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EFFECTS OF LASER PROCESS PARAMETERS ON Al_2O_3-TIC CERAMIC USING A NANOSECOND PULSED LASER

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Abstract. *Laser surface texturing (LST) is a potential technique to improve the load capacity, friction properties, and wear resistance of ceramic components. However, to obtain product quality and process efficiency in laser processing of ceramics, the optimization of laser process parameters is essential. This paper reports a study on the effects of laser parameters on the laser surface texturing of the structural ceramic* Al_2O_3*-TiC with a nanosecond pulsed laser. Factorial design of experiments was performed. The surface morphology and width of the ablated region generated with different pulse durations, laser powers, and pulse overlaps are analyzed by scanning electron microscope (SEM). Laser parameters were decisive in the ablated zone. The effect of pulse duration in ablated region width is higher than the effect of laser power and pulse overlap. The increase in pulse duration, laser power, and pulse overlap led to the formation of continuous grooves due to higher laser energy that causes higher material removal. Microcracks were formed even in the least intense energy condition. The results obtained are a contribution to a better selection of laser parameters for laser processing of* Al_2O_3 *based ceramic materials.*

Keywords: *Laser surface texturing. Laser micromachining. Nanosecond pulsed laser.* Al_2O_3*-TiC ceramic.*

1. INTRODUCTION

Excellent properties like high hardness, thermal resistance, and chemical stability have increased the use of structural ceramics such as alumina (aluminum oxide, Al_2O_3) for several electronic, automotive, and medical applications (Tuersley et al., 1994). Al_2O_3 is applied in components like seals, piston rings, bearings, valves, medical implants, tools, and substrates in hybrid circuits. However, the applications of alumina are limited by its intrinsic brittleness. Hence, TiC (titanium carbide) is commonly combined to Al_2O_3 to improve the strength, hardness, and toughness of the Al_2O_3 based ceramics (Fei et al., 2014; Kumar et al., 2018). Nevertheless, the Al_2O_3 based ceramics exhibit high friction coefficient and low adhesion resistance when in contact with ceramics or metallic materials, therefore, techniques to improve the friction and wear properties of the ceramic materials has been researched (Xing et al., 2018).

Surface texturing is an efficient and widely used approach to modify the interaction between surfaces for better lubrication, controlled friction, and enhanced wear resistance of engineering materials (Mao et al., 2020). Several techniques can be used to generate textures on the component surface, like thermal energy-based micromachining, mechanical micromachining, and electrochemical micromachining (Ranjan and Hiremath, 2019; Sharma and Pandey, 2016). Among these techniques, the laser surface texturing (LST) stands out since the advantages like better surface topography and lesser contamination of surface in comparison to other methods (Gajrani and Sankar, 2017; Ranjan and Hiremath, 2019). In addition, hard and brittle materials (such as ceramics) are difficult to processing with mechanical micromachining, meanwhile, LST is suitable for micromachining of these materials (Samant and Dahotre, 2009). Since laser is basically a thermal process, the efficiency of micromachining depends on the thermal and the optical properties of the material. Likewise, laser is non-contact process, so energy transfer from the laser to the ceramic through irradiation eliminates cutting forces, tool wear, and machine vibration (Chryssolouris, 1991). However, LST also has some drawbacks such as Heat Affected Zones (HAZ), periodical structures, and surface defects (Wan and Xiong, 2008).

The understanding of laser–material interactions is an essential topic to the micromachining of structural ceramics. Several studies observed that the laser process parameters have an important effect on the quality control and dimensional accuracy of laser-textured ceramic products (Li et al., 2017; Mohammed et al., 2019; Vora et al., 2013; Xing et al., 2013; Xing et al., 2014; Xing et al., 2018). An evaluation of the effects of laser process parameters on Al_2O_3-TiC ceramic material was developed by Xing et al. (2018) using a nanosecond pulsed laser. The authors related that laser parameters strongly affect the surface quality and the dimensions of micro-channels: the width and depth of microchannels increase within a certain range with higher laser power, lower scanning speed, higher frequency, and higher number of overscans, due to the higher material removal induced by higher energy accumulation on the surface. On the other hand, excessive energy accumulation causes the reduction of microchannels or causes the formation of larger amounts of recast layers surrounding the microchannels. Moreover, energy accumulation leads to thermal shock that generates microcracks and pores at the bottoms and brims of the channels. Employing a femtosecond laser, Xing et al. (2013) reported that microchannels on Al_2O_3-TiC are not formed by low pulse energy at high scanning speeds or high pulse energy at low scanning speeds. With low pulse energy at high scanning speeds, there are some bumps on the ceramic surfaces, while some micropores are produced on the surfaces with high pulse energy at low scanning speed. High pulse energy, low scanning speed, and high number of overscans, result in large surface roughness and deep ablation.

Mohammed et al. (2019) found that high pulse overlaps and high fluences give rise to V-shaped microchannels in Al_2O_3 ceramic, because in these conditions there is a higher energy density, resulting in a high volume of molten material ejected out of the channel through the cross-section. This molten material corrodes the upper edge and causes a wider opening of the channel. Furthermore, at higher energy levels, due to the greater depth of the formed channel, part of the molten material is not ejected and remains at the bottom of the channel. This suggests that low material removal per scan values with a greater number of laser scans are recommended to achieve the desired depth. Li et al. (2017) described that crater depth increases linearly with the increase of pulse energy (each pulse removes approximately the same depth of material from the crater), while the crater diameter increases sharply at the initial stage and then paces down in the micromachining of Al_2O_3 with a nanosecond pulsed laser. Vora et al. (2013) affirmed that the increase of multiple laser pulses (millisecond pulses) causes an increase of material removal (Al_2O_3) due to evaporation (increase crater depth) and an increase of the liquid expulsion created by the recoil pressure (increases the pileup height). However, after a critical crater depth (~260 µm), the magnitude of the recoil pressure is insufficient to eject a significant amount of liquid material out of the crater and hence the liquid material solidifies inside the crater wall, leading to the formation of a typical teardrop shape topography. Moreover, the increase in the pulse rate and/or the increase in the average laser energy density causes an increase in the surface roughness of the ceramic.

According to Umer et al. (2017), to obtain better product quality and process efficiency with laser micromachining of ceramics, the optimization of various process parameters to achieve multiple objectives is indispensable. An inadequate selection of laser parameters in LST of ceramics usually leads to problems like changes in surface morphology due to phase transformation, recast layers due to cooling effect, microcrack formation due to residual stresses, and heat affected zones (Burck and Wiegel, 1995). In this context, this research aims to evaluate the effects of laser parameters (laser pulse duration, laser power, and pulse overlap) on the surface texturing of a structural ceramic Al_2O_3-TiC using a nanosecond pulsed laser.

2. METHODOLOGY

The sample material was a mixed-ceramic composed by Al_2O_3 (70%) + TiC (29%) + others (1%). Figure 1 shows the micrography and the corresponding EDX (energy dispersive X-ray) analyses of the material. The dark-grey zone is Al_2O_3 particles while the light-grey area is TiC particles.

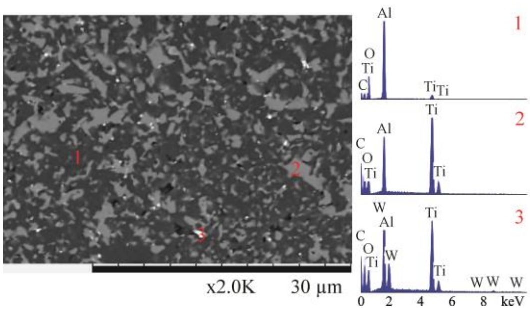

Figure 1. SEM micrography and EDX analyses of Al_2O_3-TiC ceramic.

The experiments were carried out on a nanosecond pulsed ytterbium fiber laser, model YLPN-1-1x120-50-M manufactured by IPG, with a wavelength of 1064 nm, a maximum average power of 50 W, and beam quality (M^2) of 1.8. The focus and scan of the laser beam were performed with two mirrors galvanometric scanner with f-θ lens (f = 170 mm), Aerotech AGV-14HPO. The angle of incidence of the laser beam was 90° with the surface of the samples.

To analyze the effect of laser parameters on the ablated region, a full factorial design with 3 factors (pulse duration, laser power, and pulse overlap) with different levels was performed, according to shown in Tab. 1. The values of pulse duration were defined based on the laser settings used in this experiment. All experiments consisted of a single scan and the pulse repetition rate (PRR) was fixed (PRR = 120 kHz). Morphology and width of the ablated region were examined using scanning electron microscopy (SEM) by HITACHI, model TM3030. The software ImageJ was used to measure the ablated region width.

Table 1. Factors and respective levels analyzed.

Laser power (W)						
10		30		50		
Pulse duration (ns)						
2	8	16	30	50	120	
Pulse overlap (%)						
70.0	80.0	85.0	90.0	92.5	95.0	97.5

The scan speed (v) to obtain the pulse overlap (o) for each combination of pulse duration and laser power was determined according to Eq. (1). Therefore, firstly, a full factorial design with two factors: pulse duration and laser power, with six levels (2, 8, 16, 30, 50, and 120 ns) and three levels (10, 30, and 50 W), respectively, were performed to determine the single spot ablated diameter (w_p) when used the pulse repetition rate (PRR) of 120 kHz (Fig. 2). At the combination of 2 ns with 10 W the w_p was not visible in the SEM images, thus, in this case was considered the w_p of 2 ns + 30 W to calculated v.

$$o = 1 - v/(2 * PRR * w_p) \quad (1)$$

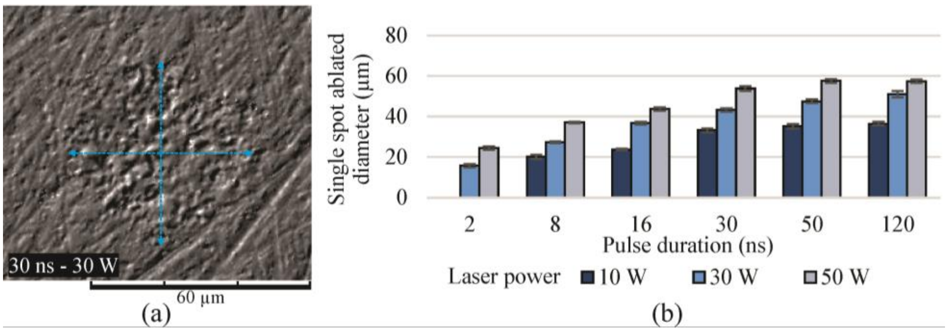

Figure 2. a) Example of single spot ablated on Al_2O_3-TiC surface (30 ns + 30 W) and b) Single spot ablated diameter (w_p) for each combination of laser pulse duration and laser power (pulse repetition rate = 120 kHz).

3. RESULTS AND DISCUSSION

The three laser parameters tested (pulse duration, laser power, and pulse overlap) affected the morphology of the laser ablated region (Fig. 3). In the shortest pulse duration (2 ns) the laser ablation hardly occurred. It is observed in Fig. 3a for pulse duration of 2 ns only isolates and small surface changes in the region irradiated by the laser; these results were obtained to all laser parameters combinations when used the pulse duration of 2 ns. Increasing the pulse duration, ablated region has become more intense and from 30 ns the ablated surface has become more regular. Moreover, the increase in pulse duration occasioned the formation of continuous grooves. The rise in laser power and pulse overlap caused the same tendency of the increase in pulse duration: the higher the laser power and/or pulse overlap, the more homogeneous was the ablated surface and higher the tendency to generated continuous grooves (Fig. 3b and Fig. 3c). However, even with the increase in laser parameters (i.e., increase in the laser energy intensity), the application of only one scan was not enough to create grooves with significant depth, indicating that only one scan is not enough to cause significant material removal.

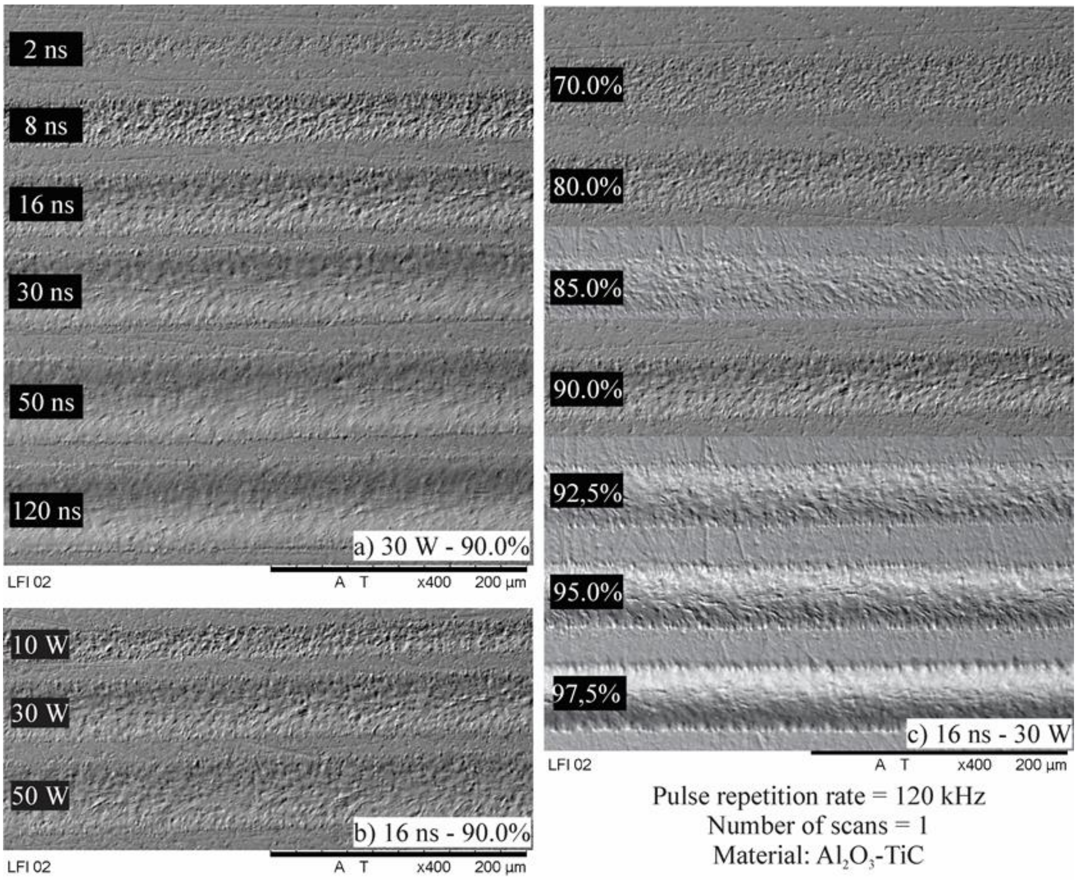

Figure 3. Morphology of Al_2O_3-TiC surface processed with different a) pulse durations b) laser powers, and c) pulse overlaps.

Morphology images (Fig. 4) revealed the existence of a microcracks network in all conditions (except at 2 ns + 10 W, in this condition microcracks were not identified since the ablated region was not visible in SEM images). The microcracks network rises with the increase in the laser parameters values (pulse duration, laser power, and pulse overlap) due to the higher intensity of laser energy. The intense interaction between the strong thermal nature of laser beam and the ceramic causes thermal damage to the material because of its high hardness, high brittleness, and low thermal conductivity (Li et al., 2017). The formation of microcracks occurs because of the high laser energy that promotes thermal shock and tensile stresses in ceramic materials (Xing et al., 2018). Although the textured ceramic material has additions of TiC that promote increment in thermal shock resistance, the main phase is Al_2O_3 (70%). The alumina is a material with high thermal expansion coefficient and, consequently, low thermal shock resistance (Richerson and Lee, 2018).

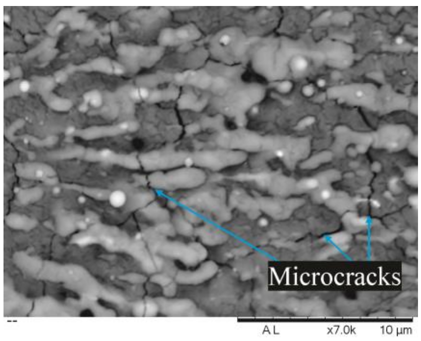

Figure 4. Microcracks network generated by laser process in Al_2O_3-TiC ceramic (pulse duration = 16 ns, laser power = 30 W, pulse overlap = 90.0%, pulse repetition rate = 120 kHz and number of scans = 1).

During the laser process, the machined material undergoes heating and melting, generating high-temperature gradients in the machined section. Consequently, high thermal stress levels are generated in the laser irradiated area

(Yilbas et al., 2016). When the maximum thermal stress is higher than the material fracture stress, microcracks are induced and formed, causing distributed multidirectional microcracks in the ceramic cut surface area (Yilbas et al., 2013). A simulation of laser-controlled thermal stress cutting of alumina realized by Hu et al. (2010) indicated that normal stress on the laser cutting path undergoes a process of no stress → tensile stress → compressive stress → tensile stress → no stress during the cutting process until the microcrack grows. Moreover, the authors related that maximum temperature is proportional to the laser power and approximately inverse to the cutting speed, thus, when the laser power increases or the scan speed decreases, the microcrack initiates earlier and becomes larger due to the excessive tensile stress. According to Xiaohong et al. (2014), microcracks generated by laser can severely reduce the mechanical properties and surface integrity of the alumina. Gomes et al. (2015) reported that the removal rate on alumina with a nanosecond pulsed laser is indirectly proportional to the final material strength, pointing out that this type of laser process causes considerable surface defects, even for moderate beam fluences.

As noted on the topography images (Fig. 3), the width of the ablated area is influenced by laser parameters. The combination of laser parameters tested generated ablated region width ranging from 13.43 ± 2.50 µm (8 ns + 10 W + 70.0%) to 88.00 ± 1.56 µm (in the most intense condition, i.e., 120 ns + 50 W + 97.5%). Figure 5 presents ablated region width in function of the pulse duration, laser power, and pulse overlap. Ablated region width increased with the increase of pulse duration, laser power, and pulse overlap.

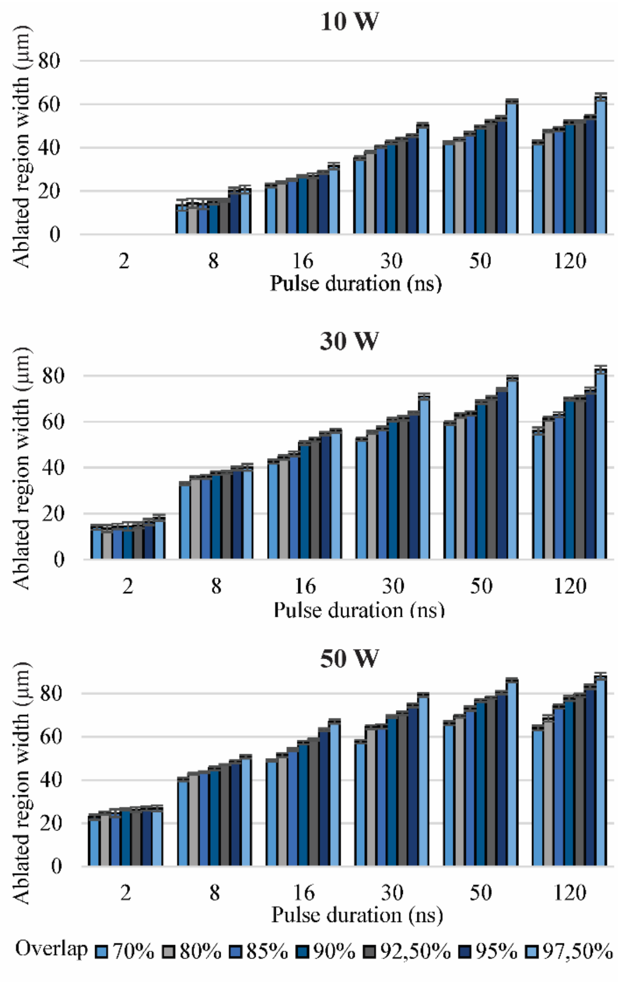

Figure 5. Ablated region width variation with different laser parameters: pulse duration, laser power, and pulse overlap (pulse repetition rate = 120 kHz, number of scans = 1).

The three-way ANOVA (analysis of variance with three factors) indicated that the three laser parameters (pulse duration, laser power, and pulse overlap) and the interactions of these parameters significantly affected the ablated region width (all P-values < 0.000). The ablated region width dependence on each laser parameter is summarized in Fig. 6. Since that greater the rate of change in ablated region width as a function of the change in factor level, the greater is the factor influence, it is observed that laser pulse duration is the parameter that most influenced the ablated region width. The effect of pulse overlap in ablated region width was a lot smaller than the effect of pulse duration and laser power.

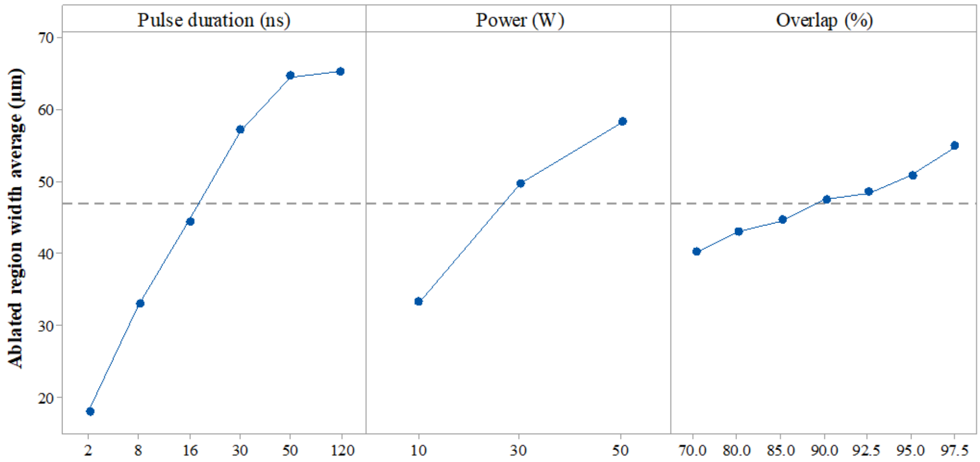

Figure 6. Ablated region width dependence on pulse duration, laser power, and pulse overlap.

The pulse duration effect in ablated region width was higher at shorter pulse durations (between 2 ns and 50 ns the ablated region width increased from 18.01 to 64.58 µm), whereas from 50 ns the ablated region width hardly changed. Likewise, regarding the laser power, it was found that between 10 and 30 W the ablated region width undergoes an average increase of 49.25%, and between 30 and 50 W this increase is only 17.11%. According to Mohammed et al. (2019), the ablated region width change is higher in the lower fluence range since the energy absorption change into the material is higher at lower fluence, while in the high fluence range the energy absorption reaches saturation limit leads to a minimal variation in ablated region width. Pulse overlap influence in ablated region width is low: at the higher overlap (97.5%) the width is only 36.01% greater than in the lower overlap (70.0%). It is important to note that in this study the minimum pulse overlap is considerably high (70.0%) and the increment from one level to another level is small. Pulse overlap indicates the area in common between two adjacent pulses, so it is an indication of how close a pulse is in relation to the previous one. Umer et al. (2017) affirmed that pulse overlap is more important to increase the groove depth than the groove width. These results suggest that the pulse duration and laser power are decisive parameters to define the texture's width, however, to produce textures with depth is necessary to use a higher number of scans.

4. CONCLUSIONS

Based on the results obtained in these experiments on the textured surface of Al_2O_3-TiC ceramic with a nanosecond pulsed laser, the following conclusions can be drawn:

- The morphology and the dimensions of the ablated region are significantly dependent on laser parameters. The increase of pulse duration, laser power, and pulse overlap causes the increase of microcracks and width of the ablated region due to the higher energy accumulation per unit surface.
- Even at the lowest pulse duration, laser power, and pulse overlap, the laser energy induces the creation of microcracks in the ceramic material surface.
- The pulse duration is the laser parameter with the greatest effect on the ablated region width. However, from pulse duration of 50 ns the ablated region width is less affected by the pulse duration.
- The pulse overlap does not change a lot the ablated region width, but the pulse overlap increase generates continuous grooves.
- Only one laser scan does not promote high material removal. To create textures with higher depth is necessary to use a higher number of scans.

The results related in this paper can be a direction to define better laser parameters to the fabrication of textures on Al_2O_3 based ceramic materials.

5. ACKNOWLEDGEMENTS

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