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ORIGINAL ARTICLE

A study on the laser-assisted ball-end milling of difficult-to-cut materials using a new back-and-forth preheating method

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Abstract Laser-assisted machining is an effective process to facilitate the material removal processes of difficult-to-cut materials by laser preheating. Machinability of several difficult-to-cut materials, such as Inconel 718, zirconia, and silicon nitride, was studied including a newly developed back-and-forth preheating method used as an enhanced method to heat the workpiece effectively. Experiments were performed according to the inclination angle of the workpiece, for three-dimensional machining using a computed laser power and feed, on a 5-axes machining center with an additional axis for a laser module. The characteristics of the cutting force and surface roughness of the machined workpiece and the wear of the cutting tool were measured and discussed. Decreases in the cutting force and the enhancement of the surface quality were confirmed using the proposed back-and-forth preheating method in laser-assisted milling on Inconel 718, zirconia, and silicon nitride.

Keywords Machinability · Surface quality · Laser-assisted milling · Thermally enhanced machining · Difficult-to-cut materials

1 Introduction

Difficult-to-cut materials such as ceramics and metal alloys are widely applied in various industrial fields because of their superior characteristics, including durability, wear resistance, decay resistance, and heat resistance. However, their applications are limited by machining and manufacturing difficulties and high cost. Laser-assisted machining is one method to overcome the difficulties. It is an effective process to facilitate material removal processes for difficult-to-cut materials, by laser preheating [1–4].

Laser-assisted machining has already been studied by many researchers. However, it has only been studied in turning and micro end milling in relation to one-dimensional machining. For wider application, it is necessary to study machining of workpieces with complicated shapes and, therefore, three-dimensional laser-assisted machining.

Chang and Kuo [5] evaluated the surface roughness and material removal rate of laser-assisted turning of ceramics using a statistical method. Yang et al. [6] investigated mechanisms of edge chipping in laser-assisted milling of silicon nitride. Brecher et al. [7] developed a spindle-tool system for laser-assisted milling of advanced materials. Shen and Lei [8] evaluated the surface and subsurface quality of silicon nitride in laser-assisted milling. Ding et al. [9] analyzed laser-assisted micro-milling of difficult-to-machine alloys. Wiedenmann et al. [10] investigated the main parameter influencing a laser-assisted milling operation using a design of experiments (DOE). Zamani et al. [11] studied three-dimensional simulation and process optimization of laser-assisted milling of Ti6Al4V. Kim and Lee [12] experimentally studied cutting force and preheating temperature prediction equations for laser-assisted milling of Inconel 718 and AISI 1045 steel. Kang and Lee [13] developed a constitutive equation for silicon nitride in a laser-assisted milling process using a laser power control method. Sim and Lee [14] studied the laser preheating effect of an Inconel 718 workpiece with rotated angle. Wiedenmann and Zaeh [15] investigated process modeling and experimental validation in laser-assisted milling. Kizaki et al. [16] studied the cutting of zirconia ceramics

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using a heated cutting tool. However, only a very small depth of cut could be obtained in comparison with efficient laser-assisted machining. There are no laser-assisted milling (LAM) research works of difficult-to-cut materials with an inclination angle for three-dimensional LAM.

In this study, ball-end mills were used for a basic investigation of three-dimensional LAM using a workpiece with inclination angle. LAM was performed using laser power and feed for Inconel 718, zirconia, and silicon nitride by finite element method (FEM) thermal analysis, on a 5-axes machining center with an additional axis for a laser module. A back-and-forth preheating method was used as an enhanced method to heat the workpiece effectively [13]. Furthermore, unlike the laser power control method of the previous study [13], a temperature control method was used.

2 Laser-assisted milling

2.1 Thermal analysis to obtain proper preheating temperature

A proper preheating temperature should be determined based on the characteristics of the materials, because the preheating temperature is very important in LAM. The mechanical strength of Inconel 718 decreases significantly in the temperature range 650–950 °C [7, 12]. Zirconia and silicon nitride decrease between 900 and 1000 °C and between 1150 and 1250 °C, respectively [7, 8, 17].

The compositions of these workpieces are listed in Tables 1, 2, and 3.

To predict temperature distribution and depth of cut, a thermal analysis was performed.

The three-dimensional transient analysis by temperature-dependent inputs is explained by Eq. (1) as

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q} \quad (1)$$

Table 1 Material compositions of Inconel 718

Element	Weight %	Weight % sigma	Atomic %
Al	1.45	0.06	3.08
Si	0.19	0.04	0.38
Ti	0.90	0.07	1.08
Cr	15.44	0.16	17.05
Fe	18.60	0.20	19.13
Ni	55.94	0.30	54.72
Nb	4.28	0.19	2.65
Mo	3.19	0.21	1.91
Total	100.00		100.00

Table 2 Material compositions of zirconia

Element	Weight %	Weight % sigma	Atomic %
O	30.93	0.31	71.86
Zr	69.07	0.31	28.14
Total	100.00		100.00

where ρ, c_p, k, and $Q^{\cdot}$ represent density, specific heat, thermal conductivity, and power generation per unit volume, respectively.

The initial condition at time (t)=0 is given by Eq. (2) as follows:

$$T(x, y, z, 0) = T_0 \quad (2)$$

The boundary conditions can be defined by Eq. (3) as

$$-k\frac{\partial \mathrm{T}}{\partial \mathrm{z}} = q(x, y) - h(T - T_0) \quad (3)$$

where q, h, T, and T_0 are the heat flux, heat transfer coefficient, surface temperature, and ambient temperature, respectively.

The size of the workpiece used in the study was 10 mm× 5 mm×40 mm, and the preheating speed was 40 mm/min. The shape and the diameter of the heat source were circular and 3 mm, respectively. The finite element model was composed of the finite element analysis package (ANSYS). A hexagonal mesh was employed in the analysis model which included 59, 273 nodes and 19,304 elements, as shown in Fig. 1. The mesh size of the whole model was 1 mm, and the mesh size of the heated zone was 0.3 mm. The thermal properties of the workpiece are given in Table 4 as functions of temperature [12, 18, 19]. A heat source projection method by the present authors was applied in the thermal analysis [20]. To present the moving heat source, the boundary condition of the projection method was given sequentially according to the transfer speed by the overlaps to some extent along the laser route, as shown in Fig. 2.

Figure 3 shows the temperature distribution of the whole workpiece and at the cross sections under the laser heat

Table 3 Material compositions of silicon nitride

Element	Weight %	Weight % sigma	Atomic %
C	11.99	0.47	17.87
N	33.72	0.42	43.11
O	9.24	0.19	10.35
Al	1.96	0.04	1.30
Si	42.37	0.34	27.01
Cl	0.64	0.03	0.32
Ca	0.09	0.03	0.04
Total	100.00		100.00

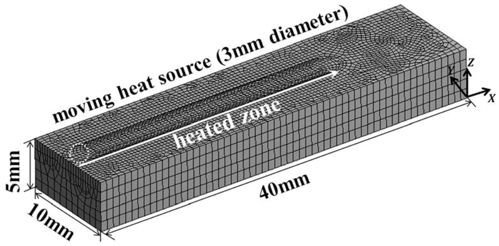


Fig. 1 Thermal analysis model

sources. Proper preheating temperatures were determined to be 800, 1300, and 1450 °C, respectively, by considering the fact that the heated temperatures at 0.3 mm below the surface of the workpiece were about 750, 1000, and 1250 °C.

2.2 Experimental setup

Figure 4 shows the schematic of the experimental setup and the equipment, which was installed in a 5-axes computer numerical control (CNC) machine with a laser module. The laser module was a high-power diode laser with a wavelength range of 940–980 nm. The diameter of the laser heat source was 3 mm with circular shape. The heat source was placed ahead of the cutting tool, generated by the laser module during machining. The distance between the edge of the cutting tool and the heat source was determined to be about 5 mm through several experiments for various kinds of cutting tool and materials to reduce the thermal effect on the cutting tool. When the distance was within 5 mm, the cutting tool was burned, and when the distance was over 5 mm, the material was not effectively preheated.

This study used the lens with 150 mm focal length in the laser module. The working distance of this lens was 138 mm. This distance was suggested by the manufacturer of laser module. It was maintained to obtain uniform laser power density.

This author has been studied the optimum distance in the previous study [21]. As the distance between the laser and workpiece surface changed, the diameter of the laser heat source changed. Furthermore, the surface temperature of preheated workpiece decreased with the change in focal length. When the error of the focal length was ±1 mm, the surface temperature of workpiece decreased to about 100 °C. Therefore, the optimum working distance between the laser and workpiece surface should be maintained exactly at 138 mm in the case of this study.

The laser module was linked to the spindle system of CNC machine. Therefore, the cutting tool and laser were moved together in the experiment. The heat source which was generated by the laser module was structurally placed ahead of the cutting tool during machining. The sequence control of the machine and laser module was possible using an M code in the CNC machine.

A laser pyrometer (LPC03; Dr. Mergenthaler GmbH & Co. KG) with a temperature range of 400–3000 °C was used to measure the temperature of the heating zone. The cutting force and the surface roughness were measured using a dynamometer (9257B; Kistler Inc.) and a surface roughness instrument (SE-3500K; Kosaka Inc.), respectively. Microphotograph of the machined surface was obtained using a field emission scanning electron microscope (MERLIN; ZEISS Inc.).

2.3 Back-and-forth preheating

The size of the heat source is very small compared to the size of the workpiece in LAM, so that the temperature decreases rapidly by the time the tool arrives at the heated zone. To solve this problem, newly proposed in the previous study [13] by the present authors, the back-and-forth preheating method is used.

Figure 5 shows the schematic diagram of the back-and-forth preheating method. Milling is not performed during the back-and-forth preheating, and then the laser heat source and cutting tool are moved together to machine the workpiece. Two times back-and-forth preheating was used in this study, as determined by trial and error.

2.4 Machining parameters

The determination of a proper cutting tool is very important in the laser-assisted milling. Because LAM performs machining after workpiece preheated by high heat source, the cutting tool should maintain heat stability and hard characteristics during machining.

Figure 6 shows the cutting tool used in this study. A tungsten carbide (WC) ball-end mill with cubic boron nitride (CBN) inserts, with a diameter of 8 mm, was used. The CBN has excellent wear resistance and heat stability. It is not oxidized in the temperature range of about 1370 °C. The cutting tool was designed and manufactured specially for this

Table 4 Thermal properties of workpiece

Material	Density (kg/m^3)	Thermal conductivity (y) (W/m/K)	Specific heat (y) (J/kg/K)
Inconel 718	8190	y=0.0142T+9.8387 (for 0≤T≤1600 °C)	y=0.0002T+0.4267 (for 0≤T≤1600 °C)
Zirconia	5750	y=−0.133T+1.5396 (for 300≤T≤1700 °C)	y=21.827T+456.09 (for 300≤T≤1700 °C)
Silicon nitride	3220	y=−1.2643T+18.664 (for 300≤T≤1700 °C)	y=90.863T+724.55 (for 300≤T≤1700 °C)

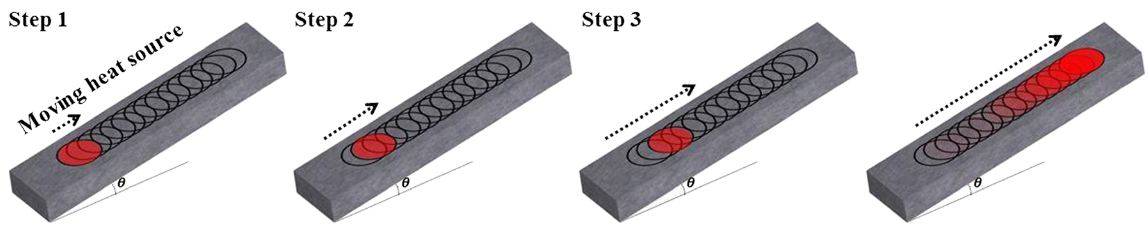
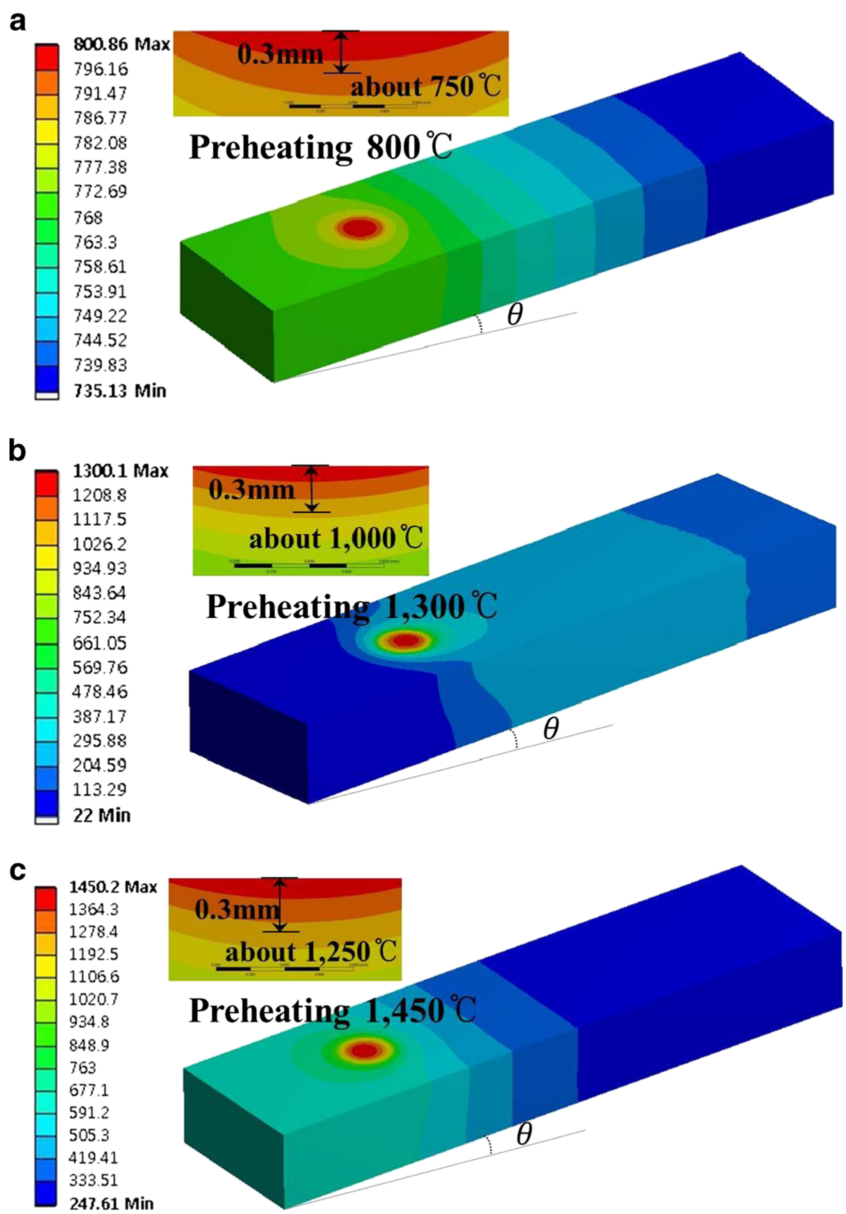


Fig. 2 Heat source projection method

study. The cutting tool for Inconel 718 by the commercial products of WIDIN Ltd. was used.

A cutting speed of 3000 rpm, a feed rate of 40 mm/min, a depth of cut of 0.3 mm, and an inclination angle of the workpiece of 0°, 10°, and 20° were used. The inclination angle of the workpiece could not be increased above 20° because of the interference between the heat source and the chucking system of the workpiece. When the back-and-forth preheating was used, the feed rate was 400 mm/min and the number of back-and-forth preheating passes was two times.

Fig. 3 The results of the thermal analysis of **a** Inconel 718, **b** zirconia, and **c** silicon nitride



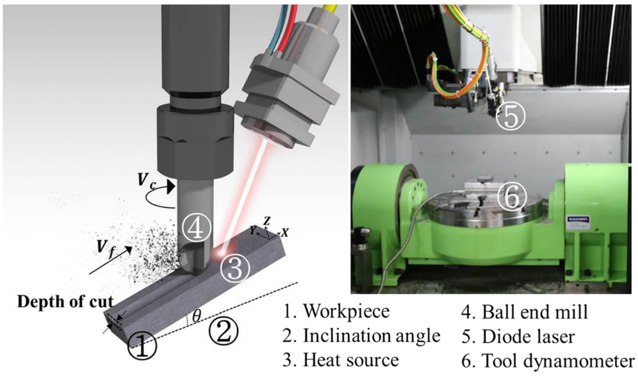


Fig. 4 The schematic of the experimental setup and equipment

3 Results and discussion

3.1 Preheating temperature measurements

Figure 7 shows the change of temperature and laser power during preheating. The workpiece was precisely preheated by the temperature control function of the laser module. The temperature control method was a method in which the desired heating temperature was maintained by automatically controlling the laser power using the pyrometer. The temperature control function was applied during actual cutting experiments.

To measure the preheating temperature, the pyrometer with a range of 400 to 3000 °C was used. So, the starting temperature and the end temperature of 400 °C are shown in Fig. 7. As was mentioned above, proper preheating temperatures of three workpieces are 800, 1300, and 1450 °C, respectively. The figure shows that the materials were preheated to proper temperature during machining time.

The laser power was not constant. The laser power was increased to about 852 W and about 746 W to rapidly increase the preheating temperature to 800 °C (Inconel 718) and 1450 °C (silicon nitride) in the initial stage of the machining, and then the laser power decreased between 393 and 233 W (Inconel 718) and between 463 and 304 W (silicon nitride) to maintain a constant preheating temperature of 800 and 1450 °C.

The graph for the zirconia was not obtained due to material characteristics. The preheating temperature is maintained

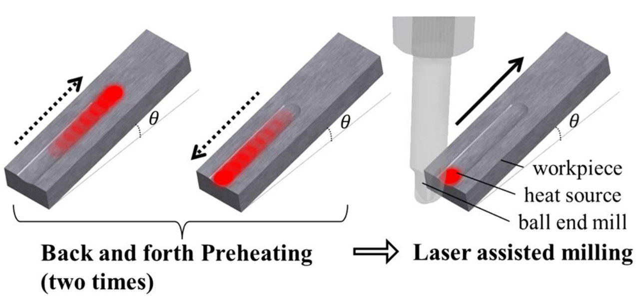


Fig. 5 The back-and-forth preheating method

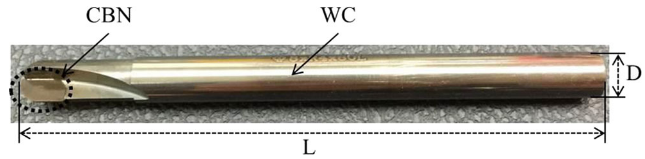


Fig. 6 Ball-end mill used in this study, with a length (L) of 100 mm, a diameter (D) of 8 mm, and two flutes

constant by varying the laser power in the temperature control method.

3.2 Laser-assisted milling of Inconel 718

Three methods were performed for the experiments: conventional machining (CM) without laser preheating, laser-assisted milling (LAM) with laser preheating, and laser-assisted milling with back-and-forth laser preheating (LAM (B&F preheating)).

Figure 8 shows the surface roughness according to the inclination angle of the workpiece.

The surface roughness was expressed by the center line average height, R_a. The measurement length was 4 mm on the machined surface of the workpiece, and the measurement speed was 0.2 mm/s. For the analysis of the surface roughness, Gaussian profile filter was used. The Gaussian filter has been recommended by ISO 11526-1996 [22] for determining the mean in surface metrology. The Gaussian filter is currently the only standardized surface texture filter. It describes how to separate the long- and short-wave content of a surface profile. The filter kernel for a Gaussian filter is expressed by Eqs. (4) and (5) as follows:

$$S(i) = \frac{1}{\alpha\lambda} e^{-\pi\left(\frac{i}{\alpha\lambda}\right)^2} \quad (4)$$

$$\alpha = \sqrt{\frac{\ln(2)}{\pi}} = 0.4697 \quad (5)$$

where λ is the cutoff wavelength.

The cutoff value of 0.25 mm was used in this study.

When the inclination angle of the workpiece increased, the surface roughness decreased. The surface roughness decreased by about 34.2 and 56.8 %, by the LAM and the LAM (B&F preheating), respectively, compared to the results of CM.

When the laser preheating was used, the surface roughness improved because the cutting resistance decreased by the laser preheating which softens the material prior to machining.

Figure 9 shows the microphotograph of the machined surface. The results of the quality of the machined surfaces were shown to be similar to the measured surface roughness. When the inclination angle of the workpiece was increased and B&F preheating was performed, the quality of the machined surfaces improved.

Figure 10 shows the measured cutting forces along F_x, F_y, and F_z according to the inclination angle of the workpiece.

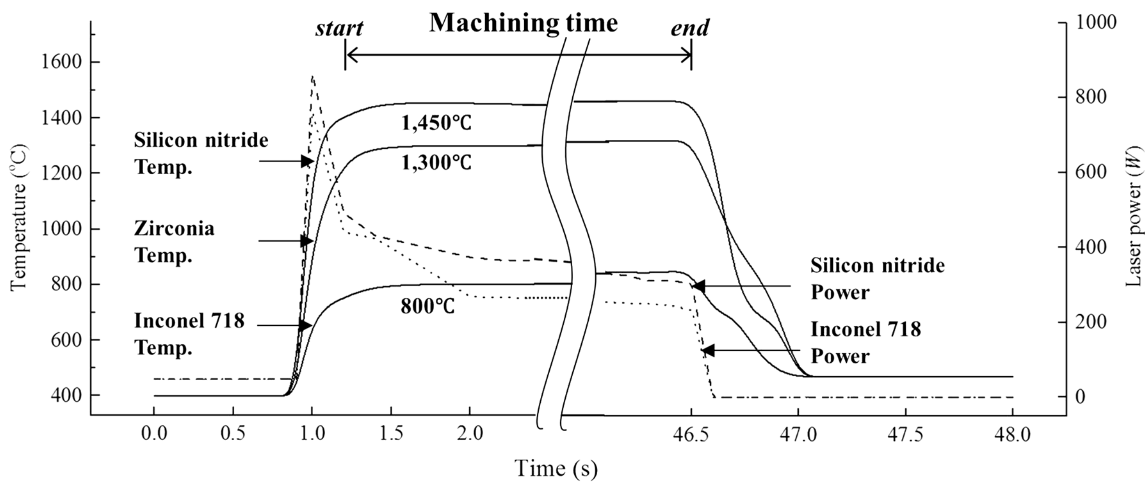


Fig. 7 Change of temperature and laser power during preheating

When the inclination angle of the workpiece increased, the cutting force decreased. The cutting forces decreased in the order of CM, LAM, and LAM (B&F preheating). The decrease in the cutting force and the enhancement of the surface finish were confirmed through the LAM experiments. LAM (B&F preheating) was confirmed to be the most effective method.

An average force during the total machining time was applied because the cutting speed, the feed rate, and the depth of cut are maintained during the machining process. The most consistent results that minimize the fluctuations of the cutting force through repeated experiments were applied.

In LAM, the cutting forces decreased because the material was softened by the laser preheating.

3.3 Laser-assisted milling of ceramics

It is impossible to machine ceramics by conventional machining because of their brittleness. Therefore, LAM and LAM (B&F preheating) should be used in machining of ceramics to prevent breakages of cutting tools and workpiece.

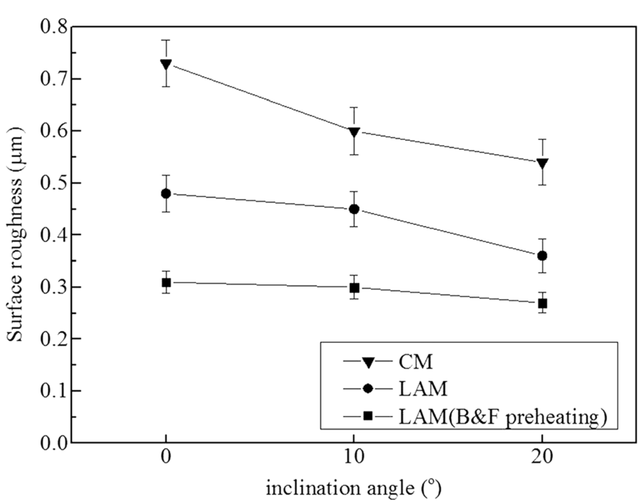


Fig. 8 Surface roughness (R_a) according to the inclination angle of workpiece

Zirconia and silicon nitride with inclination angles of 0°, 10°, and 20° were machined effectively by LAM and LAM (B&F preheating). Microphotographs of the machined surface were obtained using a SEM microscope. The measured zone on the machined surface was determined as shown in Fig. 11.

The surface machined by LAM (B&F preheating) was better compared to LAM. So, it was confirmed that LAM (B&F preheating) was the most efficient method to machine ceramics. The machined surface quality was shown to be similar to the measured results of the surface roughness.

Figure 12 shows the measured cutting forces along F_x, F_y, and F_z according to the inclination angle of the workpiece. In the case of the LAM of zirconia, when the inclination angles of the workpiece were 0°, 10°, and 20°, F_x was measured to be 20.3, 19.5, and 14.2 N, respectively. F_z was measured to be 87.6, 71.4, and 50.3 N, respectively. F_x decreased by about 6.9, 21.0, and 2.1 %, respectively, by the LAM (B&F preheating) in the order of the inclination angle as compared to the LAM. Likewise, F_z decreased by about 7.4, 11.1, and 13.1 %, respectively, by the LAM (B&F preheating) in the order of the inclination angle as compared to the LAM.

In the case of the LAM of silicon nitride, when the inclination angles of the workpiece were 0°, 10°, and 20°, F_x was measured to be 23.8, 19.6, and 17.9 N, respectively. F_z was measured to be 92.8, 76.7, and 54.5 N, respectively. F_x decreased by about 29.4, 22.9, and 46.9 %, respectively, by the LAM (B&F preheating) in the order of the inclination angle compared to LAM. Likewise, F_z decreased by about 10.5, 20.1, and 10.3 %, respectively, by the LAM (B&F preheating) in the order of the inclination angle compared to the LAM.

Figures 13 and 14 show the surface roughness according to the inclination angle of zirconia and silicon nitride. When the inclination angle of the workpiece increased, the surface roughness decreased. In the LAM (B&F preheating), the surface roughness improved because the cutting resistance

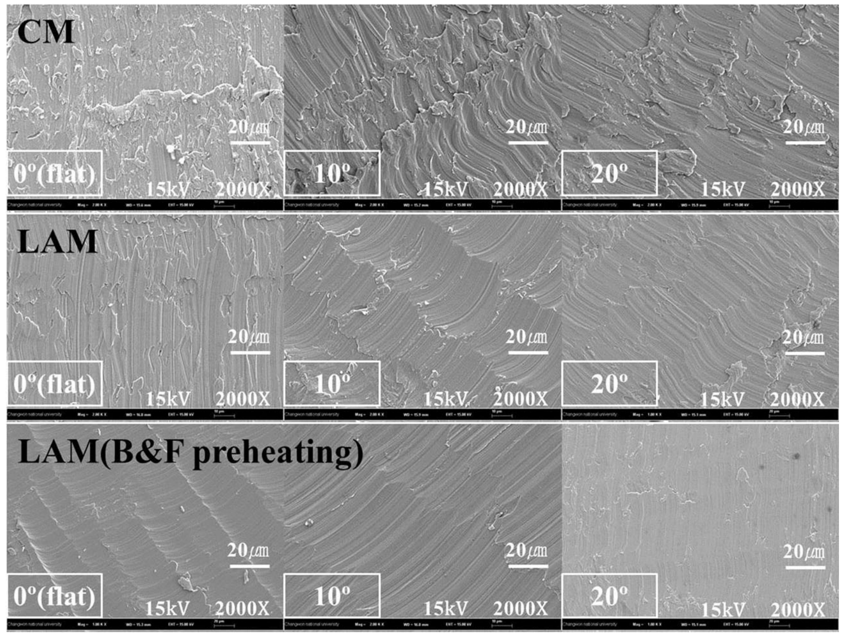


Fig. 9 Microphotographs of machined surfaces (Inconel 718)

decreased by laser back-and-forth preheating which effectively softens the material prior to machining.

3.4 Tool wear

The cutting tool wear measurements were performed. Figure 15 shows the used tools in the experiments with various machining conditions. One tool was used for machining of a workpiece in the experiments because the effect of another tool path was not shown in the used tool.

In the case of Inconel 718, the tool was not damaged after machining because the tool material is strong enough.

In the case of zirconia and silicon nitride, tools were damaged after machining with similar tendency. Burning, chip adhesion, and edge fracture occurred.

As the inclination angle of the workpiece increased, the damage of the cutting edge decreased. Moreover, LAM (B&F preheating) was better than LAM. The back-and-forth preheating in laser-assisted milling was an effective method in terms of the tool damage.

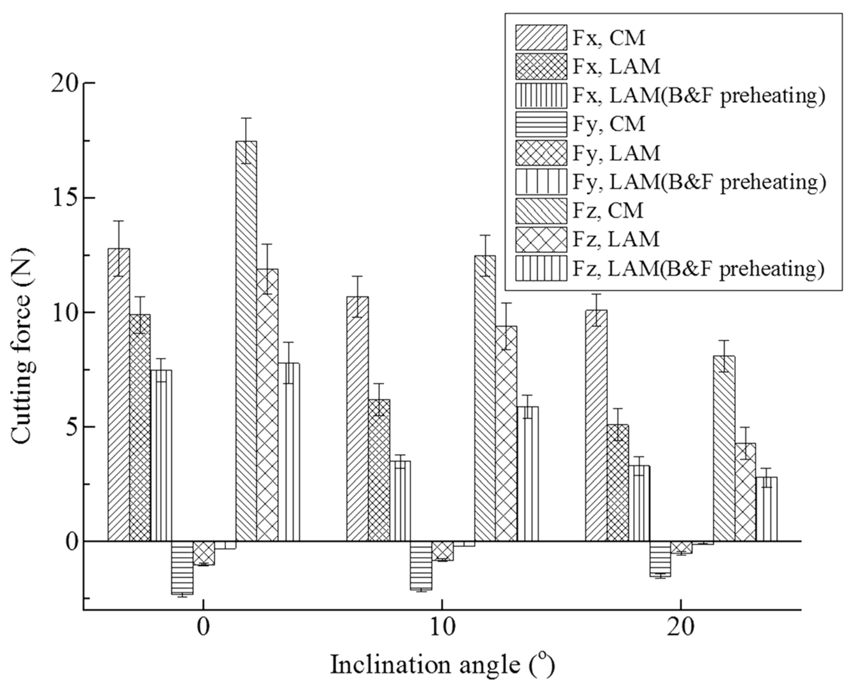


Fig. 10 Cutting forces of Inconel 718 according to the inclination angle

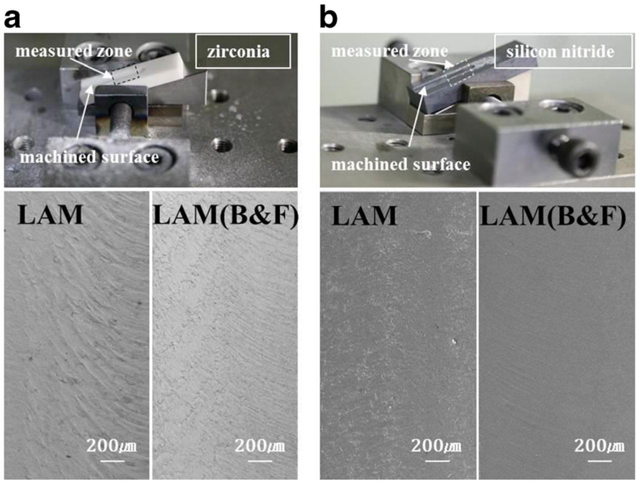


Fig. 11 Microphotograph of machined surfaces (20° inclination angle) of **a** zirconia and **b** silicon nitride

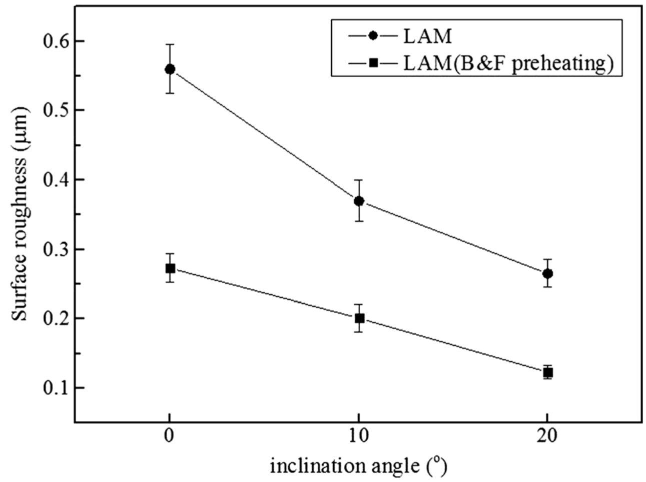


Fig. 13 Surface roughness according to the inclination angle of workpiece of zirconia

4 Conclusions

In this study, laser-assisted milling using a back-and-forth preheating method on Inconel 718, zirconia, and silicon nitride was investigated. Experiments were performed by CBN ball-end mill according to the inclination angle of the workpiece for a basic study of three-dimensional machining.

Decreases in the cutting force and the enhancement of the surface quality were confirmed using LAM and the proposed LAM (B&F preheating) using the temperature control method on Inconel 718, zirconia, and silicon nitride.

The conclusions of this study are summarized as follows:

(1) The proposed back-and-forth preheating method (LAM (B&F preheating)) was confirmed to be the most effective method to facilitate machining of difficult-to-cut materials in LAM.
(2) The proper preheating temperatures to be produced by the proper laser power and feed were determined by considering the temperature distribution under the surface of the workpiece.
(3) The surface roughness of machined Inconel 718 decreased by about 34.2 % and about 56.8 % by the

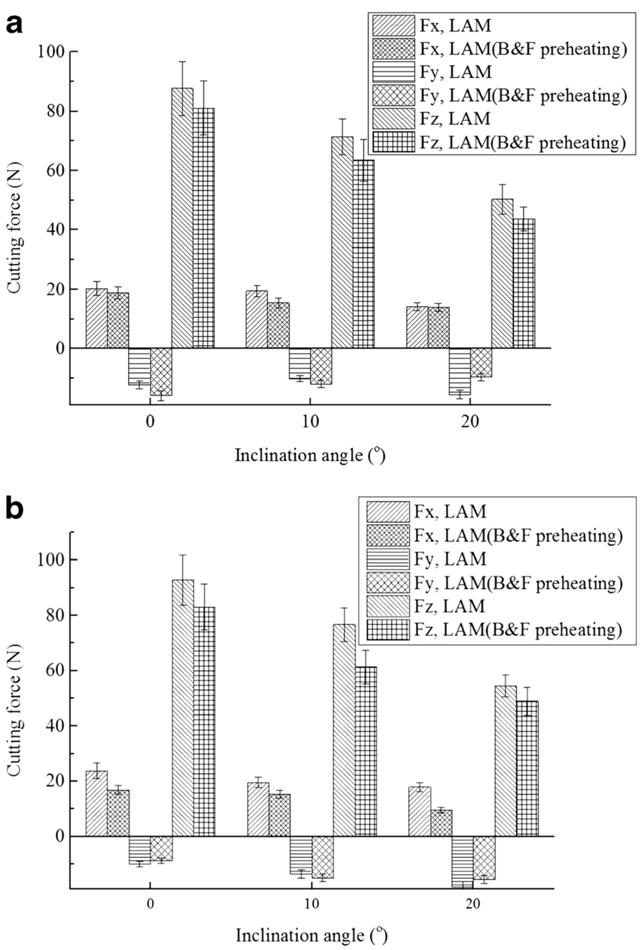


Fig. 12 Cutting forces of **a** zirconia and **b** silicon nitride

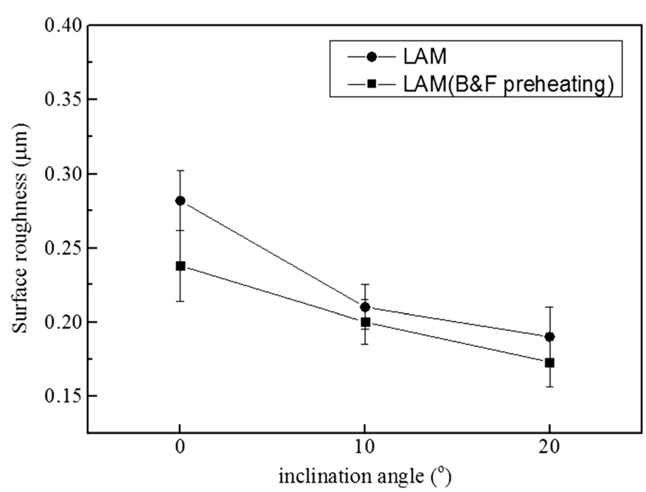


Fig. 14 Surface roughness according to the inclination angle of workpiece of silicon nitride

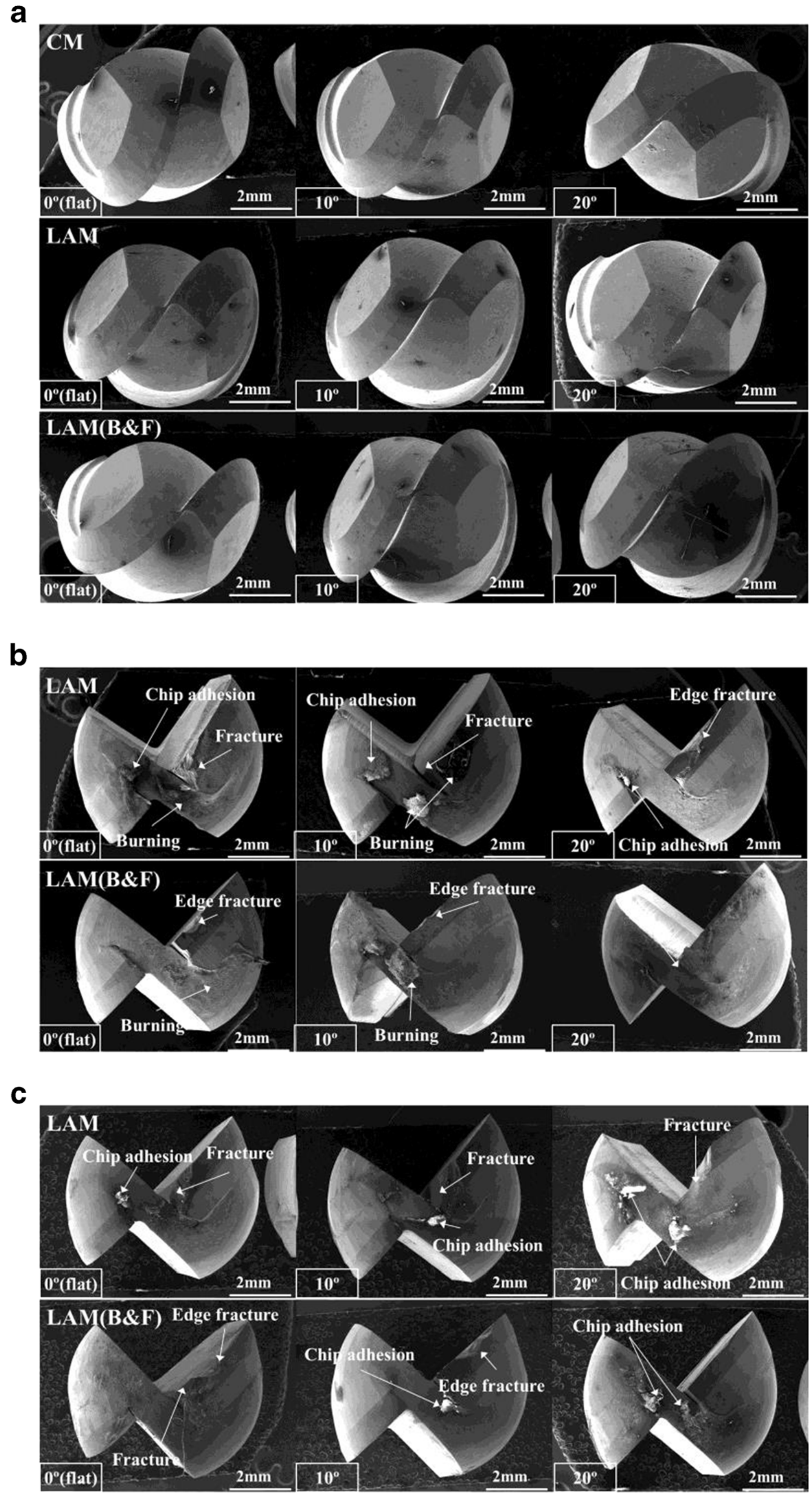


Fig. 15 SEM micrograph of the used cutting tool in experiments. **a** Inconel 718. **b** Zirconia. **c** Silicon nitride

LAM and the LAM (B&F preheating), respectively, compared to the results of CM. The cutting forces decreased in the order of CM, LAM, and LAM (B&F preheating).

(4) The surface quality of zirconia and silicon nitride after LAM (B&F preheating) was better compared to LAM. In addition, F_x, F_y, and F_z decreased according to the inclination angle of 0°, 10°, and 20°. When the

inclination angle of the workpiece increased, the surface roughness decreased. In the LAM (B&F preheating), the surface roughness improved because the cutting resistance decreased by laser back-and-forth preheating which effectively softens the material prior to machining.

(5) The cutting tool wear measurements were performed. As the inclination angle of the workpiece increased, the damage of the cutting edge decreased. Moreover, LAM (B&F preheating) was better than LAM. The back-and-forth preheating in laser-assisted milling was an effective method in terms of the tool damage.

The results of this study could have a wide application in three-dimensional laser-assisted milling of difficult-to-cut materials.

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