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A study on the development of the laser-assisted milling process and a related constitutive equation for silicon nitride

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ABSTRACT

Laser-assisted machining (LAM) has recently been evaluated as an effective process for machining of difficult-to-cut materials, such as ceramics. It is more difficult to reach a sufficient preheating temperature in laser-assisted milling than in turning. A newly developed back-and-forth preheating method is proposed to obtain proper temperature at the laser spot, which is preceding a cutting tool. Experiments were successfully performed using the calculated laser power and feed, as determined by using finite element analyses. In addition, a constitutive equation of the LAM is proposed. The proposed method and constitutive equation can be applied to the laser-assisted milling of ceramics.

1. Introduction

Difficult-to-cut materials, such as ceramics and titanium alloys, are widely used in various industries because of their good mechanical properties. It is known that silicon nitride ceramic is an excellent high-temperature resistance material that has outstanding physical properties, such as high elastic modulus, low density and low coefficient of friction [1]. Regarding these properties, silicon nitride has been widely used in the parts of engines used in the automobile and aircraft industries [2]. However, silicon nitride is difficult to machine because of high hardness and brittleness. For that reason, silicon nitride has been machined at high production cost by using grinding and diamond machining process [3].

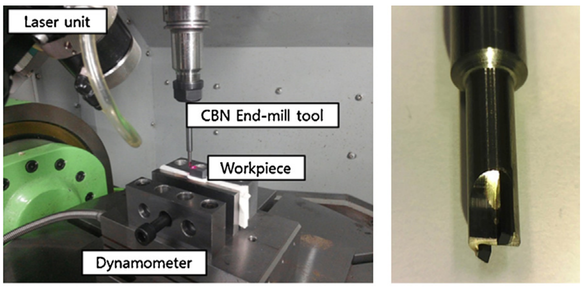
Laser-assisted machining (LAM) is one of the new processing technologies, which uses a laser beam for the processing of difficult-to-cut materials [4]. The machinability can be improved because the laser beam is used to abate the strength of difficult-to-cut materials [5]. Even though many studies regarding the LAM have been performed, most of these studies have been limited to laser-assisted turning [6,7]. Studies on the laser-assisted milling are necessary to enable the machining of difficult-to-cut materials.

Tian and Wu indicated the possibility of using the laser-assisted milling process for machining silicon nitride and Inconel-718 using TiAlN-coated carbide tool and SiC-reinforced alumina cutting tool [8]. Brecher and Emonts had attempted a new approach of laser-assisted milling to close the existing gap between the experimental stage and industrial application of laser-assisted milling [9]. Lei et al. conducted a turning experiment for the LAM of silicon nitride using PCBN tipped carbide insert and constitutive equation was determined [10].

This study aims to confirm the machinability of silicon nitride, which is one of the difficult-to-cut materials, using laser-assisted milling, as well as to obtain a constitutive equation of LAM according to the machining conditions and the experimental results. In addition, a newly modified constitutive equation is proposed for predicting material properties during the laser-assisted milling process under any mechanical conditions.

2. Thermal analysis and the first experiment

In the first experiment, silicon nitride is machined by using a 1-kW diode laser unit installed on a five-axis CNC machine. The experimental setup for the laser-assisted milling of silicon nitride is shown in Fig. 1. The circle-shaped laser spot that has a diameter of 3 mm is generated by the laser unit. During machining, the cutting force is measured using a Kistler 9257B dynamometer, which can measure the cutting force, thrust force and feed force. A cubic boron nitride (CBN) cutting end-mill tool, with a diameter of 4 mm and consisting of two flutes, was used for the experiments. The cutting tool has a helix angle of 0° and a radial relief angle of 5°; the size of the workpiece is 8 mm × 15 mm × 50 mm, the feed rate is 50 mm/min and the laser power is 200 W.



(a) (b)

Fig. 1. (a) The experimental setup and (b) end-mill tool shape.

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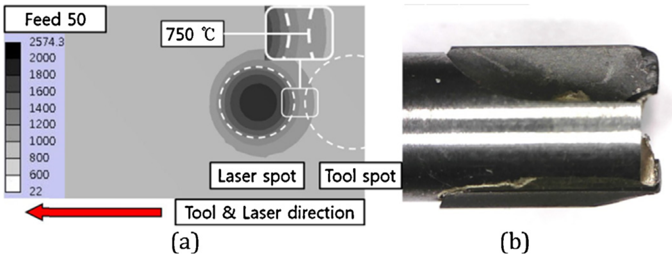

Fig. 2. (a) The temperature distribution determined using the thermal analysis and (b) microscopic view of the tool after machining.

Before machining, thermal analysis was performed to predict the thermal distribution of the workpiece and to calculate the laser power required in the first experiment. The preheating is performed in only 1 path, which is called 1-path preheating in this paper. Fig. 2 shows the temperature distribution of the workpiece determined using FEM analysis. The figure also shows the temperature at the laser spot and at the tool spot. Both the laser spot and the CBN cutting tool are moved at the same feed rate and direction. The preheating temperature should be higher than the glass transition temperature of silicon nitride, i.e., 1200 °C. The preheating temperature is higher than the glass transition temperature, but the temperature on the tool spot is approximately 750 °C. As a result, the edge of the CBN cutting tool is broken after machining because the preheating temperature is much lower than the glass transition temperature.

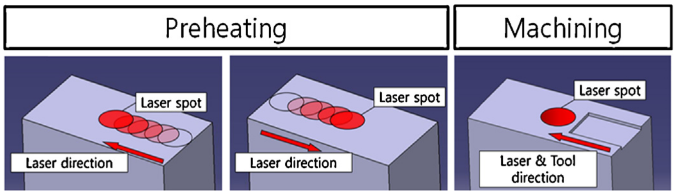

Fig. 3. Schematic of the back-and-forth preheating method.

3. Back-and-forth preheating method

If the laser power is increased to prevent the fractures of the cutting tool in the first experiment when using the 1-path preheating method, part of the oxidation zone remained after machining because the diameter of the cutting tool is much smaller than the oxidation zone. To reduce the oxidation zone after machining, a new back-and-forth preheating method is proposed. Fig. 3 shows the schematic of the back-and-forth preheating method. During preheating, the tool is stopped, and then the laser spot and tool are moved together after preheating. The advantage of the back-and-forth preheating method is that the laser spot and the tool spot temperature can be increased. Additionally, the oxidation zone can be reduced compared to the case of preheating by only increasing the laser power.

4. Thermal analysis to obtain machining conditions for the second experiment

To maintain the preheating temperature of the silicon nitride, the back-and-forth preheating method is used, and the workpiece is enclosed by an insulating material, as shown in Fig. 4(a). The thermal analysis using ANSYS workbench, a commercial software, was conducted. Fig. 4(b) shows the modelling of the silicon nitride workpiece, jig and fixture. The analysis conditions are summarized in Table 1. Table 2 shows the material properties of silicon nitride used in the thermal analysis. The emissivity of silicon nitride is shown in Fig. 5 [11,12].

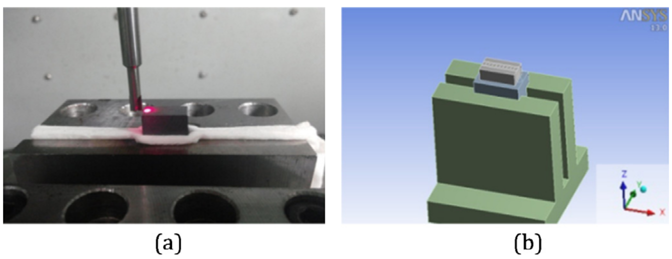

Fig. 4. (a) Set up of the workpiece enclosed by an insulating material and (b) the workpiece model.

Table 1
Analysis conditions.

Analysis	Back-and-forth feed rate (mm/min)	Machining feed rate (mm/min)	Laser power (W)
1	80	40	200
2	80	50	200
3	80	60	200
4	80	50	180

Table 2
Material properties of silicon nitride.

Temperature (K)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
500	25	910
1000	17.5	1170
1500	15	1215
2000	14	1220

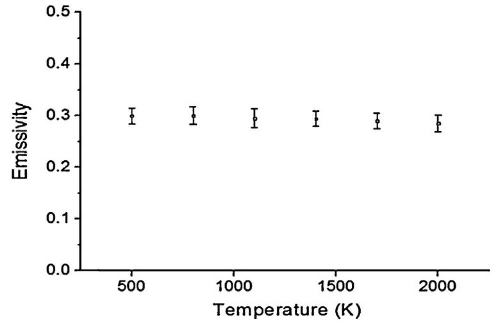

Fig. 5. Emissivity of silicon nitride.

A pyrometer was installed in experimental setup, but it can only measure temperatures of up to 1800 °C. For this reason, additional preheating experiments with lower laser power were performed to verify the thermal analysis method before performing the second experiment. A comparison of the laser spot temperature between thermal analysis results and preheating experimental results with the lower laser powers of 130 W and 160 W are shown in Fig. 6. The analyses and experiments are shown to be in good agreement. Therefore, the modelling and analysis method can be used to predict the machining conditions for the second experiment using the back-and-forth preheating method.

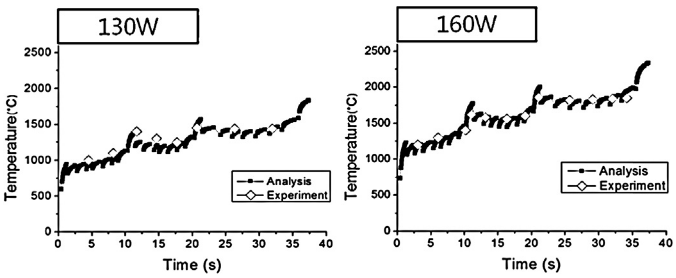

Fig. 6. Comparison of the laser spot temperature between the analysis and the experiment with lower laser powers.

The temperature distributions of the laser spot and the tool spot are shown in Fig. 7 under the analysis conditions in Table 1. The distance between the laser spot and tool spot is set to 0.5 mm to machine the workpiece before the preheating temperature drops. The tool spot temperature is maintained to above approximately 1100 °C because of the use of the back-and-forth preheating method.