Journal of the Korean Society of Marine Engineering, Vol. 34, No. 7, pp. 963~970, 2010(ISSN 1226-9549)

Characteristics of Si_3N_4 Laser Assisted Machining according to the Laser Power and Feed Rate

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(Received May 31, 2010; Revised July 5, 2010; Accepted August 10, 2010)

Abstract: This study makes an estimate of the laser-assisted machining (LAM) of an economically viable process for manufacturing precision silicon nitride ceramic parts using a high-power diode laser (HPDL). The surface is locally heated by an intense laser source prior to material removal, and the resulting softening and damage of the workpiece surface simplify the machining of the ceramics. The most important advantage of LAM is its ability to produce much better workpiece surface quality compared to conventional machining. Also important are its larger material removal rates and longer tool life. The cutting force and surface temperature were measured on-line using a pyrometer and a dynamometer, respectively. Tool wear, chips and the surface of the workpiece were measured using optical microscopy, and the surface and fractured cross-section of Si_3N_4 were measured by SEM. During the LAM process, the cutting force and tool wear were reduced and oxidation of the machined surface was increased according to the increase in the laser power. Moreover, the more the feed rate increased, the more the cutting force and tool wear increased.

Key words: LAM(laser assisted machining), Si_3N_4(silicon nitride), Laser power, Feed rate, YSiAlON

1. Introduction

Si_3N_4 is known for its high strength, excellent wear resistance, chemical stabilityand maintenance of its high strength at high temperatures compared to its weight. Hence, it is receiving attention in various fields such as construction, engineering, aerospace and medical science. However, the sintering process necessary for obtaining high-strength and high-quality Si_3N_4 ceramic reduces the measurement of the components and the precision of the shape; therefore, a finish machining process is required to obtain precise Si_3N_4 ceramic components. However, the high strength and high brittleness of Si_3N_4 ceramic materials cause difficulty in processing. As a process for obtaining desired measurements, diamond grinding is most widely used. The diamond grinding method is advantageous for obtaining materials with precise measurements, but the rate of removal and flexibility are low. Thus, this method cannot be easily used for components of Si_3N_4 with complicated shapes. In

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addition, problems such as the high processing cost and the occurrence of surface damage that lead to a reduction in the surface strength have been noted. Therefore, the production of Si_3N_4 products with excellent quality at a low cost can lead to enhanced utilization of Si_3N_4 in various fields [1-6].

As such, research on an alternative processing method of reducing the restrictions on productivity and on the economic aspects of the Si_3N_4 ceramic process is necessary. Accordingly, this study focused on the LAM of Si_3N_4 ceramics that efficiently removes the material through machining of a zone softened by local heating. In particular, the focus of this study was on the effects of the laser power and the feed rate [7].

2. Experimental Materials and Methods

2.1 Experimental Material

In this study, engineering Si_3N_4 composed of hexagon-shaped β-Si_3N_4 and amorphous YSiAlON was compressively sintered at a high temperature and high pressure using the HIP (hot isostatic pressing) method to remove internal pores and defects before use. Silicon nitride generally shows lower bending strength at 900~1000℃ and is softened with reduced YSiAlON viscosity at 1000℃ or above. To make the machining process by lather easier, round bar-shaped workpieces with a length of 150mm and a diameter of 16mm were used.

A 2.5kW HPDL with a high performance-to-price ratio was used as the heat source in this study. The laser power was varied with a fixed rotational speed of 620rpm after fixing the workpieces on the chuck and performing the cutting process at the speed of 0.013mm/rev using suitable tools. A CBN (cubic boron nitride) insert with a nose radius of 0.8mm, a thickness of 4.76mm and a negative angle of inclination of -6°(CNMA 120408) was used as the cutting tool. In addition, a pyrometer and a dynamometer were installed to measure the temperature and cutting force on a real-time basis. An optical revolver module with a maximum spindle rotation of 4000rpm and maximum axial feed rates of 30, 16 and 30 m/min for each axis was installed on the Z-axis of the complex processing machine. A specially manufactured square beam with a size of 5× 5mm was used for the optical system.

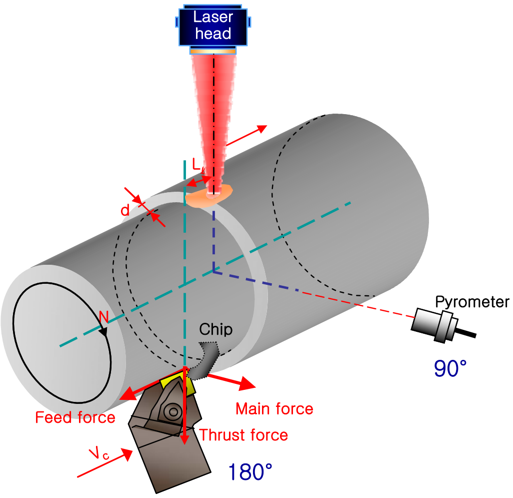


Figure 1: Schematic illustration of the laser assisted machining system

2.2 Experimental Method

Figure 1 shows a schematic diagram of the experimental device installed for laser-assisted machining. The round

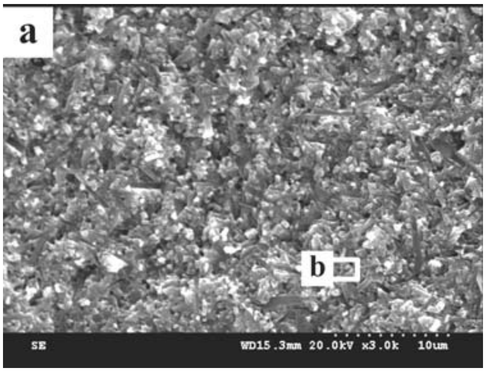
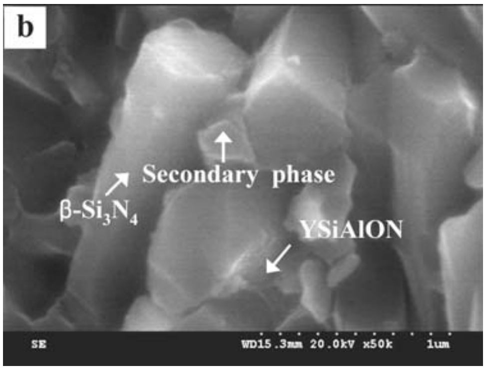
Magnification / Photo	×3,000	×50,000
SEM image		

Figure 2: SEM image of HIP treated silicon nitride

bar-shaped workpieces were fixed to a three-jaw chuck, and the pyrometer was installed at 90°. The cutting tool and dynamometer were installed at 180° from the center of the laser to measure the workpiece temperature and cutting force on a real-time basis. A lead distance of nearly 2.3mm was allowed between the laser center and the tools for efficient cutting and to prevent tool damage caused by direct laser irradiation. The rotational speed of the workpieces was fixed at 620rpm and the laser power and feed rate were varied to observe changes in thesurface temperature, heat effect, cutting force and processing surface. Chips were collected to analyze their length and shape using an optical microscope. The surface of the processed workpieces was observed through an optical microscope and SEM, and EDS was used to perform component analyses.

3. Results and Discussion

3.1 Mechanism of the LAM of Silicon Nitride

Sintered silicon nitride ceramic is mostly composed of hexagonal β-Si_3N_4 molecules and amorphous YSiAlON near the grain boundary, as shown in the SEM micrograph of the as-received fractography of Si_3N_4 with YSiAlON in Figure 2. It is compressively sintered at a high temperature and a high power. As a high-strength characteristic, silicon nitride materials cannot be processed by PCBN tools in general at room temperature. However, once the material properties are changed by increasing the surface temperature using a laser, PCBN tools can be used for machining of this material. As silicon nitride reacts with a sintering material at 1000℃ or above and softens with the reduced viscosity of amorphous YSiAlON, plastic deformation can occur and the removal of materials becomes easier due to the crack in the heat-affected parts. Transgranular fracturing of β-Si_3N_4 crystal mainly occurs before the softening of YSiAlON and intergranular fracturing mainly occurs at a high temperature of 1000℃ or above due to the plastic deformation of the softened

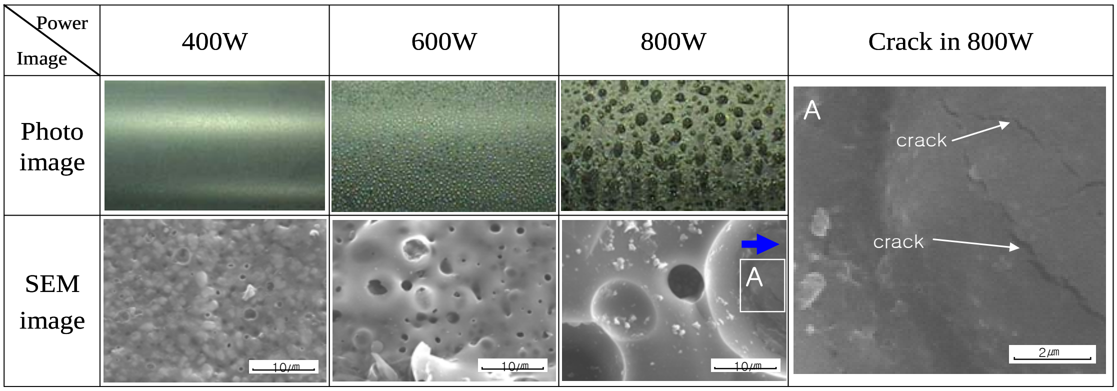


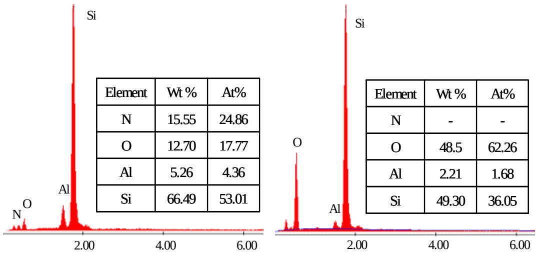
Figure 3: Photo and SEM image of surface preheated by laser power

YSiAlON. Silicon nitride can therefore be efficiently cut through machining at an increased temperature and low viscosity. The tool life can also be increased [3,8].

3.2 Characteristics of LAM according to the Laser Power

In order to observe the preheating characteristics of a workpiece surface according to power changes when the workpieces are rotated at 620rpm and machined at a feed rate of 0.013mm/rev, the power was varied at 400W, 600W and 800W for observation. The temperature of the workpiece surface was maintained at 1,270℃, 1,480℃ and 1,600℃ Figure 3 shows an actual-size photograph and SEM image of the workpiece surface and a SEM image of a crack in the surface that resulted at 800W. As shown in the SEM image, a laser power of 400W led to minute pores, suggesting formation of N_2 gas.

The workpiece surface began to swell at 600W, and such phenomena occurred more strongly at 800W with the observation of cracks under traces of N_2 gas. Figure 4 shows the result of an EDS analysis of the surface of workpieces as received and after preheating. As shown in the figure, N element was detected before preheating but not after preheating. This suggests that processing at a certain temperature or above causes the N element to combine as N_2 gas and causes the gas to burst from the surface. In addition, the oxygen content was greatly increased to oxidize the surface.



Element	Wt %	At%
N	15.55	24.86
O	12.70	17.77
Al	5.26	4.36
Si	66.49	53.01

Element	Wt %	At%
N	-	-
O	48.5	62.26
Al	2.21	1.68
Si	49.30	36.05

(a) As-received (b) Preheated

Figure 4: EDS analysis of as-received and preheated surface

Therefore, increased power was expected to make the processing easier as a result of the reduced viscosity of YSiAlON and thermal shock. Figure 5 shows photographs of the machined

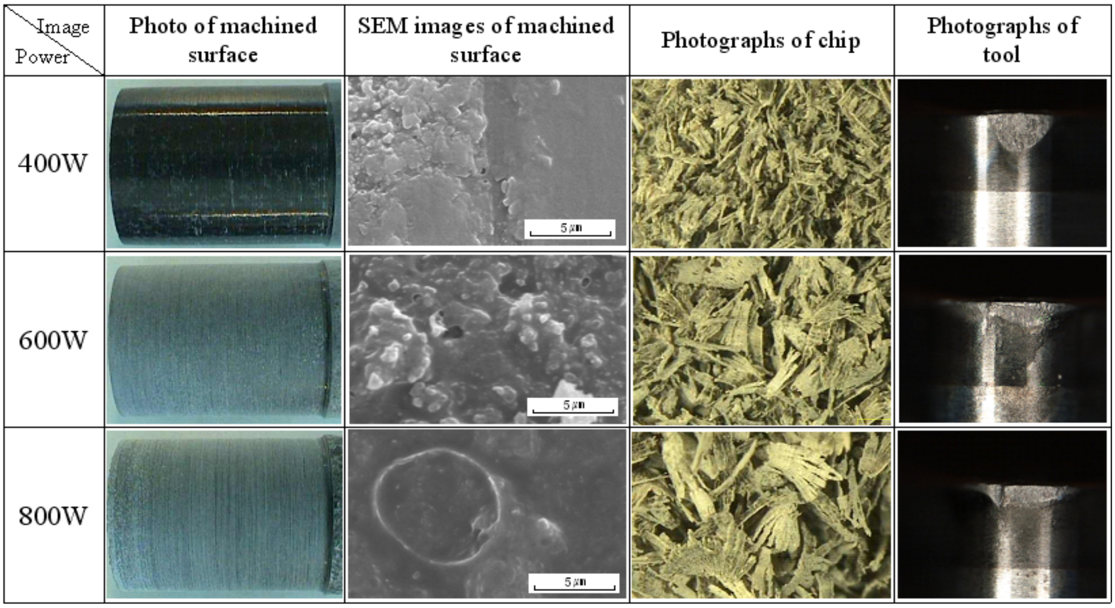


Figure 5: Photo and SEM images of the machined surface, chip and tool according to the laser power

workpiece surface as well as a chip and the tool with varying laser powers of 400W, 600W and 800W under fixed conditions of a rotational speed of 620rpm, a feed rate of 0.013mm/rev and a cutting depth of 0.3mm. An increase in the power causes the processing surface to become whiter, as the processing surface is oxidized by excessive input laser heat. Observing the chip, increased power resulted in a relatively flow-type chip. In general processing, a flow-type chip is known as a better processing condition with satisfactory surface roughness. As shown in the graph in Figure 6, an increased amount of power decreased the cutting energy. The higher temperature of the workpiece surface results in easy softening and thermal shock. As described earlier, a high temperature causes nitrogen gas defects and softening of amorphous materials, reducing the energy required for cutting. The degree of abrasion of the tools is also reduced with an increase in the laser power.

Therefore, relatively satisfactory processing conditions are observed with an increase in power. However, as maintenance of the surface strength is important in ceramic processing, it is important to determine the conditions with sufficient cutting force and flow type chip in which the oxidized part does not remain on the surface in order to prevent lowering of surface strength.

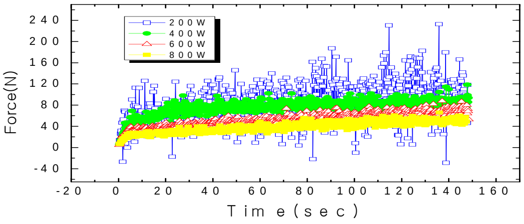


Figure 6: Graph of the main cutting force according to the laser power

3.3 Characteristics of LAM according to the Feed Rate

While fixing the rotational speed at 620rpm and varying the power with 400W, 600W and 800W, feed rates of 0.024mm/rev and 0.03mm/rev were compared with the result of the feed rate of 0.013mm/rev in the previous section. Surface changes and temperature changes according to each feed rate are shown in Figure 7. The trend of the temperature graph is similar to the case of 0.013mm/rev described earlier, but the slope and maximum temperature differ slightly. In order to visualize this, the degree of preheating according to the feed rate at a laser power of 800W is shown as a graph. As shown in the graph, a faster feed rate decreases the maximum temperature only slightly.

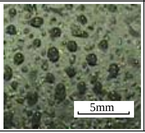
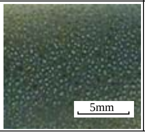
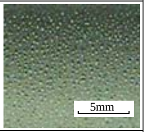
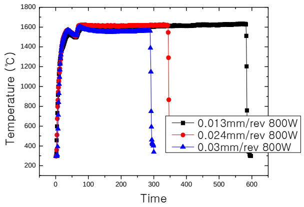
Feed rate Image	0.013mm/rev	0.024mm/rev	0.03mm/rev
Surface			
Graph			

Figure 7: Photo and graph of the temperature of the preheated surface according to the feed rate at 800W of laser power

However, as shown by the surface photograph, changes in the surface according to the feed rate are large despite the small changes in the maximum temperature. The surface temperature was increased to a greater extent. Figure 8 shows a photo of a machined surface and cutting tool according to the feed rate. It was machined while varying the feed rate at 0.013mm/rev, 0.024mm/rev and 0.03mm/rev under fixed conditions of a rotational speed of 620rpm, a laser power of 600W and a cutting depth of 0.3mm. Oxidation of the workpiece machined surface appears to decrease slightly as the feed rate is increased. Such phenomenon appeared in all conditions. Increasing the feed rate reduced the degree of change insufficiently. Therefore, a better surface status is expected to result by considering the cutting force and cutting surface status after taking the processing variables into consideration. In addition, the life of the tool is increased by reducing the feed rate. Figure 9 shows a measurement graph of the main cutting force for each feed rate at a laser power of 600W. A faster feed rate increases the

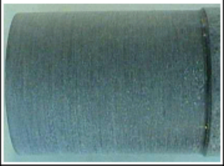
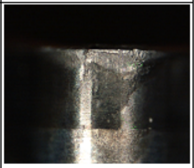
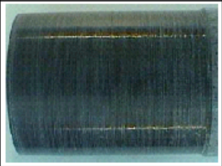
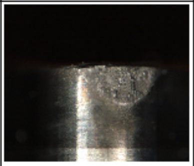
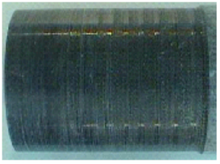
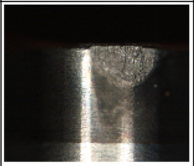
Image Feed rate	Photo of machined surface	Photographs of tool
0.013 mm/rev		
0.024 mm/rev		
0.03 mm/rev		

Figure 8: Photo of the machined surface and cutting tool according to the feed rate

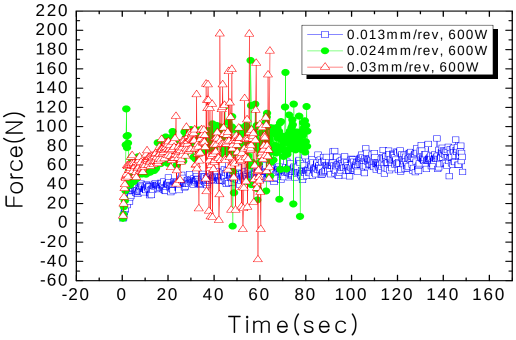


Figure 9: Graph of the main cutting force ccording to the feed rate

cutting force. That is, when the feed rate is increased, heat effects on the workpiece surface are negligible in comparison to the increase in the cutting force.

Therefore, changes in the cutting force were found to be more influential compared to changes in the workpiece surface. With these results, the author expects to find excellent processing conditions through adjustment of the laser power and feed rate.

4. Conclusions

The effects of the power and feed rate on a laser-assisted machining system developed to reduce cost and for an active application in the processing of silicon nitride ceramic were reviewed from a material perspective. The results can be summarized as follows.

1) Laser-assisted machining of silicon nitride allows effective cutting using a CBN tool by locally heating the cutting part to the softening temperature of YSiAlON using the laser as a heat source. If silicon nitride is sufficiently preheated, the surface is oxidized and N_2 gas is formed and escapes from the material, thereby making the cutting process more advantageous.

2) During laser-assisted machining, if the cutting force increases, a shear-type chip is formed and oxidation of the processing surface is low. In contrast, a high power reduces the cutting force, increases the tool life and forms a flow-type chip. Excessive power brings oxidation of the processing surface.

3) Increased the feed rate also increases the cutting energy during laser-assisted machining. In addition, while the degree of oxidation of the surface is reduced, the change in oxidation is very small compared to the change in oxidation caused by varying the power. Therefore, the feed rate has a greater influence on the cutting force than the oxidation of the surface.

4) Once appropriate cutting conditions are found by controlling the laser power and feed rate, silicon nitride ceramic can be cut more efficiently

Acknowledgment

This work was supported by the Korean Ministry of Knowledge Economy under the project, "Development of a Revolver Type Optic Module for a Laser Machining Center", "This research was supported by the MKE(The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency)" [NIPA-2010-C1090-1021-0015]

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