer and Böhme, 2008, suggested hydrocarbon and metallic absorbers for LIBWE of transparent materials [14, 15].

Demand for higher precision and clean laser based processes has driven the development of the ultrafast lasers that operate at high frequency with high average powers. Lee et al., 2009, focused on the differences between processing with nanosecond and picosecond pulses on aluminoborosilicate glass. Comparison of trepanned holes produced in glass using nanosecond and picosecond pulses revealed that the wall surfaces and the entrance holes produced by picosecond pulses were smoother than those by nanosecond ones. The picosecond laser provided high quality processing at lower speeds compared to nanosecond [16]. Although Ramil et al., 2008, demonstrated the feasibility of micromachining of soda-lime glass using the third harmonic of nanosecond Nd: YVO_4 laser [17], laser cutting of glass was presented by Loeschner et al., 2008. The investigations were carried out with a short nanosecond pulsed Nd: YVO_4 slab laser and a high repetition rate femtosecond laser. Irradiation of the material with short nanosecond pulses leads to the formation of micro defects [10].

4. Laser Micromachining of Silicon

Silicon is one of the most investigated materials. It is widely used in semiconductor industry and it is very often exploited as a substrate for many electronic devices. Polycrystalline and amorphous silicon is suitable for solar cell technology and in various chips. Many studies have compared fs- and ns-laser technology and it was established that short pulses, shorter than 15 ns and wavelength in UV region, reduce thermal effects (HAZ or deposition of molten material). Picosecond lasers have also found a number of applications in solar cells and other silicon-based applications [16, 18].

The precision of laser microfabrication is influenced by absorption, mechanism of heat transport, and energy density of the laser radiation. Figure 1 shows absorption of silicon as a function of wavelength at 25°C for a 600 μm thick sample. The graph demonstrated that the radiation with wavelength below about 380 nm is absorbed by silicon significantly better.

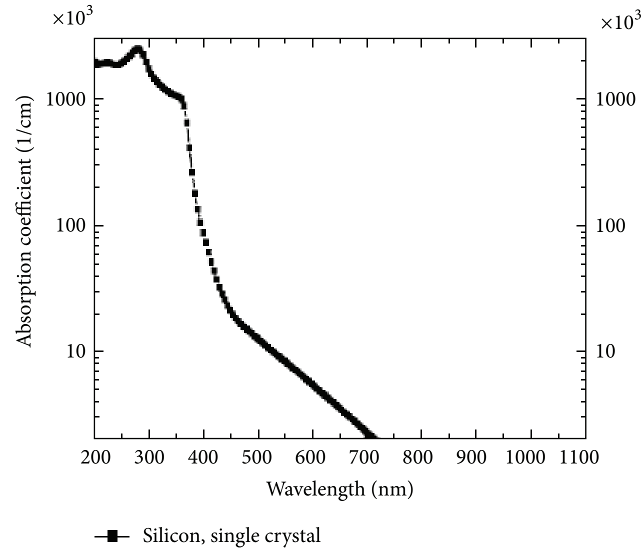

Figure 1: Absorption coefficient of silicon depending on the wavelength at 25°C for a 600 μm thick polished sample [18].

As the temperature rises, it is expected that absorption will increase as the material becomes molten [18].

Klotzbach et al., 2011, observed creation of 15 μm wide craters surrounded by 40 μm wide area of splashed melt after the application of one pulse of radiation of Nd: YAG laser emitting at 355 nm. They also focused on percussion drilling of silicon and drilled holes with diameter of 25 μm. Silicon cutting was performed by Nd: YAG lasers emitting at 355 nm and 532 nm. They found that cutting with shorter wavelength reduced the formation of melt phase and thus improved the quality of the cut [18]. Single-shot laser ablation of monocrystalline silicon with a nanosecond Nd: YAG laser at 355 nm and energy density from 10^9 J·cm^{-2} to 10^{11} J·cm^{-2} was also investigated by Karnakis, 2005 [19]. Formed craters were measured and their morphologies were analyzed. The study reported that the depth of craters increased with the increasing power density. Significant laser induced melting and droplets were presented around crater rims.

Ablation of silicon was investigated using a 1064 nm pulsed fiber laser, with pulse energy up to 0.5 mJ, peak powers up to 10 kW, and pulse widths from 10 ns to 250 ns by Hendow and Shakir, 2010. They indicated that pulses with high peak powers caused the decrease of penetration depths, while longer pulses, with lower peak powers, had a higher material removal rate with deeper scribes as ablation was accompanied by preheating of the surface, melting of the material, and a shock wave that ejected the molten material [20]. Herbst et al., 2001, investigated machining silicon wafers with thickness up to 1 mm using a diode-pumped-solid-state laser that delivered short pulses of about 15 ns at 355 nm wavelength. The results showed a small HAZ with little evidence of microcracking. But even a small increase in laser pulse width could increase the thermal damage of silicon that could be seen as an enlarged amount of the redeposited material in and around the hole [21].

Lee et al., 2009, also focused on silicon processing and optically compared drilled holes created by picosecond and nanosecond UV laser systems. The resulting hole formed by picosecond laser was cleaner on the surface and the internal wall was smoother. The nanosecond hole had some oxide residue on the top and on the wall surface. The picosecond laser provided high quality processing at lower speeds comparing to nanosecond [16]. No chipping and HAZ along the cut produced by picosecond emitting at 515 nm were confirmed also by Weiler et al., 2008 [22]. Bärsch et al., 2003, Karnakis et al., 2005, and Rizvi et al., 2011, reported that ultrashort pulses are the best choice for machining silicon as it provides excellent results, high quality, precision, and no damage [23–25]. Ren et al., 2005, and Kruusing, 2004, realized ablation of silicon under water. Their results showed that ablation in the water is faster than in the air and is characterized by small HAZ and no mechanical damage [26, 27].

5. Laser Micromachining of Ceramics

A variety of ceramic materials such as zirconium and aluminum carbide are widely used in the field of microelectronics and in other MEMS-type devices. The test devices for integrated circuits, substrates for sensors and detectors, microcavity structures inside biomedical or chemical diagnostics, and transducers are possible applications.

Several types of lasers, for example, CO_2, Nd: YAG, and excimer lasers, are used for machining of structural ceramics. Pulsed lasers are preferred for machining ceramics due to better and more effective control of process parameters compared to continuous wave mode. Four physical phenomena can be distinguished when the laser beam is incident on the ceramic surface. These are reflection, absorption, scattering, and transmission. Absorption, crucial of all the phenomena, is described as the interaction of electromagnetic radiation with the electrons of the material. It depends on both the wavelength and the spectral absorptivity characteristics of ceramics being machined (e.g., reflection coefficient). The absorptivity is also influenced by the orientation of the ceramic surface with respect to the beam direction and reaches a maximum value for angles of incidence above 80°. Thermal conductivity of structural ceramics is generally smaller than that of most metals; so radiation absorption sets in faster. Absorbed energy is converted into heat and its subsequent conduction into the material establishes the temperature distribution within the material that in turn affects machining time and depth of cavity [28].

Ablation occurs when laser energy exceeds the characteristic threshold that represents the minimum energy required to remove the material by ablation. Laser machining of ceramics is quite hard because of large scattering that appears for many common laser wavelengths, which restricts localized energy absorption. The ablation threshold is higher for metals (factor of 2–10) and more clearly defined. A combination of short pulses and short wavelengths usually leads to the best results and in many ceramics, such as alumina and silicon nitride melting, is not evident. Thermal stresses during micromachining can result in cracking, so that optimized processing parameters should be set to keep the heat input to the bulk material low and thus to avoid cracks formation. Mostly, this is ensured by precluding the formation of intense laser induced plasma. Micromachining with longer pulse lasers (micro- and millisecond regime) includes melting in material removal mechanism. This method promises processing with very high removal rates but causes a creation of glassy layer that is often regarded as the source of microcracks [4].

Nedialkov et al., 2003, studied laser ablation of alumina, aluminum nitride, and silicon nitride using nanosecond Nd: YAG laser with different wavelengths. They found that IR radiation provided the highest ablation rate. Drilling holes in Si_3N_4 had the best quality in respect to the debris and roundness compared to other ceramics [29]. Liu et al., 2007, presented ultrafast structuring of ceramics using femtosecond laser, whereas Karnakis et al., 2006, used nanosecond copper vapor laser (511 nm) and picosecond Nd: YVO_4 (1064 nm) to drill holes in ceramic materials. They reported that both nanosecond and picosecond lasers can be used for high quality laser micromilling of ceramics that is difficult to machine with ultrahigh precision using conventional methods. Both laser types were capable of excellent surface finish with relatively high material removal rates [30, 31].

Liu et al., 2007, confirmed precise, melt-free ultrafast laser microstructuring of ceramic alumina. Wang et al., 2010, also showed the results of femtosecond laser drilling of alumina ceramic substrate. They investigated the effects of various laser parameters such as different focus position, traverse speed, drilling pattern, and pausing time on the drilled holes quality, HAZ, holes circularity, or debris production. They demonstrated high-quality laser drilling with clean surface, no cracks, no recast layer, and no delamination which can be used in manufacturing of electronic devices [32]. Ho et al., 2010 created blind and through micro holes by percussion drilling as well as trepanning drilling using picosecond Nd: YLF laser. The diameters of the holes were in the range of 20 μm–1000 μm [33]. Perrie et al., 2005, and Kim et al., 2008 and 2009, realized microfabrication of alumina and nitride ceramics using femtosecond lasers. Perrie et al., 2005, compared femtosecond microstructuring of alumina ceramics with nanosecond UV processing. Femtosecond pulses caused excellent edge quality and no discoloration of the treated surface, unlike those produced by nanosecond UV pulses. Kim et al., 2008, drilled micro holes with sub-100 μm diameter, whereas Kim et al., 2009, investigated aluminum oxide and aluminum nitride ablation characteristics, specifically the threshold fluence, incubation effect, and ablation rate. The ablation characteristics of the two ceramics showed similar trends except for surface morphologies, which revealed virtually no melting in Al_2O_3 but clear evidence of melting for AlN [34–36]. Bärsch et al., 2007, studied microstructuring of zirconium ceramics by femtosecond laser, whereas Zeng et al., 2007, used nanosecond Nd: YAG laser [37, 38].

6. Conclusion

In this paper we report the mechanisms of laser micromachining of materials. It is very promising technique in many industries. It is possible to machine various materials using lasers with different pulse length. In most cases ultrafast lasers bring better resolution than lasers with longer pulses. We concluded that ultrafast micromachining is characterized by excellent quality of treated materials, high precision of the process, small HAZ, and production of no microcracks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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