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Through-the-thickness selective laser ablation of ceramic coatings on soda-lime glass

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ABSTRACT

This paper investigates through-thickness laser ablation characteristics of ceramic coating deposited on the bottom surface of the soda-lime glass substrate. Experimental studies were focused on determining the effects of energy density, hatch distance and coating color on the ablation completion index. Effect of glass thickness was also tested to verify the robustness of the designed process. Up to a certain threshold limit, the ablation completion index is energy-limited and has an inverse U-shape relationship with the energy density input. Since greater hatch distance means faster ablation and lesser ablation completion index, there must be a tradeoff between ablation completion index and hatch distance. During through-thickness laser ablation of ceramic coating, energy density input should be in the range of 0.049 J/mm^2 – 0.251 J/mm^2 for black ceramic coating and 0.112 J/mm^2 – 0.251 J/mm^2 for other coatings. Finally, the designed process is capable of ablating the ceramic coating effectively through varied thickness.

1. Introduction

The glass container, the largest sector of the European glass industries, covers nearly 70% of the total EU glass production. It provides European and worldwide customer base with a wide variety of glass packaging products for food and beverages as well as flacons for perfumery, cosmetics, and pharmacy. A smaller but not less representative industrial sector of the glass production is nowadays manufacturing high-value components for optoelectronics [1], optical fibers for telecommunications [2] and OLEDs [3]. Also, these glass industries are involved in the construction of the photovoltaic cells [4], microfluidic devices for biochemical use [5], bone grafts [6] and production of the lens [7]. Soda-lime-silica glass compositions constitute nearly 90% of the glass manufactured around the world. This family of glasses includes various glass compositions utilized to make bottles and jars, decorative tableware and accessories, and windowpanes. Its preponderance is due to the facts that it is relatively cheap to manufacture, chemically stable, reasonably hard, and extremely workable.

In recent times, the production of microelectronics and other MEMS-type devices extensively used a variety of ceramic materials such as zirconium and aluminum carbide. Their possible applications also include substrates for sensors and detectors, microcavity structures inside biomedical or chemical diagnostics, and the test devices for integrated circuits, etc. Besides, marking ceramic coatings of the different chemical composition, even deposited on glass substrates is being commonly observed in various applications such as optoelectronics, microfluidics and fashion industries. In most of these cases, the glass component design requires removing the coating on functional surfaces which might reside in recessed areas which are commonly not accessible by conventional techniques based on mechanical removal. The brittle and hard nature of glass imposes several drawbacks in conventional machining and micro-machining: workpiece cracking and extreme tool wear are just an example of the technical difficulties which hinder a reliable production on a large scale. For this reason, non-conventional techniques based on energy intensification have also been tested such as Spark Assisted Chemical Engraving [8], Ion Beam Machining [9] and lasers. Among all, lasers are gaining scientific and industrial interest because of their flexibility in performing localized processing of the ceramic coating without damaging the glass substrate.

Different types of lasers, e.g. CO_2, Nd: YAG, vanadate and excimer lasers were used in the literature for ablation of ceramics. Despite to long wavelengths with emission in the IR whose removal mechanism is based on heat transfer, laser radiation in the UV range can also remove materials by photo-chemical interaction [10]. Besides, due to their better and more effective control of process parameters, pulsed lasers are preferred for ablating ceramics to other continuous-wave lasers. When the laser beam is incident on the ceramic surface, the four physical phenomena, e.g. reflection, absorption, scattering, and transmission are distinctly observed. Absorption, vital of all the phenomena,

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depends on both the wavelength and the spectral absorptivity characteristics of ceramics being machined. The absorptivity is again affected by the alignment of the ceramic surface with respect to the beam direction and its value is found maximum for angles of incidence above 80°. During ablation of ceramics with ns-ms pulsed industrial IR lasers (Nd: YAG or fiber lasers), the laser-material interaction leads to a thermal phenomenon: absorbed energy is transformed into heat and its subsequent conduction into the material forms the temperature distribution within the material, which ultimately influences machining time and removal depth [11].

During laser-induced back ablation or through-the-thickness laser ablation, a pulsed laser propagates through a transparent substrate to a thin-film of metal or metal coating developed on the opposite side of the substrate and then interacts with the metal at the metal-substrate interface resulting in ablation of metal coatings from the substrate. In recent years, this ablation process is being used in surface patterning [12], trace element injection in plasma environments [13] and as a source of metal vapor targets for laser plasma studies [14]. From the literatures [15,16], it appears that through-the-thickness laser ablation approach shows its promises mainly due to two reasons: as compared to direct ablation, the pulse energies required for the entire removal of the film are much lower and the process speeds achievements are considerably higher. Moreover, these findings have been confirmed by the first report of using such a through-the-thickness laser ablation process in mass-production [17].

Besides, the choice of the process parameters is particularly critical in order to ablate ceramic coatings on glass substrate precisely with the laser since it makes the difference between the machining operations to be done. The laser source must have a suitable wavelength and pulse duration which allows for a refined ablation of the ceramic coating without damaging the glass substrate. Because of the absorption spectrum of soda-lime glass and its first absorption peak at about 310 nm [18], an Nd: YAG laser at wavelengths of 266 nm and 355 nm (4th and 3rd harmonic respectively), and a far infrared CO_2 laser of 10.6 μm wavelength can be used for marking [19]. Nonetheless, it is reported that the soda-lime glass which is almost transparent to the near-R laser irradiation, with an absorbance of about 10% at the wavelength of 1064 nm [20], can be internally damaged by femtosecond laser pulses [21]. This special feature of laser glass interaction, therefore, allows for the employment of a pulsed fiber-vanadate or Nd: YAG lasers for ablating ceramic coatings even through the thickness of a glass substrate. This procedure can be used to perform ablation on the inner wall of a cavity, which is unattainable with other lasers and/or conventional methods. The background idea of the present research thus shows the similarities with the laser induced forward transfer (LIFT) technique [22]: both processes use a pulsed laser to remove material, originally precoated as a thin-film on a transparent support. In the case of LIFT this extremely small quantity of material is transferred from that support to a selected target substrate. LIFT is used to deposit a variety of solid thin-films, thick-films through the repetitive transfer of thin-films, multilayered structures through the transfer of appropriately layered pre-coated films, and metal silicon alloys. Although LIFT was originally developed to operate with solid films, it has been demonstrated that deposition is also viable from liquid films. In this case the transferred material is not vaporized; rather, a small amount of liquid is directly ejected from the film to the receptor substrate, where it deposits in the form of a micro droplet [23].

Considering the diversified applications of ceramic materials and the ablation capability of pulsed lasers, many researchers were motivated to study the ablation characteristics of ceramic materials using pulsed lasers of different wavelengths. Mayer and Busch [24] conducted the first fundamental studies of "laser-induced back ablation" of thin metal films using ultra-short laser pulses. However, their main goal was to study the plasma during laser-metal-vapor interaction [25]. Bullock et al. [24,26] investigated the laser-induced back side ablation of thin aluminum film using both ns and ps pulses. More recently, Ashitkov et al. [27,28] reported an experimental study on laser-induced backside ablation of Al films with high temporal resolution and theoretical considerations as well. Ho et al. [29] analytically investigated the ablation characteristics of aluminum nitride and aluminum oxide irradiated by an ultra-short pulse laser. It was found that the distinctions of properties such as thermal diffusivity, optical penetration depth, thermal expansion coefficient and reflectivity resulted in the differences in the ablated depth per pulse between aluminum nitride and aluminum oxide. Nedialkov et al. [30] investigated the ablation characteristics of various ceramic materials (alumina, aluminum nitride, and silicon nitride) irradiated by a nanosecond pulsed Nd: YAG laser of different wavelengths. Infrared radiation was found to have the highest ablation rate [20]. Karnakis et al. [31] used both nanosecond copper vapor (511 nm) and picosecond Nd: YVO_4 (1064 nm) lasers for microdrilling of ceramic materials. Both nanosecond and picosecond lasers were reported to be useful for high-quality laser microdrilling of ceramics as these lasers were capable of producing holes with an excellent surface finish at relatively high material removal rates [31,32]. Wang et al. [33] investigated the effects of various laser parameters such as focus position, traverse speed, drilling pattern, and pausing time on the drilled hole quality, HAZ, and debris production. The results showed high-quality laser drilling with a clean surface, no cracks, no recast layer and no delamination. Perrie et al. [34] and Kim et al. [35,36] made microfabrication of alumina and nitride ceramics possible with femtosecond lasers. Moreover, Perrie et al. [34] found the edge quality excellent with no discoloration for femtosecond pulses as compared to those produced by nanosecond UV pulses. Kim et al. [36] examined various ablation characteristics of aluminum oxide and aluminum nitride ceramics. The ablation rate of the two ceramics depicted similar tendencies except for surface morphologies [34 – 36].

1.1. Research objectives

As seen from the literature, the container glass encompasses almost two-third of the total EU glass production and 90% of the glass manufactured around the world is made of soda-lime-silica glass. Apart from the many applications in biomedical and electronic devices, the use of ceramic coatings with different chemical composition is becoming a frequent procedure to locally vary physical properties of a component (e.g. thermal and electrical conductivity, etc.). Pulsed laser sources are found suitable for the ablation of ceramic and other materials, and the ablation characteristics of the ceramic materials change with their properties. During ceramic ablation, photo-thermal process dominates over the photo-chemistry process for the pulsed vanadate laser to be used in this study. Moreover, the soda-lime glass substrate is almost transparent at this wavelength. Through-the-thickness laser ablation technique is found to be promising in removing various materials coated on the back side of the glass substrates or in similar industrial applications. This article, therefore, investigates through-the-thickness laser ablation characteristics of ceramic material coated on the bottom surface of the glass substrate using a nanosecond pulsed vanadate laser. The study is focused on:

1. determining the effects of energy density, hatch distance and coating color on the laser ablation characteristics, specifically the ablation completion index of the aluminum oxide ceramic coating on the backside of the soda-lime glass substrate,
2. determining the effects of glass substrate thickness on the laser ablation characteristics of the aluminum oxide ceramic coating on the backside of the soda-lime glass substrate with a view to verifying the robustness of the designed ablation process, and
3. finally, determining the optimal set of input parameters for a real industrial case, i.e. for the ablation of ceramic coating made on the inner wall of a soda-lime glass substrate for high perfumery