Koc. J. Sci. Eng., 7(1): (2024) 81-88 https://doi.org/10.34088/kojose.1363471

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

The Effect of Laser Power and Laser Exposure Time for Cavity Created on Al_2O_3 Ceramic Surface

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Article Info

Research paper

Received : *September 20, 2023*
Accepted : *January 17, 2024*

Keywords

Al_2O_3 ceramic
Laser machining
Laser parameters
Surface texture
CO_2 laser

Abstract

Al_2O_3 ceramic materials have many industrial applications, especially because they are wear-resistant. In this study, dimples of different sizes were formed on the surface of ceramic plates with a CO_2 laser. The effects of laser power and laser exposure time on the dimensions of the cavity were investigated. For this purpose, laser powers of 40, 52, 65, 78, 91, and 105 W were applied to the ceramic material for 10 seconds. In addition, 80 W laser power was kept constant and the laser beam was sent to the material for 1, 5, 10, 15, 20, 25, and 30 seconds. High-resolution images of the resulting cavities were taken with an optical microscope. Using the images, the dimensions of the cavities were measured and the effects of laser power and laser exposure time on the cavity geometry were observed. The effects of both laser power and laser exposure duration on the cavity and Heat Affected Zone (HAZ) regions showed similar characteristics. The size of the cavities and HAZ increased almost linearly as laser power increased. However, when the effect of laser exposure duration was analyzed, the increase in cavity sizes slowed down after the exposure duration exceeded 10 s. When the laser exposure duration exceeded 15 seconds, it was observed that the dimensions of the cavities did not change.

1. Introduction

Al_2O_3 ceramics, also known as alumina ceramics or aluminum oxide ceramics, is a type of ceramic material composed mainly of aluminum oxide (Al_2O_3) molecules Alumina is a compound of aluminum and oxygen and is widely found in nature. Alumina ceramics are known for their excellent combination of mechanical, thermal, and electrical properties, making them valuable materials in a wide range of industrial and technological applications [1].

Alumina (Al_2O_3) ceramics are widely used in various technical applications due to their desirable properties. The surface characteristics of Al_2O_3 ceramics play a crucial role in determining their mechanical and bonding properties [2]. demonstrated that the surface roughness of Al_2O_3 substrates significantly influences the bond strength of Ti splats deposited on them [3]. This finding underscores the importance of surface quality in determining the bonding strength of materials to Al_2O_3 ceramics. Furthermore, highlighted the influence of surface properties on bonding quality, indicating that the hardness of the copper powders, rather than the Al_2O_3 surface roughness, significantly affects the bonding quality between the copper coating and the Al_2O_3 layer [4]. Moreover, the mechanical properties of Al_2O_3-based composites can be tailored by varying the content of other materials. For instance, evaluated the mechanical properties of metal matrix composites with different weight proportions of ceramic particles, including Al_2O_3, and found that the mechanical properties varied with the weight proportions of the ceramic particles [5]. This suggests that the mechanical properties of Al_2O_3-based composites can be optimized by adjusting the composition of the composites. In addition, the fabrication and properties of Al_2O_3 ceramics have been extensively studied. highlighted the widespread use of Al_2O_3 as a

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ceramic material for technical applications, emphasizing its importance in the field of materials science [6]. Furthermore, investigated the fabrication of transparent Al_2O_3 ceramics using different commercial α-Al_2O_3 powders, demonstrating the potential for tailoring the properties of Al_2O_3 ceramics based on the raw powder used [7].

Alumina ceramics are extremely hard and wear-resistant, making them suitable for applications where components are exposed to corrosive environments or high levels of mechanical stress [8]. They can withstand high temperatures without significant degradation, making them suitable for use in high-temperature environments, such as furnace linings, spark plugs, and crucibles [9]. They have excellent electrical insulation properties, making them useful in applications where electrical insulation is required, such as electronic components and insulators [10]. Alumina ceramics are chemically inert and corrosion resistant, making them suitable for use in chemically aggressive environments [11]. Alumina ceramics are biocompatible, meaning they can be used in medical applications, such as implants and dental prostheses [12]. Alumina ceramics find applications in various industries and technologies, such as electronics, engineering applications, automotive, medical, aerospace, chemical processing, and textile manufacturing; in the electronics industry, for insulators, substrates, circuit boards, and electronic components [13], in mechanical engineering, for cutting tools, ball bearings, seals and wear-resistant parts [14], in the automotive industry, for pistons, valves, sensors, and spark plugs [15], in the medical field, for dental implants, joint replacements and medical instruments [16]. In the aerospace industry, it is used in high-temperature components, thermal barriers and radar windows [17]. They are also used in Chemical Processing, in crucibles, tubes, and liners for high-temperature chemical reactions [18]. In Textile Manufacturing, they are used in guide rollers and yarn guides for textile machinery [19].

Alumina ceramics can be produced by various methods, including advanced techniques, such as sintering, hot pressing, and spark plasma sintering. Different formulations and processing methods can result in differences in properties, allowing alumina ceramics to be customized for specific applications [20].

The surface texture of Al_2O_3 ceramics is of great importance due to its crucial role in shaping the mechanical, thermal and interfacial properties of the ceramic, thus influencing their performance in a spectrum of applications. Controlled manipulation of surface topography offers a versatile way to tailor tribological behavior, enhance adhesion, and optimize heat transfer. By precisely designing surface features, such as roughness, porosity, and microstructures, it becomes possible to increase load-carrying capacity, reduce friction, and improve wear resistance in tribological systems. Furthermore, the deliberate modulation of surface texture affects the thermal conductivity, emissivity, and wettability of ceramics, important attributes in thermal management, energy efficiency, and environmental interactions [21]. The surface texture of Al_2O_3 ceramics plays a crucial role in determining their mechanical, thermal, and tribological properties and thus influences their performance in various industrial applications.The complex interplay between surface topography, microstructure, and composition profoundly affects the functional properties of the ceramic [22]. Al_2O_3 ceramics typically exhibit a microscopically heterogeneous surface morphology characterized by features, such as grain boundaries, crystal facets, and surface defects. These qualities not only contribute to the mechanical strength and wear resistance of the ceramic but also significantly affect their interaction with the surrounding environment. The surface roughness of Al_2O_3 ceramics, resulting from the inherent properties of the ceramic material and the manufacturing processes used, has a direct impact on contact mechanics, friction and adhesion [23]. The presence of micro-scale roughnesses and irregularities on the surface can improve mechanical interlocking and promote close contact between mating surfaces, leading to improved load-bearing properties [24]. In addition, surface texture affects the thermal conductivity and emissivity of the ceramic, which are key considerations in applications involving heat transfer and thermal management [25]. The importance of surface texture becomes particularly evident in contexts where ceramics interface with other materials or media. For example, in biomedical applications, engineered surface textures can improve the biocompatibility and long-term stability of Al_2O_3 ceramic implants by promoting osseointegration, cellular adhesion and bioactivity. Similarly, in electronic packaging and microelectromechanical systems (MEMS), tailored surface topography can ensure reliable adhesion, reduce the risk of delamination and improve the mechanical robustness of Al_2O_3 ceramic substrates [26]. Furthermore, the advancement of surface engineering techniques has led to innovative strategies for creating functional textures, including laser cutting, chemical etching and nanopatterning. These methodologies provide precise control over surface properties at micro and nano scales, enabling the realization of special properties that exceed the inherent properties of the bulk material. As a result, strategically combining surface texturing strategies holds great promise in pushing the boundaries of Al_2O_3 ceramic applications spanning aerospace, automotive, energy, healthcare and beyond [27]. Furthermore, control of surface texture has become increasingly important in tailoring the performance of ceramics to specific functions. Advanced surface engineering techniques, such as polishing, grinding and surface coatings offer ways to modify surface properties to achieve desired results [28]. For example, precise control over surface roughness can facilitate optimal lubrication, reduce friction losses and improve wear resistance in tribological applications [29]. The importance of surface texture in Al_2O_3 ceramics goes far beyond aesthetics, underlining its crucial role in shaping material behavior and optimizing performance. Leveraging the synergy between surface topography, microstructure and functionality, surface texture is emerging as a transformative tool that empowers the realization of enhanced properties and new functionalities, propelling Al_2O_3 ceramics into the realm of high technological utility and innovation.

Laser surface texturing is a versatile and precision engineering technique that involves the use of laser beams to create controlled patterns, textures or features on the surface of a material, such as Al_2O_3 ceramics [30]. This process offers unique advantages in tailoring surface properties to achieve specific functional outcomes in a variety of applications [31]. Laser surface texturing typically involves focusing a high-intensity laser beam onto the surface of a material. The energy from the laser interacts with the material, causing localized melting, vaporization or ablation. As the laser beam moves across the surface, complex patterns or textures can be produced with micron- or even nanometer-level precision. The resulting surface features can include microscale craters, grooves, channels or other complex geometries. Laser technology provides precise control over the size, depth and layout of surface features, enabling custom designs that optimize specific properties [32]. This level of precision is often difficult to achieve with traditional manufacturing methods. The flexibility of laser surface texturing enables the creation of customized surface patterns to achieve desired properties, such as improved lubricity, reduced friction, increased wettability or controlled adhesion. Laser texturing can improve the tribological performance of materials by reducing friction, wear and contact fatigue. It promotes the formation of oil reservoirs or increases the retention of lubricants within surface features. Laser texturing is often a more environmentally friendly alternative to traditional methods, such as chemical etching or abrasive processes, as it produces minimal waste and avoids the use of harsh chemicals [33]. Laser surface texturing can be applied to a wide range of materials, including metals, ceramics, polymers and composites, making it a versatile technique for a variety of industries.

Alumina, a widely used ceramic material, has been the subject of extensive research in laser applications. Laser treatment has been shown to significantly affect the surface properties of alumina, with laser-treated specimens demonstrating higher surface roughness values compared to untreated specimens [34]. Additionally, laser surface modification has been identified as an advanced technique for improving the surface performance of alumina ceramics in refractory and abrasive machining applications [35]. Furthermore, the use of lasers in the additive manufacturing of alumina ceramic has been investigated, demonstrating the potential for selective laser melting to produce ceramic parts [36]. The high absorptivity of alumina for CO_2 lasers has been highlighted, indicating the effectiveness of high scanning speed and low laser power for the powder bed selective laser processing of alumina [37].

Laser textured surfaces can improve the wear resistance, friction behavior and lubrication efficiency of Al_2O_3 ceramic components, extending their lifetime and reducing maintenance needs. Laser surface texturing represents a state-of-the-art approach to tailoring surface properties, enabling the optimization of Al_2O_3 ceramics and other materials for a wide range of industrial, scientific and medical applications. Its precision, versatility and functional enhancement capacity make it a valuable tool in modern materials engineering and design.

Moreover, laser texturing of zirconia-alumina ceramics has been recognized as a promising surface modification method for various applications, such as enhancing osseointegration of dental implants and improving friction behavior of hip replacement bearing components [38]. The potential practical application of alumina-substrate composites as efficient laser-driven color converters in high-brightness projection displays has also been highlighted [39]. Additionally, laser surface engineering of alumina ceramics has been recognized as an area of technological importance for various applications, with a focus on the effect of laser radiation on the mechanical and physical properties of alumina ceramics [40].

The influence of laser power and laser exposure time on cavity preparation in dentistry has been extensively studied. [41]. Investigated the effects of pump power and laser cavity length on the signal-to-noise ratio performance of an ultrasonic sensor system, providing insights into the influence of laser power on system performance.[42] Attributed changes in cavity surface features to the effects of laser exposure, indicating a direct relationship between laser parameters and cavity characteristics. [43]. Highlighted the increased time required for cavity preparation with lasers compared to high-speed turbines, emphasizing the influence of laser exposure time on the preparation process.

Furthermore, [44]. suggested the potential use of erbium lasers for ablative effects in healthy enamel and dentin, indicating the relevance of laser power and exposure time in cavity preparation. Additionally, [45]. compared the effects of laser cavity preparation with conventional methods on microleakage, providing valuable insights into the impact of laser parameters on restoration quality. These findings collectively underscore the significance of laser power and exposure time in cavity preparation, as they influence cavity characteristics, preparation time, and restoration quality in dentistry.

In this study, micro-sized dimples were formed on Al_2O_3 ceramic plates with a CO_2 laser. The effect of laser processing parameters on the formed dimples was investigated. The effects of laser power and laser exposure time on the dimensions of the cavity were investigated.

2. Materials and Methods

In this study, cavities were formed on 10 mm thick Al2O3 ceramic plates with CO2 laser using different laser power and different laser exposure duration. The laser parameters used in the experiments are given in Table 1. Different laser power of 52, 65, 78, 91 and 105 W were applied to the ceramic material for 10 seconds. In addition, 80 W laser power was kept constant and the laser beam was sent to the material for 1, 5, 10, 15, 20, 25 and 30 seconds.

Table 1. Laser parameters used in the experiments.

Laser Power (W)		52	65	78	91	105	
Laser Exposure Durations (s)	1	5	10	15	20	25	30

3. Results and Discussion

Effect of Laser Power on cavity formation

When the laser power was changed between 52 and 105 W, the laser exposure duration was applied for 10 seconds. When the laser exposure time was changed between 1 second and 30 seconds, the laser power was kept constant at 80 W. In order to examine the change in cavity dimensions with the change in laser power, cavities were formed with laser power 52 W, 65 W, 78 W, 91 W and 105 W as shown in Table 1. Optical microscope images of the formed cavities were given in Figure 1.

The diameter of the laser beam used is 200 µm. Within the laser beam diameter, the energy decreases from the center outwards in a Gaussian distribution. Ablation occurs around the center where the laser beam touches the surface. As it moves away from the center, traces of the heat affected zone (HAZ) can be seen by eye. Using optical microscope images, the average diameters of both the cavity formed as a result of ablation and the heat-affected zone observed in the outer region were measured as shown in Figure 2. The measurement results are given in Table 2.

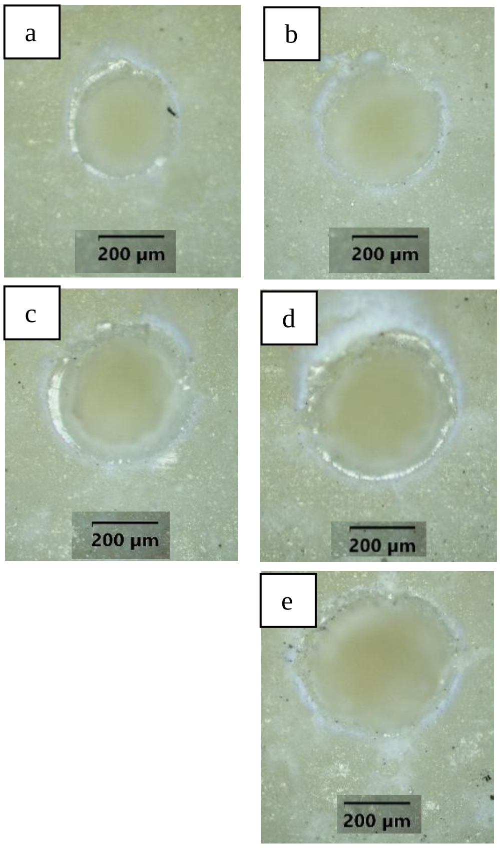

Figure 1. Optical microscope images of the cavities obtained when the laser powers were changed. a) 52 W, b)65 W, c) 78 W, d) 91 W and e) 105 W

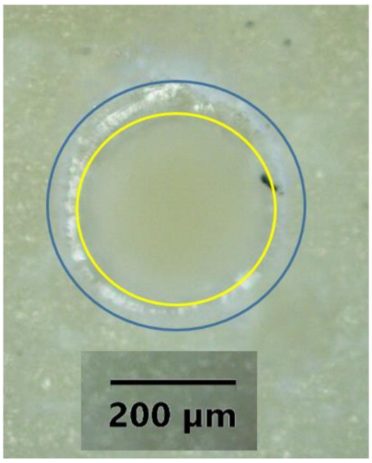

Figure 2. Representative figure showing the measurement of the average diameters of the cavity formed as a result of ablation and the heat-affected zone observed in the outer region (sample obtained with 52 W). The region shown in yellow indicates the approximate boundaries of the cavity obtained by ablation and the region shown in blue indicates the approximate boundaries of the HAZ.

Table 2. Results of the cavity and HAZ diameter measurements against laser power variation.

Laser Power (Watt)	Cavity Diameter (µm)	HAZ Diameter (µm)
52	324	422
65	368	443
78	400	508
91	411	519
105	432	562

The graph showing the change of cavity and HAZ diameters with the applied laser power is given in Figure 3.

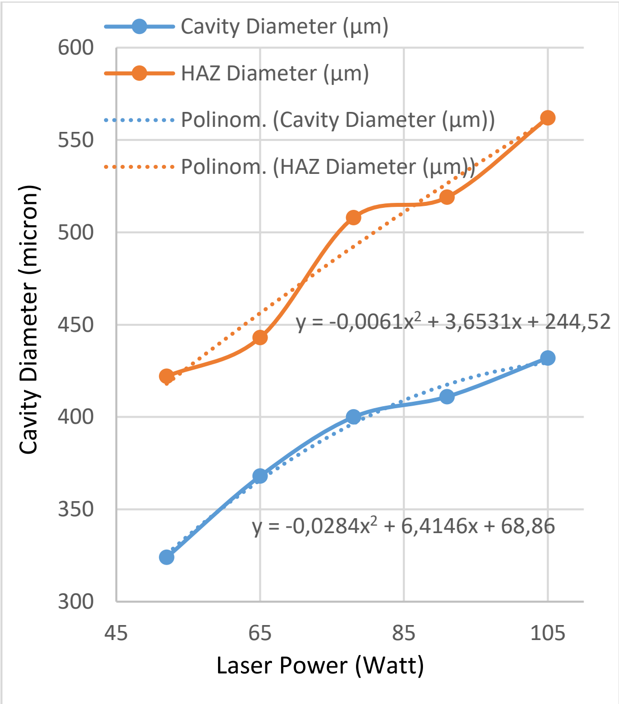

Figure 3. Variation of the cavity and HAZ diameters with applied laser power.

As can be seen from the graphs in Figure 3, as the laser power increases, both cavity and HAZ diameter increase. However, the rate of increase in cavity diameter slows down. As the laser power increases, the increase in HAZ diameter is also clearly seen. However, there is a fluctuation in this increase. One of the reasons for this fluctuation is thought to be due to the irregularity in the structure of the material. The 2nd order trend lines of the graphs and the equations of these lines are also shown in the figure. Although there are differences due to fluctuations, the equations of the 2nd order polynomial trend lines have similar characteristics.

Effect of Laser Exposure Duration on Cavity Formation

To examine the change of cavity size with laser exposure duration, laser exposure duration in Table 1 was applied as 1, 5, 10, 15, 20, 25, and 30 sec and cavities were formed. Optical microscope images of the formed cavities are given in Figure 4.

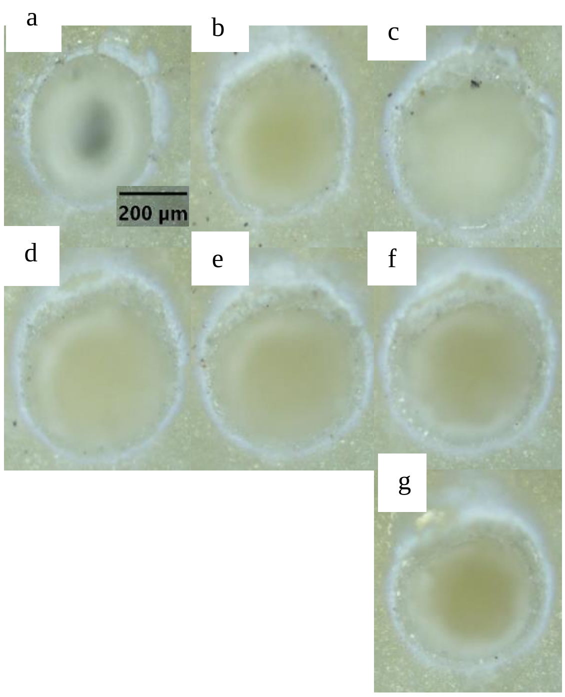

Figure 4. Optical microscope images of the cavities obtained when the laser exposure durations were changed. a) 1 sec, b) 5 sec, c) 10 sec, d) 15 sec, e) 20 sec, f) 25 sec, g) 30 sec.

Optical microscope images were used to measure the mean diameters of both the ablated cavity and the heat affected zone observed in the outer region. The measurement results are given Table 3.

Table 3. Results of cavity and HAZ diameter measurements against laser exposure duration change.

Laser Exposure duration (Sec.)	Cavity Diameter (µm)	HAZ Diameter (µm)
1	389	465
5	400	476
10	432	541
15	443	562
20	443	562
25	443	562
30	443	562

The graph showing the change of cavity and HAZ diameters with the applied laser exposure duration is given in Figure 5.

As can be seen from the graphs in Figure 5, both cavity and HAZ diameters increased exponentially during the first 10 seconds of exposure duration. However, the increase in both diameters slowed down after the 10th second. After 15 seconds, no change was observed in both cavity and HAZ diameter. When the graph is considered as a whole, trend lines have similar characteristics to the equations of 5th-order polynomials.

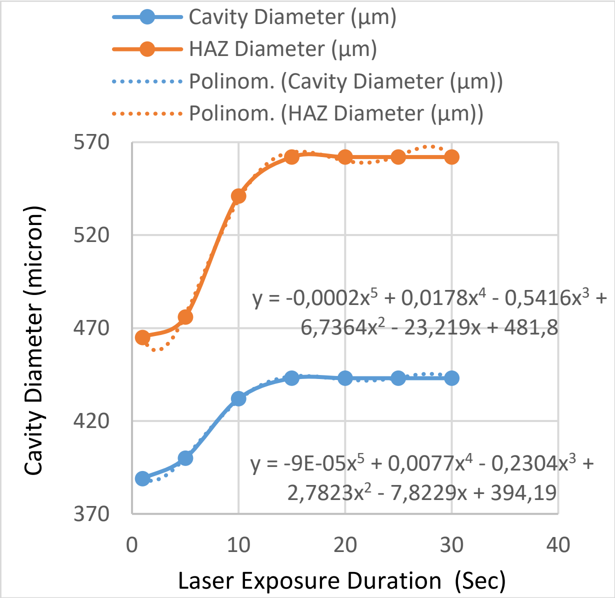

Figure 5. Variation of the cavity and HAZ diameters with applied laser exposure duration

4. Conclusions

In the first part of the study consisting of two parts, when the laser power was increased by keeping the exposure duration constant, the cavity diameters increased almost linearly.

In the second part of the study, laser power was kept constant and laser exposure duration was increased. It was observed that laser exposure duration had no effect on cavity diameters after a certain period of time.

In line with these results;

- It can be said that laser power is a more dominant parameter than laser exposure duration in the dimple geometry to be formed on ceramic material.
- If it is desired to obtain a wider dimple with a fixed laser beam diameter, laser power should be increased.
- If a deeper cavity is desired with an increase in width or a slight increase in width with a fixed laser beam, the laser exposure duration should be increased.

When the duration of laser exposure was increased in the second part of the experiment, both cavity and HAZ dimensions increased during the first 15 seconds, but no change in cavity and HAZ dimensions occurred after the 15th second. This may be due to the change in the thermophysical properties of the material with temperature. The slowing down of the increases in the first 15 seconds may also be evidence of this. As the interaction time increased, the temperature of the material increased and the heat transfer coefficient started to decrease. After a certain frequency value, heat could not be transmitted to further distances within the ceramic material.

Another reason for the inability to transmit heat may be that as the laser application time increases, the amount of heat lost from the surface increases with time.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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