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Comparative Study on Ablation Characteristics of Ti-6Al-4V Alloy and Ti_2AlN Bulks Irradiated by Femto-second Laser

Ki Ha Hwang*, Hua Feng Wu*, Won Suk Choi**, Sung Hak Cho**, Myungchang Kang*,#
*Graduate school of convergence science, Pusan National University, Busan 46241, Republic of Korea,
**Department of Laser & Electron Beam Application, Korea Institute of Machinery and Material,156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon 34103, Republic of Korea

펨토초 레이저에 의한 티타늄 합금과 티타늄질화알루미늄 소결체의 어블레이션특성 비교연구

황기하*, 오화봉*, 최원석**, 조성학**, 강명창*,#
*부산대학교 융합학부, **한국기계연구원 나노공정연구실

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ABSTRACT

Mn+1AXn (MAX) phases are a family of nano-laminated compounds that possess unique combination of typical ceramic properties and typical metallic properties. As a member of MAX-phase, Ti_2AlN bulk materials are attractive for some high temperature applications. In this study, Ti_2AlN bulk with high density were synthesized by spark plasma sintering method. X-ray diffraction, micro-hardness, electrical and thermal conductivity were measured to compare the effect of material properties both Ti_2AlN bulk samples and a conventional Ti-6Al-4V alloy. A femto-second laser conditions were conducted at a repetition rate of 6 kHz and laser intensity of 50 %, 70% and 90 %, respectively, laser confocal microscope were used to evaluate the width and depth of ablation. Consequently, the laser ablation result of the Ti_2AlN sample than that of the Ti-6Al-4V alloys show a considerably good ablation characteristics due to its higher thermal conductivity regardless of to high densification and high hardness.

Key Words : Ti_2AlN(티타늄질화알루미늄), MAX-phases(맥스 상), Spark plasma sintering(방전 플라즈마 소결), Femto-second laser(펨토초 레이저), Ablation(어블레이션)

1. Introduction

Titanium alloys are widely used in various devices and parts owing to their high specific strength and excellent high-temperature properties, especially creep characteristics[1]. In particular, titanium alloys are machined into micro-channel shapes that are applied to micro-heat exchangers, jet engines of aircrafts, turbine blades, and electronic control devices [2].

Corresponding Author : kangmc@pusan.ac.kr
Tel: +82-51-510-2361, Fax: +82-51-510-7396

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However, difficult-to-cut materials, such as titanium, form heat-affected zones, cause tool wear, and shorten life due to the heat concentration phenomenon caused by the low thermal conductivity of the material during cutting and special processing [3].

Max-phase titanium aluminum nitride (Ti_2AlN) is a high-functionality material that exhibits the properties of metal and ceramic. It can be used effectively in high-temperature components because it has the high electrical and thermal conductivity of metal and the high hardness and wear resistance of ceramic [4]. With the recent miniaturization trend of industrial products, interest in ultra-micro-shape processing is rising. Typical micro-shape processes include traditional milling, water jet, discharge, and laser process[4]. In particular, the femto-second laser for laser processing is an ultra-short-pulse laser of 10^{-15}s that has material removal properties not possessed by other lasers[2]. Futhermore, the femto-second laser has an extremely high laser intensity that discharge a peak power of several hundred giga watts to tera watts per pulse. Hence, the femto-second laser is a machinable method for any material regardless of the hardness or strength.

In this study, the ablation characteristics of a commercial Ti-6Al-4V alloy and MAX-phase sintered Ti_2AlN was produced using the spark discharge sintering method, and its hardness, electrical conductivity, and thermal conductivity were measured. In addition, the ablation tendency of this sintered material was inferred by referring to the laser ablation characteristics of existing titanium and ceramic materials. Further, the width and depth of ablation were defined for each material, and the ablation values according to the laser intensity and repetition rate were analyzed using a confocal microscope. Based on the results of this analysis, this study proposes the applicability of titanium alloy and Ti_2AlN materials to micro-channel processing according to the laser conditions.

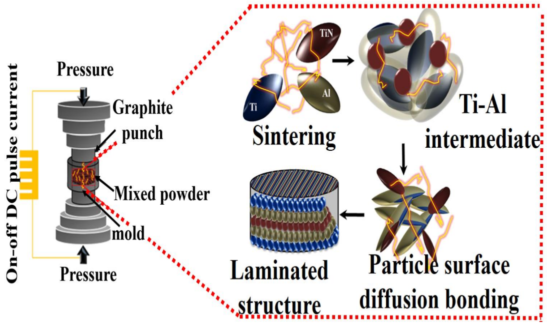


Fig. 1 Schematic of Ti_2AlN bulk materials using spark plasma sintering equipment[4]

2. Experimental Setup and Method

2.1 Production of sintered Ti_2AlN

Fig. 1 shows the production process of Ti_2AlN bulks proposed in this study. For the powders of each raw material, Ti (99.5 %, 45 μm), Al (99.6 %, 45 μm), and TiN (99.5 %, 5 μm) produced by Whole Win Materials Science & Technology in China were used. To synthesize Ti_2AlN, Ti, Al, and TiN were measured for the molar ratio of 1:1:1, and stainless balls 10mm in diameter were mixed with the powders at 15:1. The mixed powders were placed in a graphite mold with an outer diameter of 35mm and an inner diameter of 20mm. Then, a highly dense sintered material was produced by raising the temperature by 100℃ per min from the sintering temperature of 1100℃ with a retention time of 10 min and a pressure of 40 MPa using a discharge plasma sintering apparatus (SPS-825, SPS Syntex, Japan) [2,5]. To verify the properties of the sintered material, its crystallization, hardness, electrical conductivity, and thermal conductivity were tested by X-ray diffraction (XRD, D8Advance, Bruker, Germany), a Vickers hardness meter (WMT-X, Matsuzawa, Japan), a four-point probe (CMT-SR100N, Advanced Instrument Technology, USA), and the laser flash method (LFA-467, Netzsch, Germany), respectively[2].

2.2 Femto-second laser equipment

Fig. 2 shows a schematic of the laser processing machine. When channel and hole shapes are machined, it moves in the X-axis direction. It is composed of an optical system, X-Y stage, and Z-axis slide, which enables it to transmit laser beams with a Gaussian shape and linear polarization[6]. For the laser ablation experiment, a femto-second laser source (Yb:KGW, PharosSP, Germany) was used. The specimen was mounted with resin powder in the machine and fixed with bolts on both ends, and then ablation was performed. The size of each specimen was 20× 20 × 3 mm. The ablation shape was acquired as a profile through a confocal microscope (VK-X1000, KEYENCE, Japan), and the depth and width of ablation were measured.

Table 1 lists the parameters of the laser experimental conditions used in this experiment. The laser can be used for micro-machining because it has a wavelength of 1027 nm and a high maximum repetition rate of 200,000 per sec.

Fig. 3 shows the laser ablation shapes of titanium and ceramic (Zirconia) materials thar reported in the past. Fig. 3(a) shows the recast phenomenon caused by the low thermal conductivity, which is a major characteristic of Ti-6Al-4V.

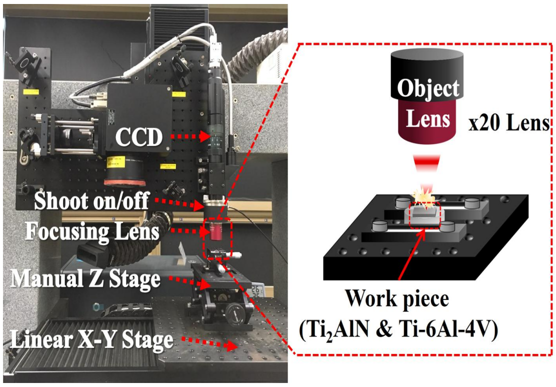
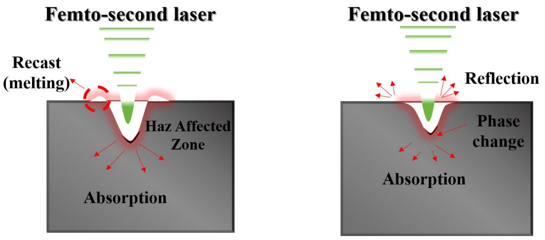


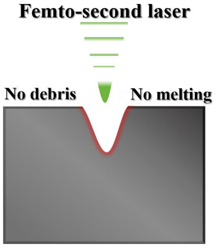
Fig. 2 Photo and workpiece for femto-second laser micro machining set-up

Table 1 Specification of experiment set-up using femto-second laser

Laser parameter	Description
Laser source	Yb:KGW
Wavelength	1027 nm
Max. laser intensity	100 %
Average power	6 Watt
Repetition rate	200 kHz



(a) Ti-6Al-4V alloy (b) Zirconia ceramic



(c) Ti_2AlN bulk

Fig. 3 Schematic diagram of femto second laser ablation with (a) Ti-6Al-4V[7], (b) Zirconia[7] and (c) expected ablation of Ti_2AlN bulk

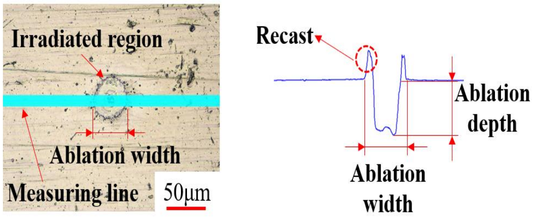
Fig. 3(b) shows the absorption and reflection phenomena of the ceramic material. Most of the laser is reflected from the ceramic material. Based on these results, the ablation phenomenon caused by the femto-second laser of Ti_2AlN, which has metal and ceramic properties, was inferred by a relative comparison of the two materials in this study. This was established as a hypothesis for this study.

2.3 Femto-second laser experimental conditions

To summarize the reported results of past studies, the threshold of materials and machined shape by pulse laser were examined for Ti alloy materials and the changing behaviors of the materials according to the threshold were investigated for zirconia materials[7].

Table 2 Experimental conditions for laser ablation

Parameter	Value (unit)
Repetition rate	6 (kHz)
Laser intensity	50, 70, 90 (%)
Number of pulses	1, 10, 20, 50, 100



(a) Irradiation and measuring (b) Ablation parameter

Fig. 4 Definition of width, depth and recast relating to ablation characteristics irradiated by femto-second laser

Table 3 Comparisons of material properties for Ti_2AlN bulk and Ti-6Al-4V alloy[2]

Property (unit)	Ti_2AlN (This result)	Ti-6Al-4V (Reference)
Relative density (%)	98.8	97.4
Hardness (GPa)	6.7	3.5
Electrical conductivity(S/m)	4.562	1.317
Thermal conductivity(W/mk)	56.2	21.9

Through a preliminary experiment on the laser conditions of ablation, the effects on the lens magnification, scan speed, repetition rate, and number of pulses was examined. First, for a single pulse, the laser energy was absorbed on the surface of the workpiece and the material-removal was observed.

To evaluate the ablation characteristics of each material, as shown in Table 2, the laser was irradiated 10, 20, 50, and 100 times with a single pulse at 50, 70, and 90% intensity. To determine the reproducibility of the ablation phenomenon, the characteristics were investigated by repeating the experiment three times. The confocal microscope can observe the size and shape of each ablation for the measurement baseline in the ablation region. As shown in Fig. 4, the width, depth, and recast of each ablation region were defined.

3. Experimental Results and Discussion

3.1 Fabrication of sintered Ti_2AlN and evaluation of material properties

Table 3 lists the material properties of the Ti-6Al-4V alloy and sintered Ti_2AlN. The Ti_2AlN produced by spark plasma sintering was highly densified to the relative density of 98.8%. Futhermore, its hardness, electrical conductivity, and thermal conductivity were approximately 1.9, 3.5 and 2.6 times higher than those of Ti-6Al-4V[2]. The ablation characteristics were examined by comparing the two materials using material properties and a femto-second laser.

Fig. 5 shows the XRD diffraction analysis result of Ti_2AlN sintered with Ti, Al, and TiN at the molar ratio of 1:1:1. After ball milling each powder for 12 hr, the mixture was analyzed by XRD. As a result, no peak was observed expect for the Ti, Al, and TiN powders. Futhermore, the XRD analysis after discharge plasma sintering clearly showed the peak of the Ti_2AlN crystallization, and it was in line with the result of an existing study[2].

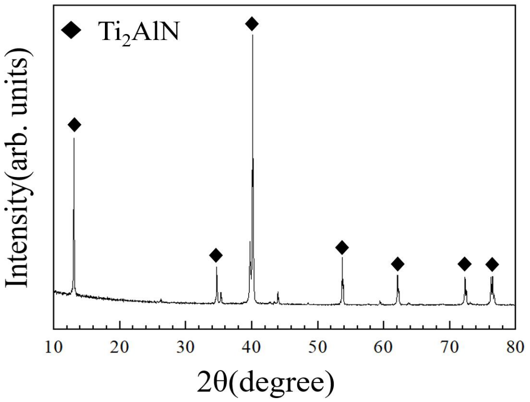


Fig. 5 XRD pattern of Ti_2AlN bulk sintered by spark plasma sintering method

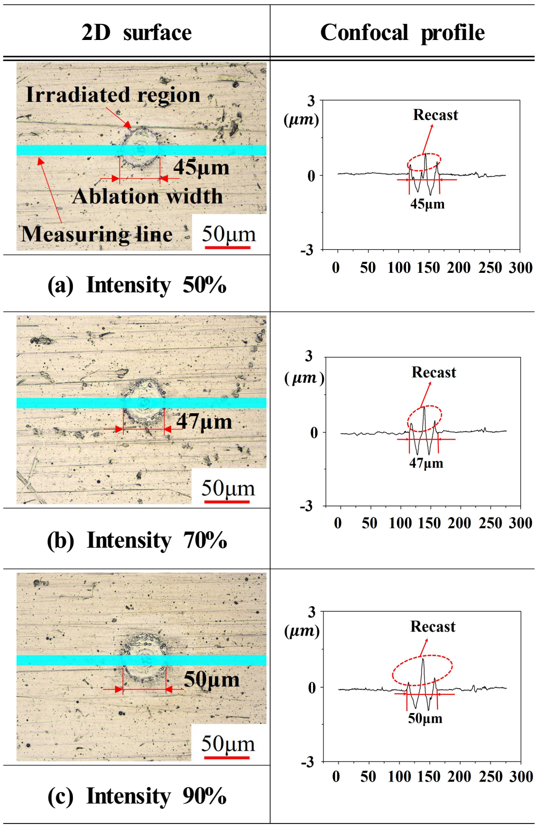


Fig. 6 Measuring results of ablation phenomenon according to laser intensity at single pulse in case of Ti-6Al-4V alloy

3.2 Ablation characteristics with single pulse and laser intensity

In Fig. 6 and 7, the ablations according to laser intensity for a single pulse of the Ti-6Al-4V alloy and sintered Ti_2AlN are compared. In Fig. 6, the Ti-6Al-4V alloy forms a laser-irradiated region even at a somewhat low threshold due to the properties of metal. As the laser intensity increases from 50% to 90%, the ablation width and recast in the ablation region slightly increase[6]. In Fig. 7, the sintered Ti_2AlN shows higher values of electrical conductivity and thermal conductivity compared with titanium, but no significant change in material behavior is observed in a single pulse. However, a minute trace of material reaction is observed irradiated region.

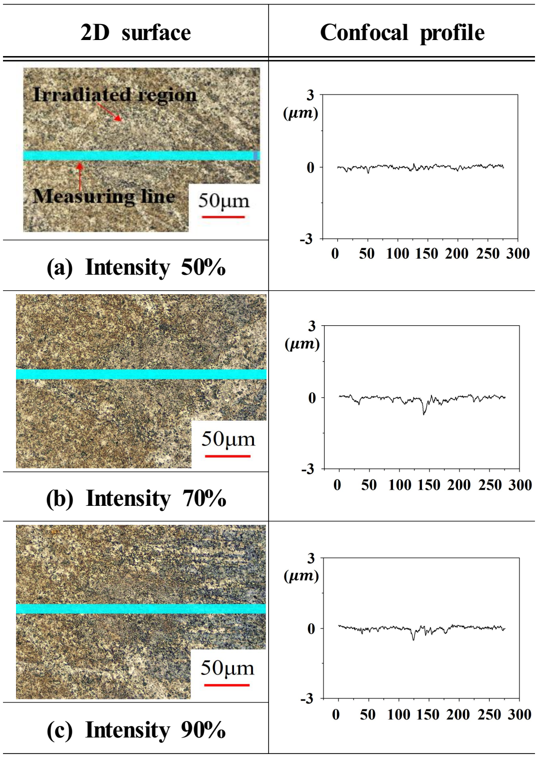
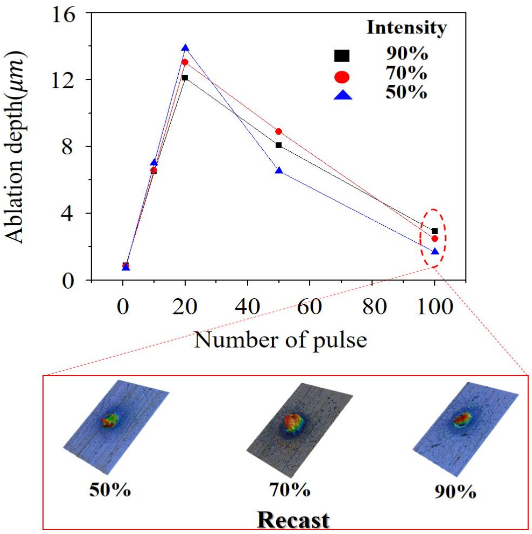
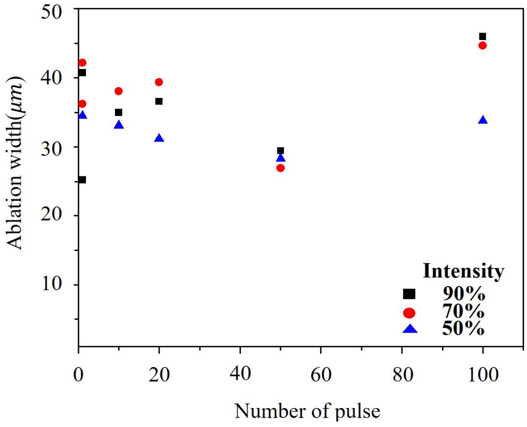


Fig. 7 Measuring results of ablation phenomenon according to laser intensity at single pulse in case of Ti_2AlN bulk



(a) Influence of depth of Ti-6Al-4V alloy



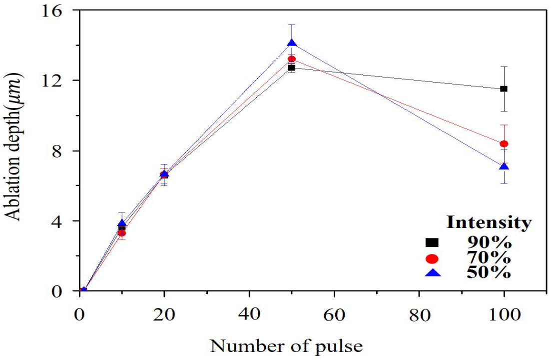
(b) Influence of width of Ti-6Al-4V alloy

Fig. 8 Ablation characteristics according to laser intensity and multi pulse in case of Ti-6Al-4V alloy

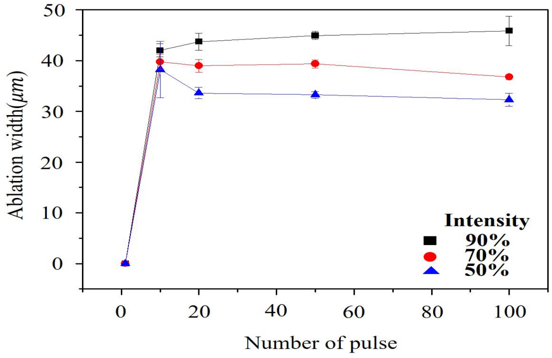
3.3 Ablation characteristics with multiple pulse and laser intensity

Fig. 8 shows the ablation shapes according to he number of multiple pulses and laser intensity for the Ti-6Al-4V alloy. As shown in fig. 8(a), when the number of pulses increases from 1 to 20, the ablation depth quickly increases with material melting, but after 20 pulses, the ablation depth is filled by the melted material due to the recast phenomenon of titanium. Furthermore, as shown in Fig. 8(b), according to the increased number of pulses, the ablation width and size show highly irregular tendencies due to the melting of titanium. Meanwhile, the ablation characteristics according to the laser intensity under the given laser experimental conditions show a similar behavior change to that of the number of pulses. This result indicates that the recast phenomenon of the Ti-6Al-4V alloy has a close correlation with ablation[6,7].

Fig. 9 shows the ablation characteristics according to the number of multiple pulses and laser intensity for



(a) Influence of depth of Ti_2AlN bulk



(b) Influence of width of Ti_2AlN bulk

Fig. 9 Ablation characteristics according to laser intensity and multi pulse in case of Ti2AlN bulk sintered Ti_2AlN by the same laser conditions and ablation assessment method as in Fig. 8. In Fig. 9(a), the maximum value of the ablation depth exists at 50 pulses. Above 50 pulses, it shows a similar behaviour to that of the Ti-6Al-4V alloy tue to the recast phenomenon. Furthermore, in the number of pulses from 1 to 50, the increase of laser intensity does not change the ablation depth. Futhermore, in fig. 9(b), the ablation width rapidly increase until 10 pulses and then increases slowly at a constant rate according to the change of laser intensity.

From the above experimental results, sintered Ti_2AlN showed better material properties than the Ti-6Al-4V alloy. Under the given laser conditions, it was found that there is a number of pulses and a laser intensity condition that can determine the ablation width and depth at which the generation of recast layers decreases. Thus, these can be used as basic conditions for the microprocessing of micro-channels and other shapes.

4. Conclusions

Ti_2AlN of the MAX-phase structure was obtained by spark plasma sintering, and its properties were evaluated. The ablation characteristics and surface shapes of the sintered Ti_2AlN and commercial Ti-6Al-4V alloy were compared using a femto-second laser. The following results were obtained.

The sintered Ti_2AlN showed a very high relative density of 98.8% and better material properties. The hardness, electrical conductivity, and thermal conductivity of sintered Ti_2AlN were approximately 1.9, 3.5, and 2.6 times higher than those of the Ti-6Al-4V alloy. The Ti-6Al-4V alloy showed a recast phenomenon according to the single pulse and laser intensity, whereas the sintered Ti_2AlN showed no change in material behavior due to material properties. The conditions for the actual ablation effects in the sintered Ti_2AlN were 50 multiple laser pulses and 50% laser intensity.

In the future, we will conduct research on more diverse material synthesis ratios and optimal laser processing conditions can be apply to micro-channel processing.

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