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ORIGINAL ARTICLE

A study on the development of milling process for silicon nitride using ball end-mill tools by laser-assisted machining

Tae-Woo Kim · Choon-Man Lee

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Abstract Silicon nitride is a non-oxide ceramic that represents strong characteristics in high strength, abrasion resistance, corrosion resistance, and thermal shock resistance at high temperatures and that has been widely used in the industry. However, it also exhibits high levels of hardness and brittleness, and machining of silicon nitride is usually implemented using a diamond grinding process. This presents difficulties in machining due to increased machining cost and time, and a machining method to reduce these is needed. Current studies on an alternative approach to the problem have been focused on laser-assisted machining (LAM) methods that facilitate machining by softening a workpiece using a laser heat source. The advantages of a LAM process are decreases in tool wear and cutting force and reductions in catastrophic tool failures and the occurrence of chatter. In this study, a high-power diode laser (HPDL) is used as a heat source for machining of silicon nitride. Machining experiments were carried out using cubic boron nitride (CBN) tools. The proper laser power for the experiment was determined through thermal analysis. A back-and-forth laser-path preheating method was newly proposed to obtain sufficient temperature for softening the silicon nitride. Machining experiments were performed using back-and-forth method and insulation material for protecting heat. The machining of silicon nitride was performed successfully by a laser-assisted milling (LAMill) process using a CBN ball end-mill tool, which is stable at high temperatures. In the machining with applying three times of a back-and-forth laser-path preheating process, tool breakage and gas marks were not occurred at the 170 W for processing a depth of cut of 0.15 mm. It is expected that the results of machining experiments can be used to process the various shape of silicon nitride material.

Keywords Laser-assisted machining · Finite element method · Silicon nitride · High-power diode laser · Cubic boron nitride

1 Introduction

Due to their high strength, excellent abrasion resistance, and chemical stability at high temperatures, ceramics have become very popular and are widely used in various industrial fields (for example, machines, architecture, medical applications) [1, 2]. However, as ceramics exhibit high levels of hardness and brittleness, machining them has usually been performed using a diamond grinding process that costs more than 60 % of the entire machining cost [3–5]. There are also many problems related to the long machining time. To solve such problems, a number of studies have focused on laser-assisted machining (LAM) methods that facilitate the machining of ceramic workpieces by softening them using a laser heat source [5–11].

Germain et al. [12] verified an increase in tool life and decrease in cutting force in a LAM machining experiment of Inconel 718, using carbide and ceramic inserts. Rozzi et al. [13–15] analyzed the influence of conditions on machining silicon nitride in a LAM experiment and also investigated chips and the characteristics of machining surfaces. They also predicted the temperatures of machining areas using a heat transfer simulation. Lei et al. [16, 17] proposed constitutive equations by performing a modeling of the behavior of silicon nitride according to temperatures as a mathematical manner and performed a study on tool life through experiments.

Studies on LAM have generally been performed in connection with laser-assisted turning (LAT) processes [18, 19]. In practical products, however, milling requires complicated

T.-W. Kim · C.-M. Lee (✉)
School of Mechanical Engineering, Changwon National University,
#9 Sarim-dong, Changwon-si, Gyeongsangnam-do 641-773,
Republic of Korea
e-mail: cmlee@changwon.ac.kr

and precise machining processes. Although it is possible to implement overall preheating by fixing a laser heat source at a specific point and rotating a workpiece in LAT, there is some difficulty performing this during a milling process due to the need to move the laser heat source [20–23].

Thus, studies on laser-assisted milling (LAMill) are required. The present authors also used thermal analysis to predict the proper laser power and feed rate under various conditions in LAMill, before processing ceramic machining. These predictions were verified through a preheating experiment. In addition, it has revealed that cutting force and surface roughness are improved by applying LAMill for AISI 1045, Inconel 718, and Nickel 201 [24–26]. Kang et al. [27] suggested a constitutive equation for silicon nitride by experiments using flat-end mill. The machining of silicon nitride was performed successfully by a LAMill process using a CBN ball end-mill tool, which is stable at high temperatures [28, 29].

In this study, a high-power diode laser (HPDL) was used as a heat source for machining of silicon nitride. A machining experiment was carried out using cubic boron nitride (CBN) tools, and the proper laser power for the experiment was determined through thermal analyses. A back-and-forth laser-path preheating method was newly proposed to obtain sufficient temperature for softening the silicon nitride. Prior works about LAM have been carried out mainly using flat-end mills for machining of flat workpieces, but ball end-mills are used to apply for three-dimensional LAM by the present method.

2 Finite element method

2.1 Analysis method

For LAM, it is very important to predict the preheating temperature of a workpiece and to maintain proper machining temperature by controlling the laser power according to changes in the feed rate. Before the machining experiment, a finite element analysis was carried out, using an ANSYS Workbench thermal analysis, in order to predict the laser preheating temperature of a silicon nitride workpiece. The thermal analysis was carried out sequentially by input of the laser heat source, which is overlapped by 1/2, according to time along to the path of the laser heat source as shown in Fig. 1. That is, the step movement was set at 1.5 mm because the diameter of the laser heat source was 3 mm [24, 25].

The thermal conductivity and specific heat of the workpiece change according to changes in temperature. As represented in Table 1, the thermal conductivity and specific heat were used to perform the analysis.

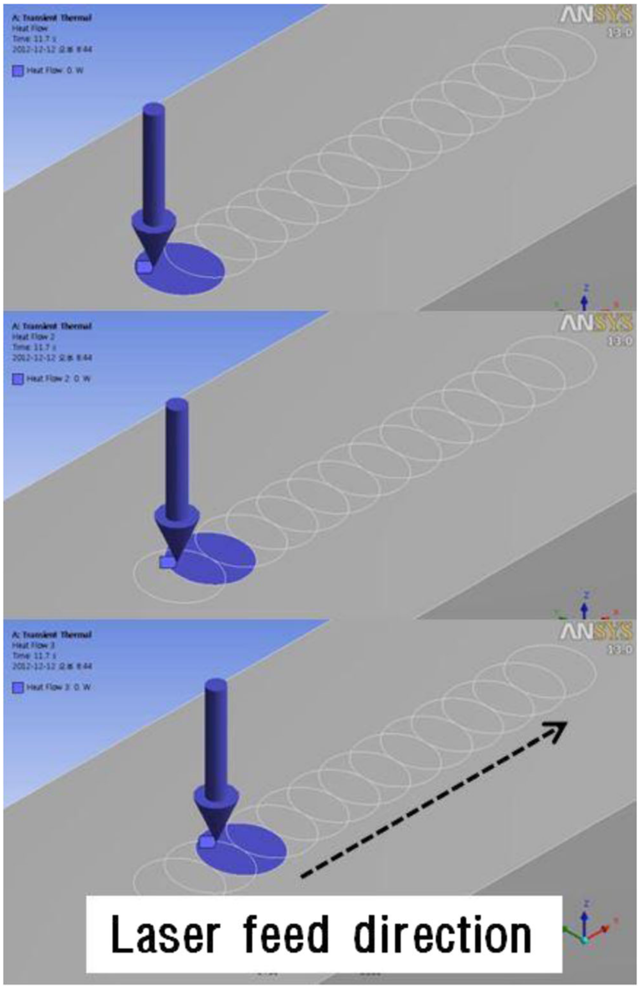


Fig. 1 Sequence of the analysis

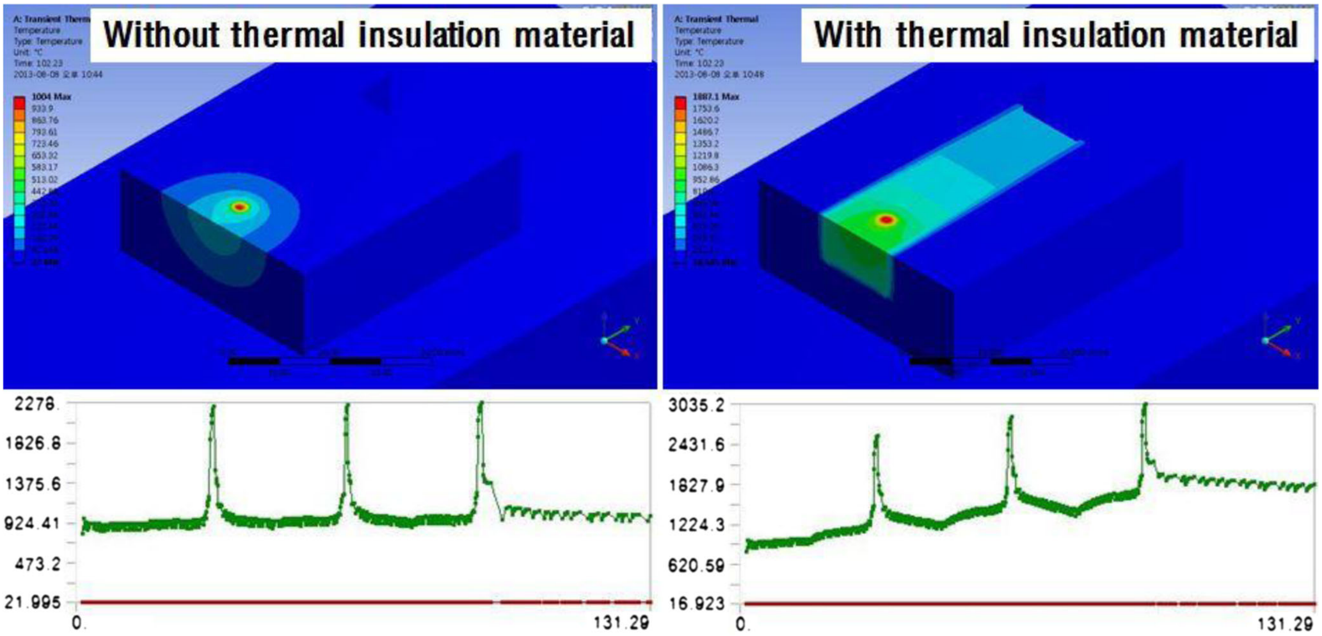
2.2 Analysis conditions

The absorptance of the silicon nitride in a diode laser (70 %) was applied to the analysis [30]. Because the temperature decreases due to convection in air as the workpiece is preheated by laser, the natural convection condition, 5 W/m^2 °C, was applied to the analysis.

To maintain a temperature sufficient for machining, a thermal insulation material was attached between the workpiece, and the jig and fixture. A back-and-forth laser-path preheating method is suggested.

Table 1 Properties of the silicon nitride according to temperature change

Temperature (K)	Thermal conductivity (W/mm K)	Specific heat (J/kg K)
500	25	910
1,000	17.5	1,170
1,500	15	1,215
2,000	14	1,220



(a) (b)

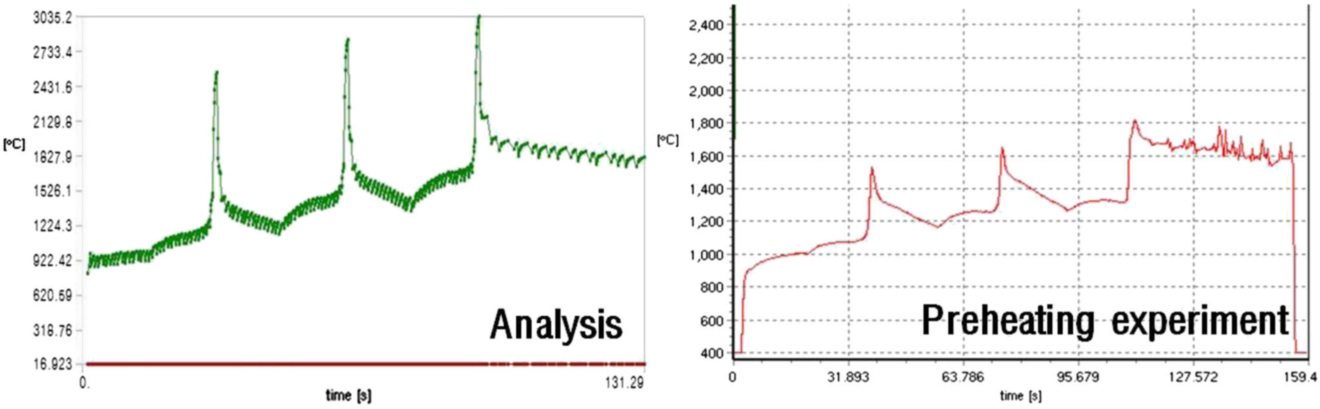
Fig. 2 Results of thermal analysis **a** without thermal insulation material and **b** with thermal insulation material between the workpiece and the jig and fixture

3 Thermal analysis and preheating experiment

3.1 Back-and-forth laser-path preheating method

As described in Sect. 2, silicon nitride has a high thermal conductivity, and this leads to a rapid drop in temperature due to heat conduction into the jig and fixture. To prevent this, a thermal insulation material was set up between the workpiece, and the jig and fixture. Then, a new back-and-forth laser-path preheating method was used to heat a silicon nitride workpiece to a specific temperature to facilitate effective machining.

Figure 2 represents the results of a thermal analysis with and without thermal insulation material for the workpiece that was machined at 150 W after three times back-and-forth laser-path preheating. In a thermal analysis, the maximum temperatures of a laser heat source in machining with and without thermal insulation material after applying the back-and-forth laser-path preheating method were 1,870 °C, which was due to the accumulation of heat in the workpiece, and 1,030 °C, respectively. It was verified that the thermal insulation



(a) (b)

Fig. 3 Temperature distribution after back-and-forth laser-path preheating at 150 W: **a** thermal analysis and **b** preheating experiment

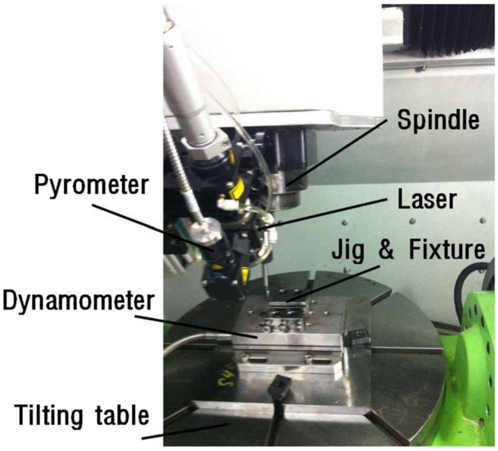


Fig. 4 Experimental setup for LAMill

Table 2 Conditions of the thermal analysis

Materials	Silicon nitride
Block size	60×15×8 mm
Laser feed rate	Preheating: 100 mm/min Machining: 40 mm/min
Laser power	150, 170, 190 W
Laser heat source size	3 Ø
HPDL absorption ratio of silicon nitride	0.7
Convection heat	5 W/m^2 °C

material significantly reduces the thermal conductivity between the jig and fixture.

Figure 3 shows the comparison of the temperature data obtained from the thermal analysis and from the experiment carried out at 150 W. Figure 3a shows the temperature distribution determined by thermal analysis, and Fig. 3b shows the surface temperatures measured using a pyrometer. The analysis results show good agreement with the experimental ones, except for the temperature of the regions at both ends where the laser preheating paths overlapped.

For applied laser power of 80, 100, 120, and 140 W (and considering the absorption ratios of 56, 70, 84, and 98 W), the maximum surface temperature at each laser power level was 1,155, 1,352, 1,555, and 1,758 °C, respectively.

3.2 Experimental setup for preheating

In the machining experiment, a high-power diode laser with maximum power of 1 kW that has a wavelength of 808–980 nm by Laserline was set up to the machining center spindle, Hyundai-Wia Hi-V560M 5 axes (3+2-axes-kinematic) as shown in Fig. 4. Also, a pyrometer was set up to measure the surface temperature of the workpiece in real-time. A dynamometer (9257B by Kistler) was used to measure the cutting force, and a charge amplifier (5019 by Kistler) was used to amplify the voltage measured by the dynamometer.

3.3 Thermal analysis

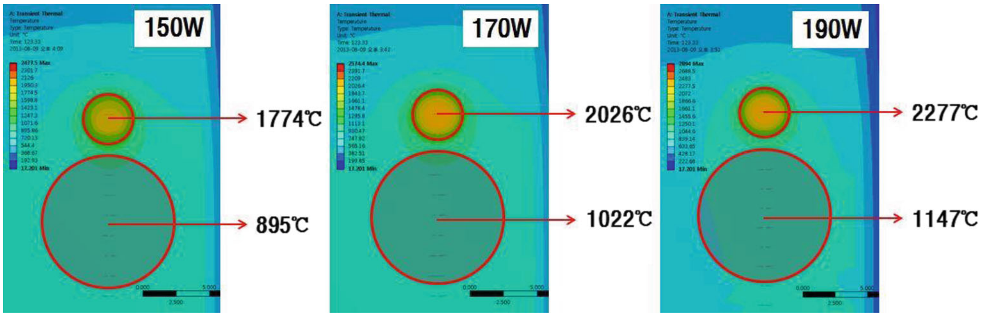
Table 2 shows the thermal analysis conditions. Analyses were carried out for machining laser power at 150, 170, and 190 W, after applying three times of the back-and-forth laser-path preheating process at 150 W. The distance between the center of the laser heat source and the center of the machining target, which is contacted by a tool, was set at 6 mm. Figure 5 shows the maximum preheating temperature at the laser heat source and at the machining point, according to laser power. The maximum temperature was calculated to be 1,774, 2,026, and 2,277 °C according to increases in the power. Also, the temperature at the machining point was calculated to be 895, 1,022, and 1,147 °C according to increases in the power.

4 Machining experiment

4.1 Experimental setup and machining conditions

Machining experiments are carried out using experimental setup shown in Fig. 4. CBN is an artificial diamond formed

Fig. 5 Temperature distribution by the thermal analysis of the preheated zone and center of the machining zone



(a)150 W (b)170 W (c)190 W

Table 3 Conditions of the experiment

Materials	Silicon nitride
Block size	60×15×8 mm
Laser feed rate	Preheating: 100 mm/min Machining: 40 mm/min
Laser power	150, 170, 190 W
Spindle rpm	4,000
Depth of cut	0.15 mm
Tool	2F 8 Ø CBN ball end-mill
Laser heat source size	3 Ø

by bonding boron (B) and nitrogen (N) as a type of compound. It does not well react with iron. In particular, it maintains hardness to more than 1,000 °C without any oxidation and can be used to high hardened steel machining or for high-speed machining of cast iron. A CBN ball end-mill with exceptional stability at high temperature was used for the experiment.

The machining conditions applied to the experiment are presented in Table 3. As the same as the thermal analysis, the machining laser power was applied at 150, 170, and 190 W after applying three times of the back-and-forth laser-path preheating process at 150 W.

4.2 Experimental results and discussion

Figures 6 and 7 represent the machined workpiece surface according to the laser power level. They show white regions around the machined area that increased according to increases in the laser power. After 190-W laser power was applied, gas marks were present on the surface. Glass transition temperature is 1,100~1,200 °C. And, silicon is precipitated from workpiece matrix at 1,300~1,500 °C. When the precipitation of silicon is initiated, cracks are generated on

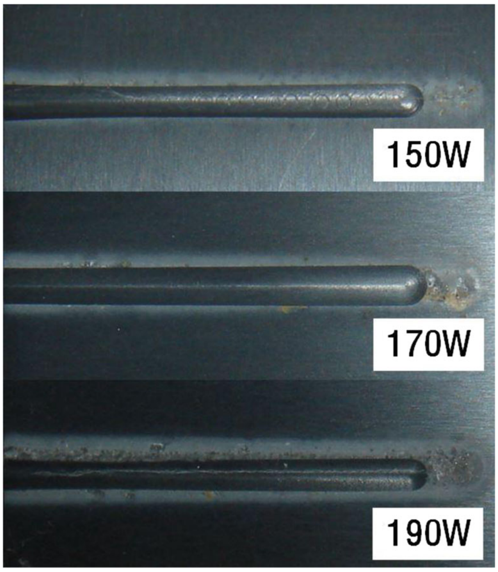


Fig. 6 Machined surfaces using the CBN ball end-mill

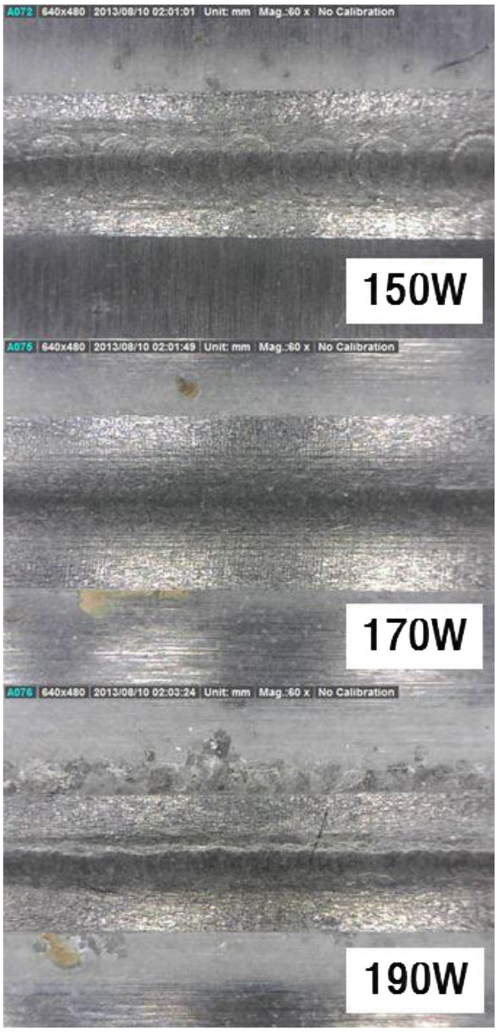


Fig. 7 Digital microscope pictures of the machined surface

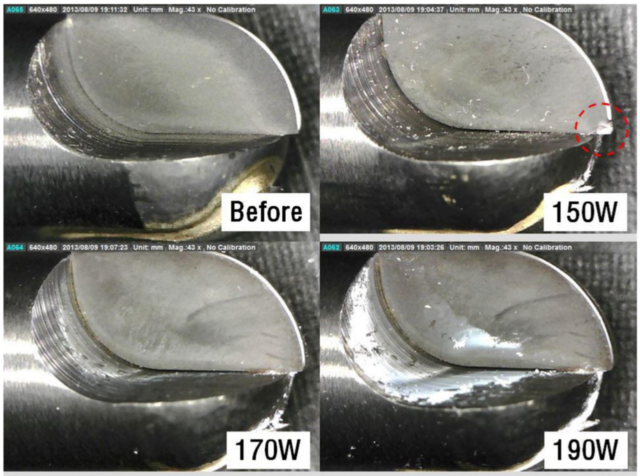


Fig. 8 Digital microscope pictures of the CBN ball end-mill

Table 4 Measured cutting force

Laser power (W)	Cutting force (N)	
	Fx	Fz
150	12.06	12.56
170	6.45	4.04
190	5.25	2.83

the workpiece after machining. So, the low laser power is selected to maintain preheating temperature 1,100~1,300 °C.

Figure 8 shows the images of the CBN ball end-mill surface using an electron microscope. As shown in Figs. 6 and 7, tool breakage occurred at 150 W and that caused abrasions due to the broken tool-end. However, when laser powers of 170 and 190 W were applied, the tools were still in good condition. Regarding the results at a laser power of 190 W, the gas marks should be removed by machining the workpiece with a depth of cut more than 0.15 mm.

The principal cutting force (Fx) and axial cutting force (Fz) for each level of laser power are presented in Table 4. In the measurement at 150 W, the cutting force was about two times higher than that of 170 and 190 W. For 150 W, it is considered that the cutting force was high due to the low preheating temperature and tool breakage.

5 Conclusion

In this study, a machining experiment was carried out using ball end-mill tools, and the proper laser power for the experiment was determined through thermal analyses. Ball end-mills are used to apply for three-dimensional laser-assisted machining by the present method. A back-and-forth laser-path preheating method was newly proposed to obtain sufficient temperature for softening the silicon nitride. The machining of silicon nitride was performed successfully by a LAMill process using CBN ball end-mill tools, which are stable at high temperatures. Then, the results of this experiment are summarized as follows:

1. Silicon nitride exhibits high thermal conductivity that leads to a rapid drop in temperature due to heat conduction into the jig and fixture. Use of a thermal insulation material significantly reduced heat conduction from the workpiece into the jig and fixture during the back-and-forth laser-path preheating. The use of thermal analyses and experiments was helpful for successfully developing the milling process for silicon nitride by LAMill.
2. It is shown that the machining of the silicon nitride can be performed successfully using CBN tools, which are stable at high temperature, in conjunction with the back-and-forth laser-path preheating method.
3. In the machining with applying three times of a back-and-forth laser-path preheating process, tool breakage occurred at 150 W due to the low preheating temperature and lack of workpiece softening. Gas marks occurred due to surface oxidation because of excessive heat input in the preheating process at 190 W. It is considered that the proper laser power in the machining is 170 W for processing a depth of cut of 0.15 mm.

The results obtained in this study can be used as data for predicting the proper back-and-forth laser-path preheating and machining laser powers according to different depths of cut in the similar ceramic materials for the laser-assisted milling. The preheating times will be increased, and then the depth of cut could be increased in the future work.

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