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Characteristics of laser assisted machining for silicon nitride ceramic according to machining parameters †

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Abstract

This paper describes the Laser Assisted Machining (LAM) that cuts and removes softened parts by locally heating the ceramic with laser. Silicon nitride ceramics can be machined with general machining tools as well, because YSiAlON, which was made up ceramics, is soften at about 1,000℃. In particular, the laser, which concentrates on highly dense energy, can locally heat materials and very effectively control the temperature of the heated part of specimen. Therefore, this paper intends to propose an efficient machining method of ceramic by deducing the machining governing factors of laser assisted machining and understanding its mechanism. While laser power is the machining factor that controls the temperature, the CBN cutting tool could cut the material more easily as the material gets deteriorated from the temperature increase by increasing the laser power, but excessive oxidation can negatively affect the quality of the material surface after machining. As the feed rate and cutting depth increase, the cutting force increases and tool lifespan decreases, but surface oxidation also decreases. In this experiment, the material can be cut to 3mm of cutting depth. And based on the results of the experiment, the laser assisted machining mechanism is clarified.

Keywords: Silicon nitride; HPDL (high power diode laser); LAM (laser assisted machining); Oxidation; LAM mechanism

1. Introduction

Ceramics is one of the major materials, such as metals and plastics, being used by many industries. These high quality ceramic materials are widely used in the architecture, engineering, engine, medical applications, aerospace and marine fields, and are gaining attention in other fields due to their outstanding characteristics, such as immense strength, excellent wear resistance, chemical stability, and immense strength at a high temperature [1, 2]. However, due to the unique characteristics of the high quality ceramics, engineering these ceramics can easily cause problems such as surface defect flaws, microcracks, and subsurface damage due to their immense strength and high capacity for brittleness. Due to these characteristics, it is difficult to use them as a product because it requires high cost and long hours for product machining. Therefore, there has been significant limitation in the wide application of these materials in various fields.

Therefore, Laser Assisted Machining (LAM) for the silicon nitride ceramic was studied. The silicon nitride ceramic is one of the engineering ceramics that cuts and removes only the softened parts by heating it locally with a laser beam. The silicon nitride ceramic can become softened at about 1,000℃, and at a high temperature, the hardness significantly decreases, making this material more likely to be cut machined with a general cutting machine, such as a Cubic Boron Nitride (CBN) cutting tool. The LAM of silicon nitride has been studied by other researchers for long time [3-5]. The laser beam can heat material locally by concentrating on highly dense energy, so it can control the temperature of the heated part of the specimen very effectively [6, 7]. However, the studies used the silicon nitride ceramics that were 8mm in diameter and a CO_2 laser as the heating source. But running cost of a diode laser is cheaper than a CO_2 laser, and it is easier to transfer the laser beam using a fiber than a CO_2 laser. So, a diode laser is handled easily on the CNC, robot, scanner, etc because the laser head is small and light in weight. Therefore, a diode laser can be used in the various processing industries because of these advantages. However there are no enough experiments data of LAN using a diode laser until now. Accordingly in this report, LAM of the High Power Diode Laser (HPDL) were studied to practical use. And it was possible to machine the

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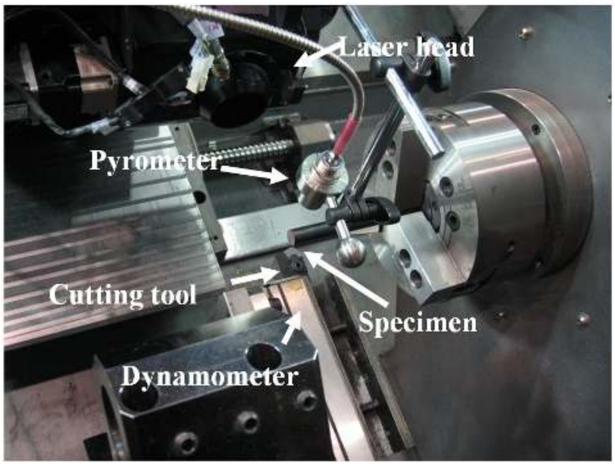


Fig. 1. Experimental system for laser-assisted machining.

larger size of silicon nitride than earlier studies. In this study, since LAM is a process that combines the cutting process with laser preheating, which involves many machining variables, it is necessary to grasp the complex relationship of the laser, lathe, and machined material, as well as the tool aspect and deduce optimal process variable, in order to let LAM run successfully.

This paper intends to propose an efficient machining method for silicon nitride ceramic by deducing the machining governing factors of LAM and understanding its mechanism.

2. Experimental procedure

2.1 Materials

Silicon nitride has a small dispersion coefficient of nitrogen within the crystal. It can be thermally decomposed to Si and N when the temperature reaches 1,883℃ in a 1 bar nitrogen atmosphere. The sintered silicon nitride ceramic is composed of a crystalline secondary phase, β-Si_3N_4 particles of a hexagonal bar shape, and an amorphous YSiAlON near crystalline particle. The hexagonal particles of the silicon nitride used in this study was about 7 ㎛ long.

Such silicon nitride ceramic has a high strength at room temperature, and thus cannot be cut with a CBN tool. However, as this substance can experience plastic deformation due to the decrease in viscosity and the deterioration of YSiAlON's strength and the vitreous phase that exists in the intergranular area at a high temperature, it can be cut with a CBN tool.

In this study, a round bar shaped silicon nitride specimen was used for LAM, and the specimen was 150mm long and 16mm in diameter.

2.2 Experimental procedure

In this study, a 2.5kW level HPDL was used as the heat source, the wavelength of it is 0.91 and 0.98 ㎛ and a spectral absorptivity of Si_3N_4 is about 0.8. In addition, for real time measurement of the cutting force and surface temperature, a dynamometer and pyrometer were used, respectively. As for the tool used in this experiment, a CBN tool was inserted with a noise radius of 0.8mm, a thickness of 4.76mm, and a negative slope angle of -6° that has two mutually combined body centered cubic lattices similar to a diamond.

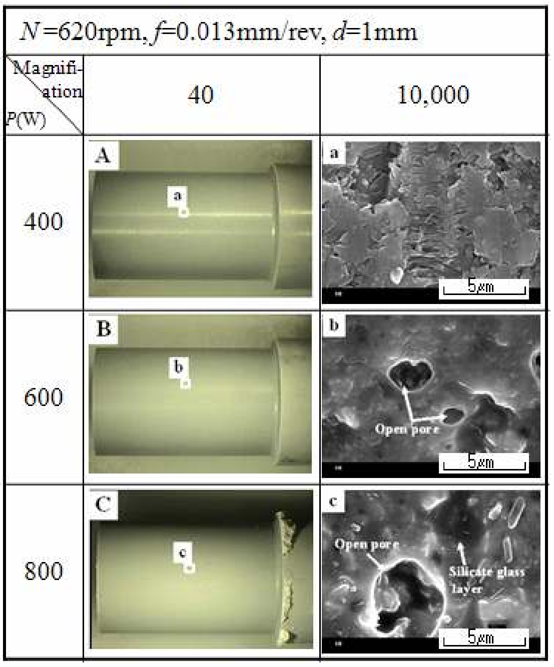


Fig. 2. Photos and SEM images of surface for silicon nitride machined according to laser power.

Fig. 1 shows a photo of the experiment device installed for LAM. In order to prevent chattering during the machining by specimen eccentricity, the specimen was fixed by 3-jar-chuck and whether eccentricity exists or not was checked by using a dial gauge. The pyrometer was installed 90° from the laser irradiation part and the dynamometer was installed 180° from the location in order to get the data.

3. Results and discussion

3.1 Variation of surface machined according to the changes in the machining parameters

With the silicon nitride ceramic fixed to the machining conditions of a rotation speed (N) of 620rpm, a feed rate (f) of 0.013mm/rev, and a cutting depth (d) of 1mm, the specimen surface was machined by laser power. The macro and SEM photos of the surface are shown in Fig. 2. In the case of the laser power of 400W, the surface looked good when it was observed visually. When it was observed with a SEM photo magnification of 10,000, a flow surface from plastic floating was found, but the silicate glass layer was barely observed. It was found that with an increase in the laser power, the machined face deteriorated. From 600W of laser power, the amount of heat input was greater than at 400W even when the

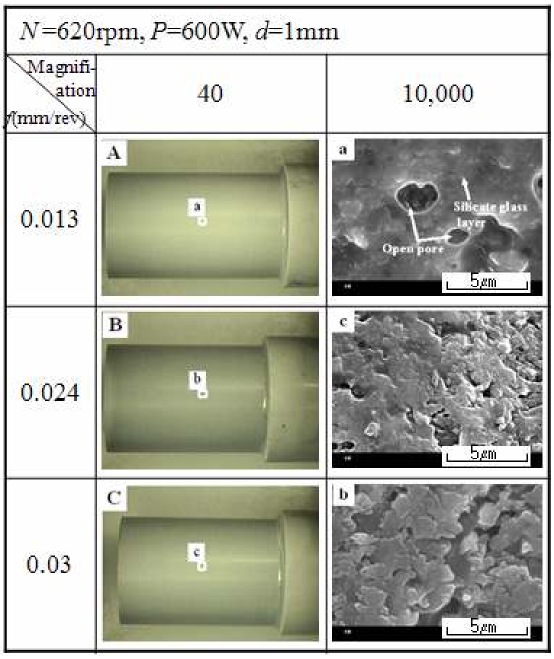


Fig. 3. Photos and SEM images of surface for silicon nitride machined according to feed rate.

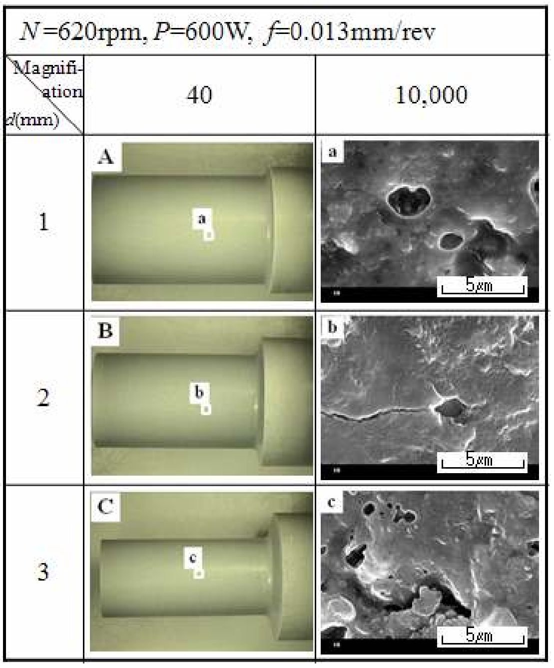


Fig. 4. Photos and SEM images of surface for silicon nitride machined according to cutting depth.

oxidized layer was removed. Therefore the silicate glasses and open pores formed from oxidation at the machined part because of the heat forming from preheating before cutting. The post heat formed from heat transferring from the irradiating part of the laser beam at the tip of the cutting face after machined. At 800W of laser power, not only the pore size and quantity opened, but the thickness of the silicate glass layer was also found to have been increased. In other words, the more the laser power increases, the more the surface temperature rises, which promotes the softening of the specimen, making the energy required for cutting decreases. However, the thermal decomposition of silicon nitride on the surface, or inside the cut part from excessive heat input, produces N_2 gas, leaving open pores or oxides, and thus decreasing the surface's roughness.

Fig. 3 shows photos of the silicon nitride ceramic surface, which were put to LAM by changing the feed rate respectively to 0.013, 0.024 and 0.03mm/rev with the specimen rotation speed fixed to 620 rpm, laser power to 600W, and cutting depth to 1mm. With an increase in the feed rate, the specimen surface decreased in oxidation degree. At a feed rate of 0.013mm/rev, the open pores and silicate glass phase were found on the surface due to the effect of post heating at a relatively slow machining speed. With a feed rate of 0.024mm/rev, such phenomenon disappeared, and flow surface from plastic machining was found.

Fig. 4 shows photos of the specimen surface observed from microscope and SEM when the cutting depths were changed to 1, 2 and 3mm with a specimen rotation speed fixed to 620 rpm, a laser power fixed at 600W, and a feed rate fixed at 0.013mm/rev. As the cutting depth deepened, the depth of removing the Heat Affected Zone (HAZ) deepened. Therefore Fig. 4 shows that as the distance between the tip of the cut part, machined part, and irradiated part by laser beam becomes farther, the effects of post heat decrease, improving the degree of machined part oxidation and deterioration.

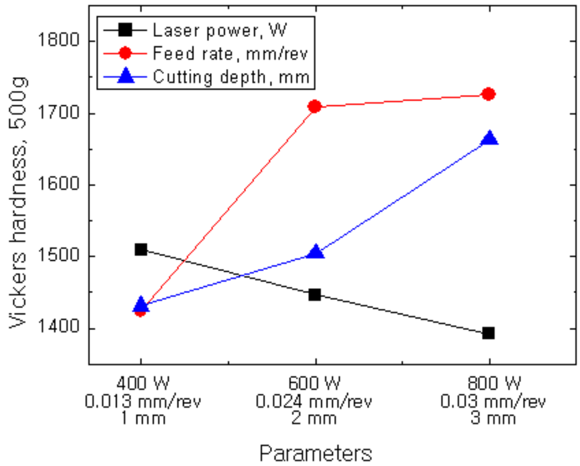


Fig. 5. Graph of vickers hardness for silicon nitride machined by parameters.

The changes of the machined surface in the above conditions are shown on the graph of Fig. 5. As shown in the graph, the more the laser power increases, the more the hardness decreases, and that is due to the deterioration of the surface from excessive heat input. It is shown that at a laser power of 600W and cutting depth of 1mm in LAM, if the feed rate increases, the surface hardness increases. That indicates that

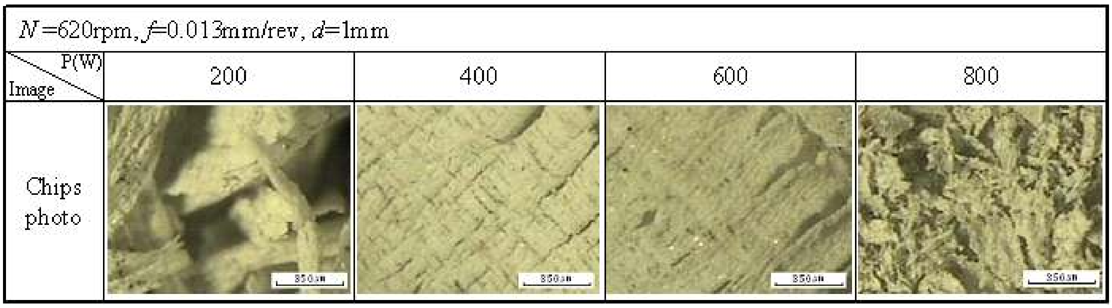


Fig. 6. Photos of chips for silicon nitride machined according to laser power.

with an increase in the feed rate, the amount of heat input decreases, reducing the oxidation and deteriorating the machining part surface, which improves the surface hardness. It is shown that as the cutting depth deepened, the value of the hardness largely increased. That means that under the same laser power, the effect of the heat differs with the depths. Therefore, removing the material to the maximum extent of the depth that received the effects of the heat is the method that can improve the quality of the product surface. According the results of this experiment, surface roughness of specimens machined by LAM has almost same roughness with the diamond machined one which was 0.4 ㎛ Ra.

3.2 Variation of chips shape according to machining parameters

The LAM characteristics of the silicon nitride ceramic were observed with the use of the shape of cutting chips. Fig. 6 shows the chips generated when there was a change in the laser power with the rotation speed fixed to 620 rpm, the feed rate to 0.013mm/rev, and cutting depth to 1mm. At a laser power of 200W, shear type chips were produced, and as the power increased, the chip types transitioned from 400W to flow type chips. As the laser power increased to 600W and 800W, the fluidity and continuity of the chips grew more vivid.

The comparison of the chip shapes with the feed rate and cutting depths is shown in Fig. 7. In the case the powers and cutting depths are the same, the change in the chip shape by the feed rate was not notable, but as the feed rate increased, the fluidity tended to decrease little by little. In addition, with an increase in the cutting depth, the chip thickness grows, making it easier for the chip shape to remain floating, and that subsequently creates floating chips more easily. It was observed that in the case of chips cut to 1mm of cutting depth, the chips are of a flow type, but compared to the chips with a cutting depth of 2 and 3mm, continuity and fluidity declined.

3.3 Cutting force and tool lifespan of laser power, feed rate and cutting depth

Main cutting forces of the laser power of silicon nitride ceramic are shown in Fig. 8. At a laser power of 200W, it is shown that the cutting process stopped due to the tool damage during the cutting process, and the cutting force was high with

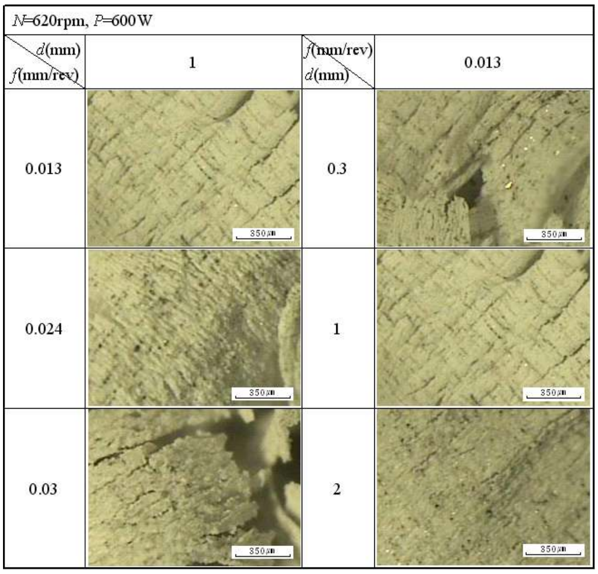


Fig. 7. Photos of chips for silicon nitride machined according to feed rate and cutting depth.

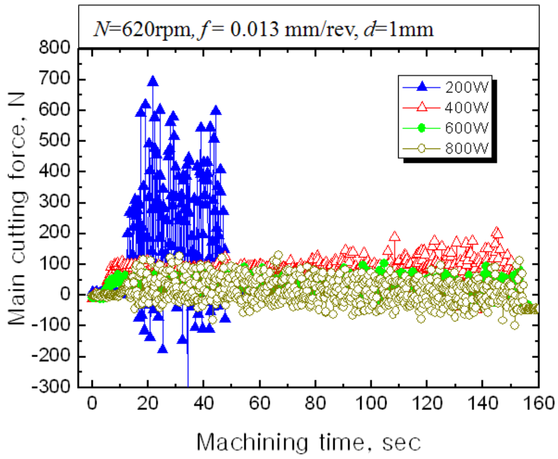


Fig. 8. Graph of main cutting force for Si_3N_4 according to laser power.

large chattering. At the same time, as the power increases, the main cutting force decreases, and that is because the cutting force was reduced through cutting by plastic deformation as the specimen surface is preheated and YSiAlON is softened due to high temperature. That also reduces the abrasion of the

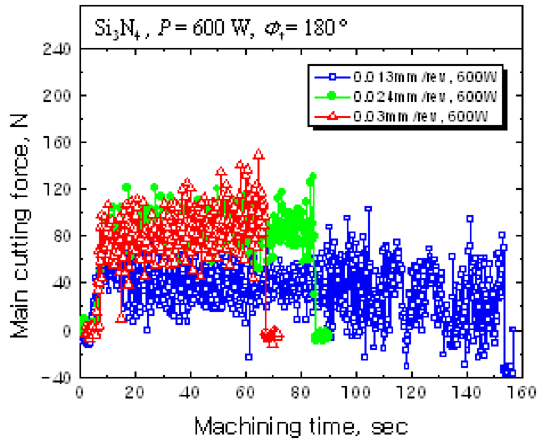


Fig. 9. Graph of main cutting force for Si_3N_4 according to feed rate.

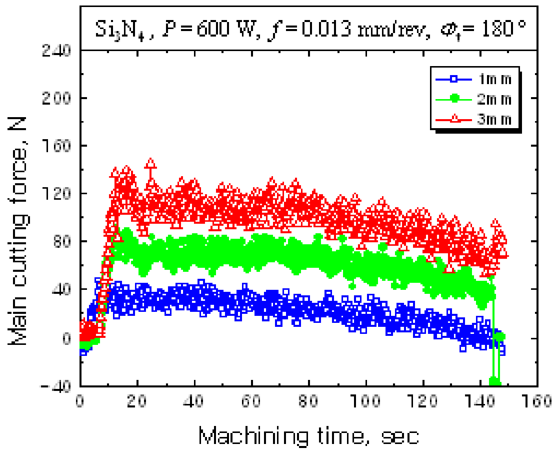


Fig. 10. Graph of main cutting force for Si_3N_4 according to cutting depth.

cutting tool and increases the tool lifespan. In addition, since the chattering decreases, the roughness of the machined surface is also expected to improve. Therefore, if the degree of oxidation of the specimen surface is not considered, the machining conditions become better such as an increase in the tool lifespan with an increase in power.

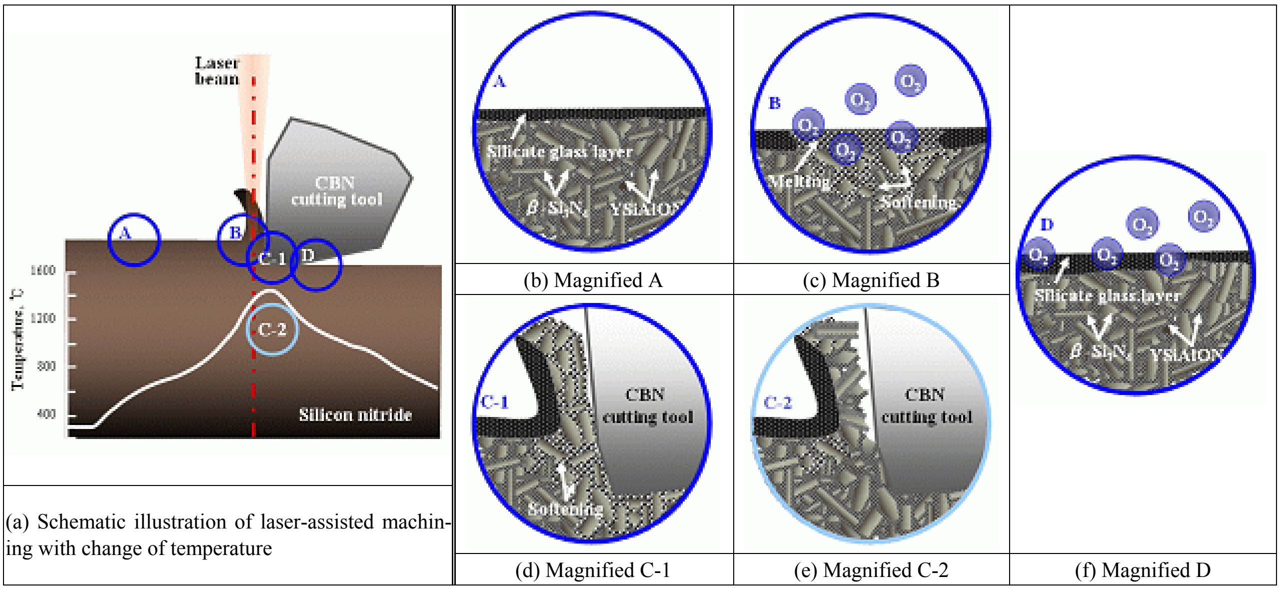
Fig. 9 shows the cutting force with the changes in the feed rate. As the feed rate increases, the machining time decreases and the cutting force increases. Therefore, increasing the feed rate may cause a reduced tool lifespan. Fig. 10 compares the cutting forces with the cutting depths. As a result of changing the cutting depth to 1, 2 and 3mm at a laser power of 600W, which is relatively good machining condition, the cutting force increases due to the increase in the cutting force. That is because the temperature rose in the specimen surface toward the depth direction, making preheating become deficient and YSiAlON not sufficiently softened. Therefore, a stronger cutting force is required. If the degree of surface oxidation is not considered, the side with a lower cutting depth can increase the tool's lifespan.

3.4 Mechanism of LAM for silicon nitride

The mechanism of LAM was clarified based on the contents described above and is shown in Fig. 11. Fig. 11(a) shows the diagram of cutting using the specimen temperature and tool from laser irradiation during LAM. 'A' indicates the surface of specimen before the laser was irradiated, 'B' shows the part onto which the laser was irradiated, 'C' shows the part where cutting was done, and lastly, 'D' shows the surface of specimen after cutting. As for the temperature, the value for the part slightly behind the laser beam center is shown. 'C', which shows cutting in progress, was divided into sufficiently preheated C-1 and insufficiently preheated C-2. In the magnified diagram of 'A', the silicate glass layer, which was thinly covered on the surface, was composed of β -Si_3N_4 in a hexagonal bar shape and an amorphous YSiAlON that connected with it. In the laser irradiation part of 'B', the oxidation reaction and YSiAlON softening by surface melting and oxygen infiltration by temperature rising were found. In the cutting process, when the temperature sufficiently rose, intergranular fracture occurred due to plastic deformation where silicon nitride particles dropped out instead of breaking apart due to the softening of YSiAlON as is shown in the graph. In the case of C-2, whose temperature did not sufficiently rise, and the intergranular area did not sufficiently soften, the cutting is done through transgranular fracture, where silicon nitride particles break away, instead of intergranular fracture, where plastic deformation occurs with a cutting tool. In the case of cutting with an intergranular fracture, cutting force with plastic deformation decreases, leading to an increase in tool lifespan. However, in the case of transgranular fracture, a cutting force is required for tools to break off the particles. Therefore, due to the increase in cutting force and heightening of the tool load, the material may be easily worn out or break off. Therefore, the case of C-1, where intergranular fracture was induced by plastic deformation through a sufficient temperature rise, was found to be a good machining condition. When the specimen surface was observed after cutting was done, the temperature that rose through preheating by laser irradiation still remained, as well as the specimen surface that was heated through post heating by heat transferring from laser irradiation part. Therefore, oxidation reaction occurred, generating a silicate glass layer through reactions with oxygen. Such trend is more likely when the temperature was high and excessive laser power at times formed pores on the surface after machining. As such oxidation reaction can cause problems in reducing the hardness of the machine surface, oxidation reactions after the machining of the machined face should be considered when machining selects the laser power.

4. Conclusions

As a way to develop a new machining method for active application of silicon nitride ceramics with high strength and brittleness, the potential of LAM and machining characteris-



(a) Schematic illustration of laser-assisted machining with change of temperature

(b) Magnified A

(c) Magnified B

(d) Magnified C-1

(e) Magnified C-2

(f) Magnified D

Fig. 11. Schematic illustration of laser-assisted machining mechanism.

tics by process variables were evaluated as well as the structural changes and machining mechanism of the materials. The results are arranged as follows:

(1) Silicon nitride ceramic was composed of β-Si_3N_4 of a bar shape and an amorphous YSiAlON that connected with it. As the surface was melted with a rise in the temperature at the laser irradiation area, it was oxidized by infiltrating oxygen. The amorphous YSiAlON decreased in viscosity and was softened at 1,000℃ or above. Therefore, the high strength silicon nitride ceramic was cut with a CBN tool.

(2) As the laser power increased, the temperature of the specimen surface rose, causing structural changes in the ceramic and raising the efficiency of cutting. Thus, the tool lifespan increased. However, due to the oxidation of the machined surface, the hardness value tended to decrease.

(3) As the feed rate increased, the temperature of the specimen surface relatively decreased. Therefore, during machining, the cutting force increased and the degree of surface oxidation decreased. However, the difference in the cutting forces rising with an increase in the feed rate was found to be greater than the decrease in hardness from surface oxidation. Through an increase of tool abrasion, the tool lifespan decreased. Therefore, the feed rate significantly affected the tool lifespan.

(4) It is shown that with an increase in power, the material temperature goes up, and due to the softening, the amorphous material transitioned from a shear chip to a floating chip. Therefore, as the power increases, the machining process improved through a decrease in the cutting force and an increase in the tool lifespan.

(5) As the cutting depth deepened, the cutting force and tool abrasion increased, but the degree of specimen surface oxidation decreased. Machining was possible only up a depth of 3mm.

(6) At the laser irradiation area, oxidation reaction by surface melting and oxygen infiltration and softening of YSiAlON were found at a high temperature. If the surface temperature rose sufficiently during cutting, intergranular fracture occurred due to plastic deformation as the silicon nitride particles dropped off instead of breaking off with the softening of YSiAlON. When the specimen surface was observed after cutting was completed, the specimen surface temperature become high. Therefore, oxidation reaction occurred at times where the silicate vitreous layer was created by reacting with oxygen. Therefore, how LAM functions was clarified in this study.

In this study, the potential of the LAM of a silicon nitride ceramic was examined. The cutting characteristics and cutting mechanism for each parameter were clarified. From this examination, the potential for reducing the ceramic machining time, as well as how to shape various parts and reduce machining cost, with the LAM is proposed.

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Nomenclature

N : Rotation speed (rpm)
f : Feed rate (mm/rev)
d : Cutting depth (mm)
P : Laser power (W)
Φ_t : Distance with center of laser spot and tool (°)

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