EXPERIMENTAL INVESTIGATION OF THE MACHINABILITY OF EQUAL CHANNEL ANGULAR PRESSING PROCESSED COMMERCIALLY PURE TITANIUM

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ABSTRACT

Equal channel angular pressing (ECAP) is an innovative technique that can produce bulk ultrafine-grained (UFG) materials in product forms large enough for structural applications. ECAP processed UFG commercially pure titanium (CP Ti) has recently shown increasing promise in advanced engineering applications such as medical implants and aerospace structural parts. For UFG CP Ti to be implemented into practical usage, further machining research must be conducted. In this study, UFG Ti was tested for its machinability using polycrystalline diamond cutting tools. Surface roughness, cutting forces, tool wear, and chip morphology were studied under various cutting conditions and compared to those of regular coarse-grained CP titanium. Cutting forces and chip morphology were very similar between the two metals, while UFG Ti possessed superior surface quality and tool life when compared to those of its coarse-grained counterpart.

INTRODUCTION

Ultrafine-grained (UFG) materials have been attracting increasing attention because of their unique and desirable physical properties making them ideal for advanced engineering applications. These materials have small microstructures of a granular type containing high angle grain boundaries and numerous dislocations [Lowe et al., 2000; Baro et al., 2001] with grains in the range of 10 to 1000 nm in at least one dimension [Zhu et al., 2004]. Equal channel angular pressing (ECAP), a common form of severe plastic deformation (SPD), gives a means of producing substantially large SPD materials without the reduction of cross-sectional area. A diagram of this process can be seen in Figure 1. The ECAP process has the ability to reduce the average grain size of coarse-grained commercially pure titanium (CP Ti) from 10μm to the UFG size of 260 nm (Figure 2) while increasing its mechanical properties significantly [Stolyarov et al., 2001a]. Unlike many other UFG metals such as copper [Morehead et al., 2005], the microhardness and strength of UFG titanium is still stable at elevated temperatures as high as 400-450°C [Stolyarov et al., 2001a]. UFG Ti, produced using ECAP, in particular shows many promising features ideal for use in advanced aerospace designs and especially in medical prosthetics. Many structural medical implants now are manufactured using titanium alloys, mostly Ti-6Al-4V, which has a far greater yield strength ($\sigma_{0.2}$=795 MPa) than CP Ti. The alloying elements of aluminum and vanadium, however, are considered to be toxic in the human body and much less biocompatible than CP titanium [Black et al., 1998; Stolyarov et al., 2001b]. For this reason, UFG CP Ti shows much promise in replacing many Ti-6Al-4V implants because it can possess a comparable yield strength (640 MPa) with Ti-6Al-4V [Stolyarov et al., 2001a]. The coarse-grained Ti has a typical yield strength of 380 MPa.

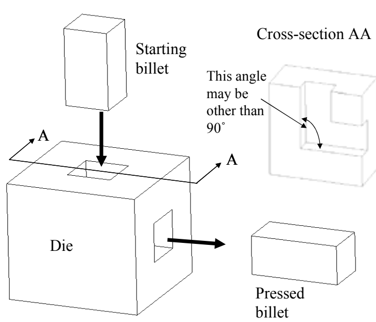


FIGURE 1. SCHEMATIC ILLUSTRATION OF AN ECAP DEFORMATION PROCESS

For UFG CP titanium to be implemented into practical usage in lightweight engineering and medical applications, further machining work is necessary to form and shape the metal into required dimensions. The major motive for conducting machining research is to discover the interaction between the cutting tool and the workpiece material so that the machining costs can be minimized while still optimizing part quality [Ezugwu, 2005]. Because of its relatively high cost and high reactivity [Bhat, 2003], processing techniques for titanium and its alloys must be carefully studied and followed to ensure safe and cost effective manufacturing. Machining titanium as a finishing operation is becoming a more popular trend because of advances in tool materials and the reduction of grinding operations which can cause flame hazards with Ti [Leyens et al., 2003]. This metal, however, is considered hard to machine since it exhibits many unique properties: poor thermal conductivity, high strength at elevated temperatures, resistance to wear and chemical degradation [Ezugwu, 2005].

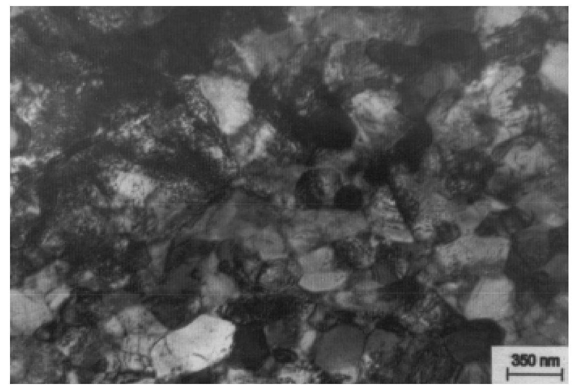


FIGURE 2. TEM IMAGE OF UFG TITANIUM'S GRAIN STRUCTURE FROM B_C ROUTE.

In this study, Grade 2 coarse-grained CP Ti and ECAP processed UFG CP Ti (route B_c in [Stolyarov et al., 2001a]) were tested for their relative machinability using polycrystalline diamond (PCD) cutting tools. This ECAP processed Ti has a grain size of 260 nm and a 0.2% offset yield stress of 640 MPa. While its definition is difficult to classify, machinability defines the ease at which a material can be machined using the appropriate tooling and cutting parameters [Kalpakjian et al., 2003; Ezugwu, 2005]. Measuring the machinability of a material focuses on determining the cutting conditions, tool material properties, cutting forces, tool wear, surface quality, and cutting temperature [Liu et al., 2002]. In order to evaluate the machinability of UFG Ti, surface roughness, cutting forces, tool wear, and chip morphology were studied and compared to that of coarse-grained CP Ti. In this paper the experimental setup and design is first outlined, and then the results and discussion on machinability of the two forms of Ti are given. Finally, conclusions and recommendations on further research are proposed.

EXPERIMENTAL SETUP AND DESIGN

Machining Test Setup and Preparation

All precision cutting operations were conducted on a Hardinge CNC lathe. The PCD tools (Kennametal TPGN160308 KD100) and tool holder (Kennametal CTAPR-123B) used led to an effective cutting geometry with a 5° rake angle and a 6° clearance angle. The cutting was performed dry, to better study the machining performance. The cutting forces were measured using a Kistler 9257B force dynamometer, tool wear was measured using a Sun DISM-2 optical microscope as well as a non-contact surface profilometer (Wyko NT-2000), and workpiece surface roughness was also measured using the above profilometer. Scanning electron microscopy (SEM) (Hitachi S-3500N) was further used to classify chip morphology and to quantify the composition of the worn tools to help determine their wear mechanism(s).

Most research on Ti material machining is on machining Ti-6Al-4V since it is widely used and has more appealing physical properties such as yield strength than those of coarse-grained CP Ti. PCD tools are typically selected to machine Ti-6Al-4V because PCD tools can give better workpiece surface finish [Nabhani, 2001] and perform better [Bhaumik et al., 1996] when compared with other tool materials. PCD tools exhibit up to 6 times the tool life as CBN when machining Ti alloys and 50 to 200 times the tool life when machining with tungsten carbide [Brinksmeir et al., 1998]. The high thermal conductivity of diamond tools aids in the dispensing of heat generated during machining which helps lower the friction at the tool-chip interface. Considering their success in cutting Ti alloys, PCD tools were also selected in this study to machine both two types of CP Ti. One potential disadvantage in machining Ti and Ti alloys using PCD tools is the chemical reaction at elevated temperatures (750 ºC), which causes the diamond tool to transform back into graphite [Konig et al., 1993; Davis, 1995]. To avoid this graphitization, the cutting conditions were carefully selected to be below 300 ºC based on finite element analysis done using the Third Wave AdvantEdge software. Even if the exact material constitutive models may be different from the Ti used here and that of AdvantEdge, it is believed that the cutting temperatures will not be higher than 750 ºC under the conditions investigated.

Experimental Design

To optimize the use of the given materials, the UFG and regular coarse-grained CP Ti bars were machined based on three different scenarios as follows: the first scenario with a cutting speed of 1 m/s, feed of 0.015 mm/rev, and depth of cut of 0.02 mm for 150 passes, the second scenario with a cutting speed of 3 m/s, feed of 0.015 mm/rev and depth of cut of 0.02mm for 150 passes, and the third scenario with a combination of cutting conditions for a pass as shown in Table 1.

The cutting speed was varied from 1 m/s to 3 m/s in the first two scenarios since cutting speed is the dominant factor in determining the tool life. Results from these two scenarios give information about the wear progression in cutting the two forms of Ti. Tool wear, forces, and chips were collected every ten passes for further study, and workpiece surface roughness was measured at the end of 150 passes.

The third scenario gives information about the relationship between cutting forces and different cutting conditions. A total of 27 different cutting passes were made as designed in Table 1 to appreciate the effects of cutting conditions on cutting forces.

TABLE 1. THREE-FACTOR, THREE-LEVEL, AND FULL-FACTORIAL DESIGN OF EXPERIMENTS

Factors	Levels
Cutting speed	1, 2, 3 (m/s)
Feed	0.015, 0.030, 0.045 (mm/rev)
Depth of cut	0.02, 0.04, 0.06 (mm)

A considerably small depth of cut of 0.02mm was chosen in order to machine a large number of passes on the relatively small piece of stock. This would allow acquiring tool wear and force data over a longer period of time while still conserving the material. A small depth of cut also reduces cutting temperatures to avoid the possible chemical reaction between the Ti workpiece and the diamond cutting tool. The small feed was chosen to give the titanium a good surface finish [Kalpakjian et al., 2003].

RESULTS AND DISCUSSION ON MACHINABILITY

Surface Roughness

The surface finish of a workpiece is significant not only for dimensional correctness, but also for other physical properties such as corrosion resistance and fatigue life, which are vital in medical implant applications. It has been shown by Chen et al. [1998] that corrosion resistance in titanium is raised with the lowering of the surface roughness. With this said, minimizing the surface roughness is crucial when using UFG Ti in corrosive environments such as the ocean or the human body.

After the completion of the 150 passes for the first two cutting scenarios, the surface roughness (R_a) was measured in three random locations on the machined surface to obtain an average. The surface roughness of the UFG and coarse-grained Ti workpieces at 1 m/s (Scenario 1) and 3 m/s (Scenario 2) were 189.1 nm and 201.6 nm respectively. These roughness values are considered to be very low for any machined metal, even on medical implant applications [Black et al., 1998]. The improved surface roughness on the UFG metal compares well with the work by Mills et al. [1983] who found that severely cold working of pure metals, such as processing CP Ti through ECAP, improves the surface integrity after machining. The surface roughness of Scenario 2 (3 m/s) was 301 nm for UFG Ti which means that the higher the cutting speed, the higher the surface roughness for UFG Ti. Scenario 2 was not performed for coarse-grained Ti since it was not of interest.

Cutting Forces

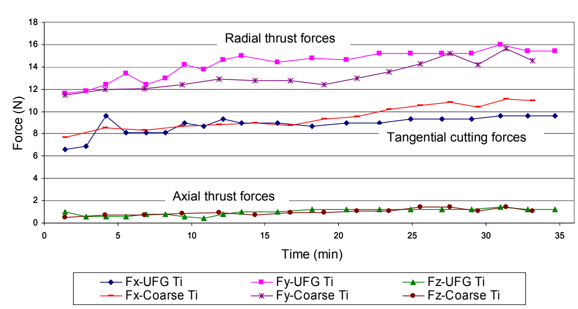


FIGURE 3. FORCE VS. TIME RESULTS OF SCENARIO 1 (FX: TANGENTIAL CUTTING FORCE, FY: RADIAL THRUST FORCE, AND FZ: AXIAL THRUST FORCE IN FEED DIRECTION).

The three dimensional cutting forces of both Ti bars under Scenario 1 (1 m/s) are shown in Figure 3. There is no pronounced cutting force difference between the UFG and coarse-grained Ti except that radial thrust force of UFG Ti is about 2 N (15%) higher. However, a sharp contrast in cutting UFG and regular coarse-grained coppers with carbide tools has been observed [Morehead et al., 2005]. Also, it can be seen that the forces generally increase with time under the cutting conditions investigated.

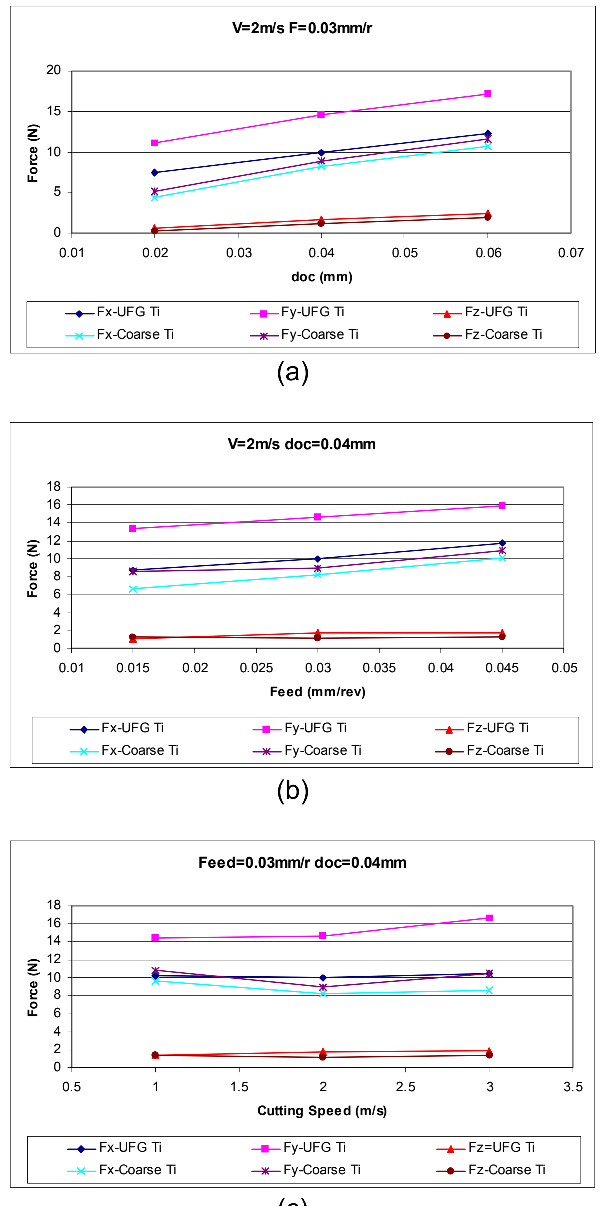


FIGURE 4. FORCE VS DEPTH OF CUT (A), FEED (B), AND CUTTING SPEED (C).

The cutting forces from the 27 combinations of cutting conditions (Scenario 3) were also studied for their similarities and differences. Only three combinations are shown in Figure 4 since they are representative of all combinations used. With exception to varying the cutting speed, cutting forces increased linearly with feed and depth of cut for both UFG and coarse-grained Ti. However, as seen in Figure 4(c), when the cutting speed increased from 1 m/s to 2 m/s, the cutting forces dropped slightly and then rose again when the cutting speed increased to 3 m/s. Similar force phenomena were also observed in cutting Ti alloys when cutting speeds increased [Zoya et al., 2000].

Tool Wear

Tool wear is of great concern in any cutting application because of its effects on part production, quality, and integrity. Tool wear is a function of tool material, tool geometry, and the physical, mechanical and chemical properties of both tool and workpiece [Huang, 2002; Kalpakjian et al., 2003]. From Figure 5 it can be concluded that the tool wear rate increased with the cutting speed significantly from 1 m/s to 3 m/s. This observation agrees with the finding that carbide tools wear moderately at low cutting speeds between 0.25 through 1 m/s in turning Ti alloys [Barry et al., 2001]. The UFG and coarse-grained Ti showed similar flank wear progressions when machining at 1 m/s. The tool wear difference after the 20 minute mark is believed to be an experimental variation.

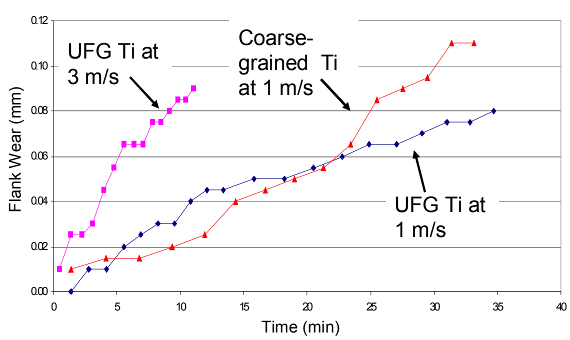


FIGURE 5. THE PROGRESSIONS OF FLANK WEAR FOR BOTH UFG AND COARSE-GRAINED TITANIUM

Cutting tools were further tested for other wear patterns and mechanisms using the surface profilometer and the scanning electron microscope. Although almost no crater wear has been observed using the profilometer, an energy dispersive spectroscopy (EDS) analysis was still performed to find the percent content of the possible titanium deposited on the tool rake and flank faces (Figure 6 and Table 2). This information on the composition was then used to classify the types of wear mechanisms that occurred. It can be seen that when machining UFG Ti at 1 m/s and 3 m/s, Ti represents 5.86% and 5.94% of the elements present on the tool tip respectively. The coarse-grained Ti, on the other hand, represents 8.40% Ti onto the tool. Since there is no crater or deposited particle on the rake face, it is assumed that there is no pronounced adhesive wear. The measured Ti on the tool tip is considered to be due to diffusion. Because of titanium's low thermal conductivity, cutting tools usually experience a higher temperature. There may even be a reaction layer of TiC between the tool and workpiece at certain temperatures [Hartung et al., 1982; Bhaumik et al., 1995]. For the conditions investigated, the cutting temperature is not high enough to generate the reaction layer, but still high enough to activate diffusion. It can be also seen that the PCD tool wears a little bit faster in machining coarse-grained Ti from Table 2(c).

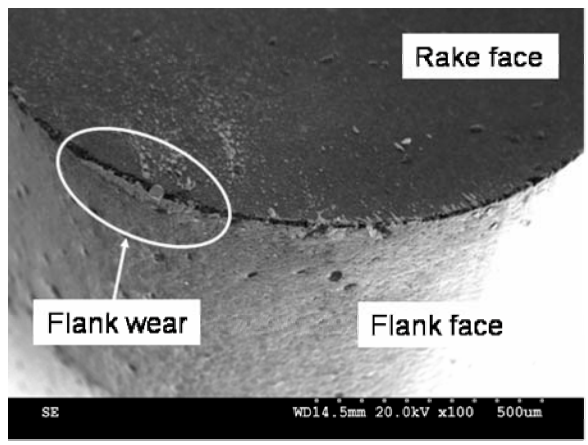


FIGURE 6. SEM OF TOOL AFTER CUTTING UFG TI

TABLE 2. EDS INFORMATION FROM THE TOOL TIPS USED FOR CUTTING: (A) UFG TI AT 1 M/S, (B) UFG TI AT 3 M/S, AND (C) COARSE-GRAINED TI AT 1 M/S.

Elements Present	C	O	Ti	Co	W	Total
Percent of Total	78.16	13.16	5.86	1.20	1.62	100.00

(a)

Elements Present	C	O	Ti	Co	W	Total
Percent of Total	80.75	11.08	5.94	1.21	1.02	100.00

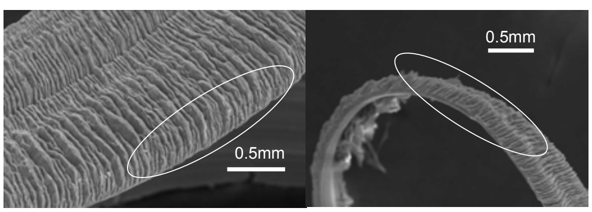
(b)

Elements Present	C	O	Ti	Co	W	Total
Percent of Total	74.61	14.77	8.40	1.24	0.98	100.00

(c)

Chip Morphology

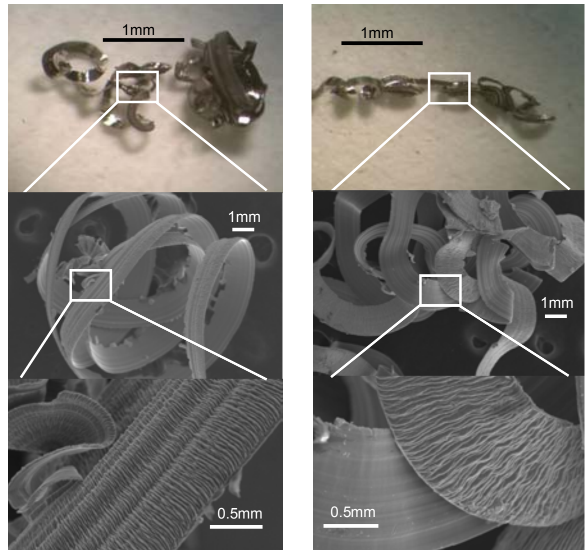
When machining Ti and its alloys, serrated or segmented chips are commonly observed since the materials have a low thermal conductivity. Segmented chips are known to promote rapid tool wear, detrimental machine and workpiece vibrations, and low material removal rates [Hua et al., 2004]. Although these chips are typically produced in machining Ti and its alloys [Hua et al., 2004; Barry et al., 2001; Ezugwu, 2005; Sheikh-Ahmad et al., 2004], segmented chips were not observed when machining both the UFG and coarse-grained Ti under the conditions investigated. Chips generated during this experiment under all cutting conditions were fairly continuous with little to no serration or saw tooth form as shown in Figure 7. It is speculated that the continuous chips can be attributed to the lower cutting temperature that occurred from using a small depth of cut, feed, and cutting speed. Barry et al. [2001] also predicted that if the values of depth of cut are small enough (in the order of microns as in this experiment), then continuous chips can be formed in machining Ti-6Al-4V.



(a) (b)

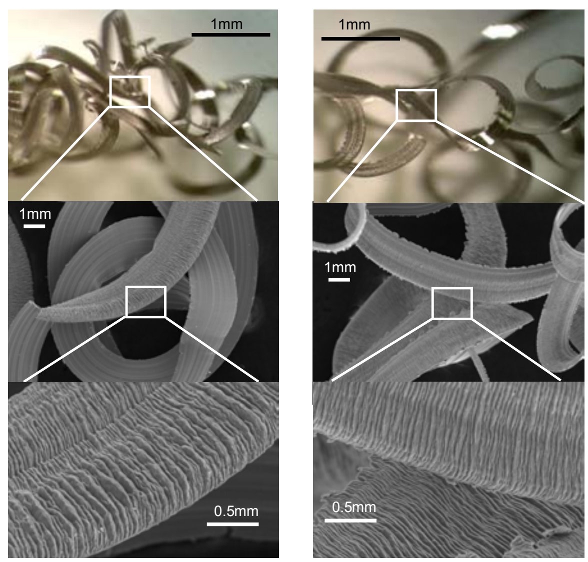
FIGURE 7. TYPICAL CHIP CROSS SECTIONAL VIEWS IN MACHINING (A) UFG TI AND (B) COARSE-GRAINED TI.

There was negligible difference of the chip morphology during the wear progression, and it implies that tool wear had little effect on the chip morphology. These chips along with their corresponding cutting conditions can be seen through some representative optical and electron microscope images as shown in Figures 8 and 9. These images show that UFG and coarse-grained Ti produced similar chips when machining under the same cutting conditions although UFG Ti chips had relatively smaller curvatures. Comparing the two figures, it can also be seen that when increasing the cutting speed, depth of cut, and feed, the chips produced were less curled and compacted.



(a) (b)

FIGURE 8. OPTICAL AND SEM MICROGRAPHS OF CHIPS PRODUCED FROM (A) UFG TI AND (B) COARSE-GRAINED TI WITH CUTTING SPEED OF 1 M/S, FEED OF 0.015 MM/REV, AND DEPTH OF CUT OF 0.02MM.



(a) (b)

FIGURE 9. OPTICAL AND SEM MICROGRAPHS OF CHIPS PRODUCED FROM (A) UFG TI AND (B) COARSE-GRAINED TI WITH CUTTING SPEED OF 2 M/S, FEED OF 0.03 MM/REV, AND DEPTH OF CUT OF 0.04 MM.

CONCLUSIONS

UFG Ti shows many promising applications in the medical and aerospace industry. In this study, machinability of ECAP processed UFG Ti was investigated and compared to that of regular coarse-grained Ti. Surface roughness, cutting forces, tool wear, and chip morphology were studied using a turning process. Dry machining was performed using PCD tools while cutting conditions were varied throughout the experiment to help determine their impacts on machinability.

It was found that there were no pronounced cutting forces and tool wear differences between the UFG and coarse-grained Ti. The main tool wear mechanism is concluded as diffusion. However, UFG Ti could have a relatively better surface finish and its surface finish increased with the cutting speed. Unlike machining Ti-6Al-4V, the UFG Ti bar produced continuous chips that were not serrated under the conditions investigated. Chip morphology of both Ti did not change with tool wear, and UFG Ti produced relatively smaller curvature chips.

To further research the machinability of UFG Ti, different tool materials such as cubic boron nitrate or coated tungsten carbide may be used and compared to the performance of PCD tools. Corrosion resistance and bio-compatibility may also be examined after machining is done. Because UFG materials are known to have thermally unstable microstructures, TEM images of grains should be helpful in determining whether or not any detrimental grain growth occurs during the machining process.

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