CO\textsubscript{2} laser machining on alumina ceramic: a review

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Abstract. Alumina is widely used for engineering applications due to its strength, insulation characteristics, and, chemical and thermal stability. Alumina is commonly used in the automotive, aircraft, medical, and other industries. However, despite its desirable characteristics, this material is brittle and difficult to be machined. Some researchers and practitioners adopted diamond abrasive cutting process for alumina machining, but the lengthy machining time and excessive tool wear increase machining cost by 60-90%. One other alternative to the traditional machining method is laser Beam machining (LBM). The LBM process is characterized by good machining quality, environmentally friendly, and cost-effective because there is no tool wear, vibration, and cutting force. Those characters are of benefit to productivity. However, there are still issues reported such as microcrack and surface roughness during alumina laser machining that needs to be further investigated. This paper reviews the published works on alumina laser beam machining (LBM). The review focuses on the CO\textsubscript{2} LBM system.

1 Introduction

Alumina ceramic materials have been successfully used in industrial applications including automotive components, aircraft components, electronic devices, medical devices and some other high technology components, some of the advantages of this material because it has high hardness, wear resistance, resistance to high temperatures, the ability to excellent corrosion, low thermal conductivity and chemical [1–3]. However behind the high hardness, this material is also brittle so it is difficult to be machined, the machining process that may be carried out mechanically is a diamond abrasive cutting process[4-5].

Conventional machining processes such as grinding are always considered capable as the easiest and most reliable technique for processing ceramic materials because this process can meet dimensional accuracy and good surface finish[6-7]. Yet this process has weaknesses including the long processing time so that it can cause an increase in very high machining costs, reaching 60-90% of
the final cost[8]. It was further reported that the mechanical machining of materials with a combination of ceramics always causes high wear on the cutting tools[9].

The most possible machining process for ceramic alumina material is non-conventional machining, among the many unconventional processes in the manufacturing industry, the best is the CO₂ laser beam machining (CO₂ LBM) process, this is because the laser process contributes high productivity accompanied by good cut quality[10]. Laser machining can be developed as an environmentally friendly and cost-effective machining concept because there is no tool wear, vibration, and cutting forces as mechanical machining. This alternative was chosen because the laser machining process uses smelting and ablation when it is suitable for hard materials such as alumina. In this study, the author examines the occurrence of micro-cracks caused by the laser process and discusses surface roughness which is a surface quality requirement in the CO₂ laser beam machining process.

2 Laser beam Machining

LBM is a thermal process using a laser beam to produce very high energy, with the heat concentrated on the workpiece being able to dump the material by melting it with an ablation process in the form of micron-sized granules [11]. The machining process with thermal main output has different capabilities from another unconventional machining, some of the advantages of the LBM process that can be used with automation systems using CNC for work operations. The laser machining process is very fast, has high accuracy, is capable of cutting small and large sizes, and is most suitable for hard materials such as ceramic [12]. In its application, laser machining is commonly used for cutting, drilling, and grooves. Lasers have several types of operating systems including Nd: YAG laser, Fiber Laser, CO₂ Laser, Diode Laser, and so on. The wavelength for Nd: YAG laser and fiber laser is the same, which is 1064μm while the wavelength for CO₂ Laser is 10640 μm. Nd: YAG is more often used for laser machining of micro sizes, Nd: YAG performance shows high accuracy for surface finishes. Unlike the CO₂ Laser which has a power of up to 12000 watts, so in its application, it is always used to do continuous work for a long time. The detailed scheme of the laser beam machining process is shown in the following figure 1.

![Figure 1. Schematic diagram of laser beam machining](image-url)
2.1 Material Removal Mechanism LBM

The mechanism of material removal with LBM relies on the laser. The unreflected light is absorbed and then heats the specimen surface as shown in Figure 2. Evaporation and melting of the material can occur if the heat generated by the laser is sufficient, the heat generated is small, so the melt does not produce micro-grains completely. The phase change that causes melting occurs due to the diffusion of heat into the material. Melting which then becomes evaporation is strongly influenced by the power density and beam interaction time where the heat absorption and conduction processes are required. The loss of absorption and scattering intensity can reduce the process that would normally occur under these conditions because the laser beam is too high. Therefore, laser machining depends very much on the power density of the beam, which must be greater than that lost due to conduction, convection, and radiation which results in penetrating into the workpiece. The thermal effect of the process is shown in Figure 3.

![Figure 2](image)

\( \text{Figure 2. Physical processes occurring during LBM (a) absorption and heating (b) melting (c) vaporization [13]} \)

![Figure 3](image)

\( \text{Figure 3. Process the thermal effects [11]} \)

According to the theory[13], the volume of material removal can be calculated as follows:

The Power density of the laser beam \( Pd \) is given by

\[ \text{Power density of laser beam } Pd = \ldots \]
\[ P_d = \frac{4L_p}{\pi F_l^2 \alpha^2 \Delta T} \] (1)

The size of the spot diameter \( d_s \) is

\[ d_s = F_l \alpha \] (2)

The Machining rate \( \phi \) (mm/min) can be described as follows:

\[ \phi = \frac{C_l L_p}{E_v A_b h} \] (3)

\[ A_b = \frac{\pi}{4} (F_l \alpha)^2 \] (4)

\[ \phi = \frac{4C_l L_p}{\pi E_v (F_l \alpha)^2 h} \] (5)

The Volumetric removal rate (VRR) (mm\(^3\)/min) can be calculated as follows:

\[ \text{VRR} = \frac{C_l L_p}{E_v h} \] (6)

Where:
- \( P_d \) = power density, w/cm\(^2\)
- \( L_p \) = laser power, w
- \( F_l \) = focal length of lens, cm
- \( \Delta T \) = pulse duration of laser, s
- \( \alpha \) = beam divergence, rad
- \( C_l \) = constant depending on the material and conversion efficiency
- \( E_v \) = vaporization energy of the material, w/mm\(^3\)
- \( A_b \) = area of the laser beam at focal point, mm\(^2\)
- \( h \) = thickness of material, mm
- \( d_s \) = spot size diameter, mm

However, high MRR remains a parameter by researchers, although surface quality remains important, in terms of productivity the manufacturing industry remains a priority, as reported [14] when optimizing machining on alumina ceramic material using Nd: YAG laser on Figure 4.
Figure 4. A 3D bubble chart showing the design points obtained with the output variable of DL.[14]

2.2 CO₂ Laser Machining
In theory, the CO₂ Laser is the process of releasing gas electrically by utilizing three gases including Carbon dioxide (2-5%) as active media, nitrogen (10-55%) as filling media, and helium (40-88%) as the cooler. In principle, the laser beam occurs in an optical resonator which has two cavity mirrors that are similar to a fully reflective curved mirror. CO₂ laser output power generally varies and falls into the high category ranging from 10 W to 45 KW. Continuous wave (CW) and pulsed wave (PW) are forms of the CO₂ laser. However, a pulsed wave CO₂ laser (PW) has very high peak power even though the resulting average power is low. Usually the pressure in the exhaust room depends on the type and size as well as the laser mode used. In principle, the pulsed laser always operates at a higher pressure area than continuous wave (CW) where the pulsed laser pressure value is within 1 atm. The conversion value of the CO₂ laser machining process can produce an output of 10-15%, due to atmospheric pressure and high efficiency, this CO₂ laser is very commonly used in industry for cutting, joining, and surface engineering[11].

A. British et. al [15] conducted a study on 4 mm thick alumina-coated aluminium using a 1.8 kW CO₂ pulsed laser mode, then the genetic algorithm optimization results showed a simultaneous increase in 5.2% hole quality in 416.6W laser power, pulse frequency 1.4 kHz and 0.4 s piercing time. Previously it has also been reported [16] on alumina with a thickness of 4.4 mm using 3.5 kW CO₂ laser, from the results of the study it was found that the size and temperature of the melted front significantly influence the formation of holes and spatter deposition as shown figure 5. Its front melt character is mainly determined by pulse duty cycle together in Figure 6, the peak laser power in Figure 7 and pulse repetition rate. Furthermore, to make a large size Alumina hole, the power must be between 400-1200W because if it is below 400 W, the hole making process cannot be carried out [15]. The technical specifications of the laser are shown in table 1.
Figure 5. Different hole with laser peak power [16]

Figure 6. Pulse duty cycle on spatter deposition [16]
Figure 7. Hole diameters at the fixed average laser peak power [16].

Table 1. Specifications CO\textsubscript{2} laser [15]

| Machine model       | Triumph Laser Cell 1005 CO\textsubscript{2} laser |
|---------------------|-----------------------------------------------|
| Laser wavelength    | 10.6 lm                                       |
| Laser power         | 1800–12,000W                                  |
| Working distance    | 500 mm                                        |
| Maximum field size  | 2000–1500 mm2                                 |
| Beam diameter       | 0.25 mm                                       |
| Mode operation      | Pulse typ                                     |

3 Laser Machining for Ceramic Alumina

3.1 Surface Roughness

Surface roughness is the main parameter in determining the quality of machined surfaces [17]. In the machining process using CO\textsubscript{2} laser surface roughness is strongly influenced by the ratio of power to cutting speed, the thickness of the material, composition material, type of gas, and pressure [18]. The Machining ND: YAG Laser on Alumina material shows that Intensity, Pulse overlap, frequency and combined effects of frequency and pulse duration have a major contribution in determining surface roughness as shown in Figure 8 [14].
Figure 8. The effect variables for surface roughness [14]

While in different cases [19], the roughness value of alumina ceramics is determined by the amount of energy and the laser stricken. The results of experiments and simulations found similarly stated that the relationship between the number of particles required by international standards is 0.5 µm largely determined by the size of the laser shot. When the shot increases, many particles are damaged along with the increase in surface roughness value as shown in Figure 9. This condition is caused by the greater laser shots carried out on alumina, the smaller the size of 0.5 µm the smaller as shown in Figure 6. In zone 7 with a critical roughness of 4.28 µm. Whereas in zone 1 it was shown that the particles produced were more and evenly distributed so that the roughness value was at the lowest position which was 0.17 µm.
3.2 Microcracks

Microcracks are a problem that must be avoided on a workpiece because it can cause elongated cracks on a workpiece that ends up breaking. Microcracks usually occur during laser drilling with brittle and hardened materials, otherwise, these conditions are often caused by high cooling rates or temperature gradients [20]. Also, micro-cracks can be formed because of the oxide and nitride layers on the edge of the drill as shown in Figure 10.

Figure. 9. Experiment results [19]
In line with research [21] that the appearance of microcracks marked by surface kerf is caused by high-temperature gradients, formed pouring layers, and high thermal strain on the surface area. It was further reported that high power and low-speed cutting processes did not affect the occurrence of microcracks. Figure 11. To minimize the occurrence of crabs, it was necessary to modify the temperature gradient by reducing the cooling rate by heating the subsurface layer.

![Figure 10](image1.png)

**Figure 10.** Formation of micro-cracks along the sidewall of the holes [20]

![Figure 11](image2.png)

**Figure 11.** SEM micrographs of laser cut kerf surfaces with laser power is 1500W and the cutting speed is 0.07 m/s (a) Stainless Steel (b) Inconel 625 (c) Ti-61-4v Alloy (d) Alumina[21]
4 Summary
This review paper tries to provide an overview of the use of Laser Beam Machining (LBM) in brittle and tough alumina ceramic materials because the thermal process with laser light and energy density is capable of producing localized heating at one point of the workpiece. Physically laser machining is very suitable for materials that are difficult in the machine with a scattering system and reflections on the surface of the workpiece, heat diffusion into the material which causes phase changes, fusion, and evaporation associated with the material called the material removal rate (MRR). MRR is an important parameter in LBM but the surface quality is also a major point in laser machining. CO\textsubscript{2} LBM is a process of releasing gases using electricity by using 3 gases namely Carbon dioxide, nitrogen, and helium, so this process is always used in the large-scale cutting industry. From the available literature, it can be trusted that the use of machining with CO\textsubscript{2} Laser Beam Machining is used on thick materials because it has a power of up to 12 KW.

The main parameters that determine surface roughness in alumina ceramic material still vary between them are the ratio of power to cutting speed, the thickness of the material, the composition of the material, type of gas, and pressure. Also, the influence of intensity, pulse overlap, frequency, and the combined effect of frequency and duration of pulses have a major contribution in determining surface roughness. Besides, the high value of surface roughness was also found because the number of particles required by international standards of 0.5 µm, the effect of the magnitude of the laser shot causes the number of particles of 0.5 µm to be less in conditions affecting the surface roughness value to be higher. In the alumina material damage when the laser occurs Microcracks caused by a high-temperature gradient, but these microcracks can be overcome by reducing the rate of cooling that is heating at the bottom of the workpiece.

From this literature study, it can be seen that alumina ceramic material with thicknesses above 4 mm is very much using the machining process with CO\textsubscript{2} LBM, besides the many laser machining parameters for surface roughness, as well as the machining linkage to microcracks it is very possible to conduct further studies.

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