Fatih H. Çakır
Eskişehir Vocational School,
Eskişehir Osmangazi University,
Eskisehir
Selim Gürgen
Eskişehir Vocational School,
Eskişehir Osmangazi University,
Eskisehir
Sezan Orak
Department of Mechanical
Engineering, Eskişehir Osmangazi
University, Eskişehir
M. Cemal Kuşhan
Department of Mechanical
Engineering, Eskişehir Osmangazi
University, Eskişehir
***M. Alper Sofuoğlu**
asofuoglu@ogu.edu.tr
Department of Mechanical
Engineering, Eskişehir Osmangazi
University, Eskişehir

An Experimental Investigation of the Ultrasonic-Assisted Machining of Ti6Al4V

In this study, an experimental study was performed for the ultrasonic-assisted turning of Ti6Al4V. The surface properties of titanium alloy machined by ultrasonic-assisted turning method were examined. Also, chip morphology was investigated. These measurements were compared with conventional turning operations performed with same cutting parameters. It was seen that ultrasonic-assisted turning affects surface properties. Average surface roughness was reduced, and less deformation was observed on the workpiece surface. Also, serrated and irregular chips were observed.

Keywords: Ultrasonic-assisted turning, Ti6Al4V, Surface roughness, Chip morphology

1. INTRODUCTION

Ultrasonic-Assisted Turning (UAT) is performed with low amplitude (5-30 μm) and high frequency (15-25 kHz) vibrations during cutting operations [1]. Vibrations can be applied in many directions such as cutting direction, feed direction and depth of cut direction. In some cases, the vibrations can be two or three dimensional. Due to simple of applicability and high effectivity, vibrations in cutting path are extensively preferred in UAT operations. In this process, intermittent cutting is applied in the cutting zone because oscillation of cutting tool exhibits plunging to material and back off for each vibrational cycles up to critical cutting speed magnitudes. This intermittent cutting provides a reduction in cutting forces and a duration for cooling of a cutting tool. Therefore, tool life is improved as a result of UAT method. Besides, operations are completed in more stable regions due to the reduction of chatter vibrations. For this reason, controlled chip formation is achieved while surface roughness, roundness and surface integrity of workpieces are improved significantly.

Pioneering studies on UAT method were performed in the late of 1950s. In these studies, 1D vibration was generated to excite the cutting tools. In the 1990s, 2D vibrations were benefited for the manufacturing of optic and ceramic-based components [1]. It was stated that 2D vibrations are more beneficial for the operations in comparison to 1D vibrations [2]–[4]. In the applications, 1D vibrations were generally preferable for metal parts especially in the aerospace industry [5]–[10]. An extension in tool life due reduced wear is stated in early studies [11]–[12]. As a drawback of this method, lower cutting speeds are suggested because ultrasonic vibrations are damped at high speeds which means that UAT operation turns into a conventional cutting [13].

In the literature, many attempts have been performed to understand the details of UAT method. Regarding surface finish, some early studies suggested models for predicting the surface roughness of workpiece based on vibration characteristics [14]-[15]. In some models, the relation between vibration characteristics and surface quality of workpiece was given [16]-[17]. Moreover, some investigations focused on the surface texture of workpiece after vibrational cutting methods [18]–[23]. It was observed that workpiece surface analysis of ultrasonic-assisted turning of Ti6Al4V was limited. Researchers have generally focused on cutting forces and temperatures, but the effect of ultrasonic vibration on the workpiece surface of Ti6Al4V was rarely studied.

In this study, an experimental study was carried out for the ultrasonic-assisted turning of Ti-6Al-4V. The surface roughness and microhardness of the titanium alloy (Ti6Al4V) machined by ultrasonic assisted turning method were examined. Also, obtained chip morphology was investigated. The UAT samples were compared with conventionally machined samples.

2. EXPERIMENTAL STUDY

In this study, Ti6Al4V alloy was used as the workpiece. This alloy is widely used in aerospace applications due to its advanced mechanical and chemical properties. Table 1 gives the chemical composition, and Table 2 presents the physical and mechanical properties of the Ti6Al4V alloy [24].

Table 1. The chemical composition of the Ti6Al4V alloy (%wt)

Al	V	C	Fe	N	O	H	Ti
5.5-6.75	3.5-4.5	0.1	0.4	0.05	0.2	0.015	Bal.

Table 2. The physical and mechanical properties of the Ti6Al4V alloy

Density	4.43 g/cm^3
Melting point	1650°C
Thermal conductivity	6.6 W/m-K
Specific heat capacity	565 J/kg-K
Tensile strength	950 MPa
Yield strength	880 MPa
Tensile elongation	10%
Hardness	33 HRC

In the experimental stage, UAT equipment was adapted on a universal lathe with the help of designed fixture as shown in Figure 1. The material of the horn is aluminum. SONIKEL ultrasonic system (230 volt and 2 kW) was used. The system includes ultrasonic generator (diameter=95 mm and length=275 mm) and horn (diameter=25 mm and length=185 mm). Surface roughness measurements were carried out using a Surftest SJ-310 profilometer (MITUTOYO) and three measurements were taken to obtain average values. A Future Tech FM700 hardness machine was used in the microhardness measurements. Table 3 gives the details of cutting tool and tool holder. Conventional turning (CT) and UAT operations were applied to compare the results. Feed rate and cutting depth were 0.1 mm/rev and 0.1 mm, respectively. Different overhang lengths were used to represent different stability cases. Tool holder lengths were used as 60 and 70 mm. Cutting speeds were 10, 20, 30, 40 m/min. In UAT method, frequency and amplitude of the vibrations were fixed at 20 kHz and 20 µm, respectively. Levels of experimental parameters were selected according to the early studies [9], [25].

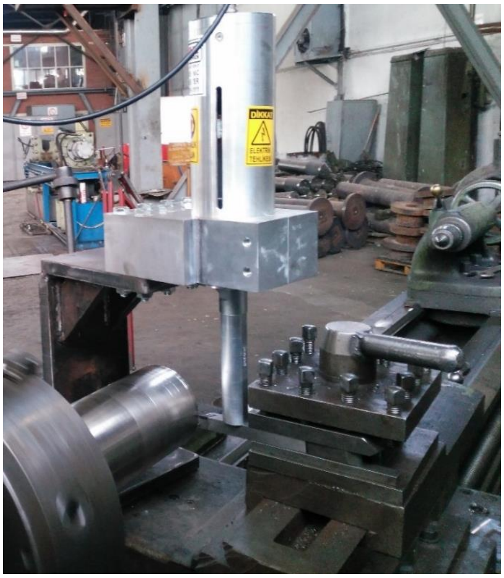
Table 3. Details of the cutting tool and tool holder

Dimensions of the tool holder	16 mm × 16 mm × 150mm
The material of cutting tool	WC + AlTiN
Rake angle	0°
Relief angle	7°
Tool nose radius	0.8 mm

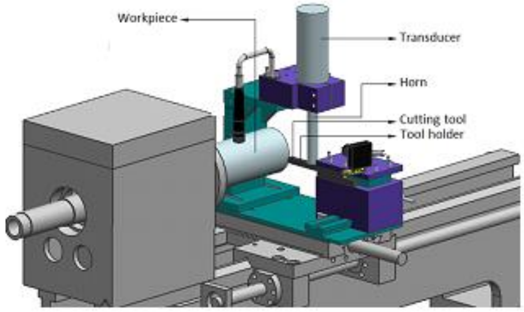
3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Surface Roughness Analysis

Table 4 gives the average surface roughness values measured for the Ti6Al4V alloy machined using two different machining methods. The results indicate that surface roughness was decreased by adding ultrasonic vibration. It was observed that average surface roughness is reduced by 11% in ultrasonic-assisted turning compared to conventional turning.



(a)



(b)

Figure 1. a) Experimental setup of UAT system; (a) photo and (b) schematic representation

Table 4. Average surface roughness values (Ra) for several cutting conditions and methods

Experiment No	Overhang length (mm)	Cutting speed (m/min)	Ra after CT (μm)	Ra after UAT (μm)
1	60	10	2.53	2.39
2	60	20	2.18	2.07
3	60	30	2.06	1.96
4	60	40	1.69	1.79
5	70	10	3.26	2.32
6	70	20	2.64	2.5
7	70	30	2.82	2.3
8	70	40	2.57	2.19

According to the experimental test with different cutting conditions; surface roughness values in the ultrasonic-assisted turning of Ti6Al4V are given in Figure 2. When the cutting speed increases and tool overhang length decreases, the surface quality increases.

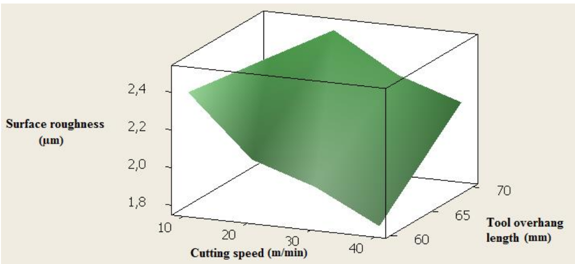


Figure 2. Variation of surface roughness in UAT

In terms of cutting method, UAT operation significantly improves the surface quality in comparison to the conventional turning method used in this study. The reason is that cutting forces are reduced because of the intermittent motion. Therefore, the surface roughness of workpiece is reduced. Also, the surface roughness of workpiece increases at lower cutting speeds as mentioned by [26]. The reason is that the occurrence of built-up edge (BUE) when machining multiphase materials at lower cutting speeds. Increasing cutting speed improves tool life. Cutting tool overhang length also affects the surface roughness because longer tool overhang length causes excessive cutting tool deflection.

3.2. Micro Hardness Analysis

Micro-hardness measurements were taken from the titanium workpiece cross-section to determine the work hardened section. The hardness measurement was carried out for conventional and ultrasonic assisted machined specimens with a cutting speed of 10 m/ min at an overhang length of 60 mm and a feed rate of 0.1 mm/rev. to understand the effect of ultrasonic vibrations. The micro-hardness tests were performed with a load of 200 g-forces and a dwell time of 10 seconds. In Figure 3, the vertical axis is the hardness value as Vickers, and the horizontal axis represents the measurement depth from the surface. Measurements were taken with 15-micron interval distances. According to the results, it was observed that the hardness values close to the surface are smaller in ultrasonic assisted turning method compared to conventional machining. Therefore, it was seen that the surface deformation and hardening are less effective in UAT and the hardening effect remains on the surface of the cross-section either. In Patil et al.'s study [9], the average hardness value on UAT surface was decreased by 16%. Less deformed grains are evident on UAT machined surface, which indicates lower machined surface hardness.

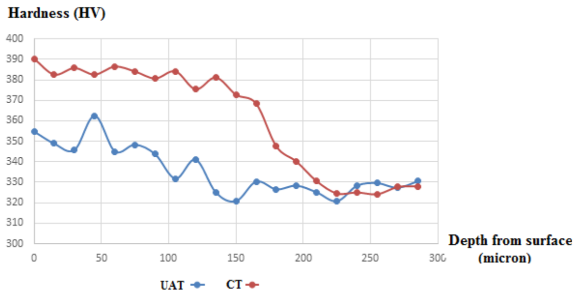


Figure 3. Microhardness values of conventional and ultrasonic-assisted machined specimens

3.3. Chip Morphology

Continuous chip was observed after ultrasonic-assisted machining. Figs. 4-6 show the chip shapes obtained after ultrasonic-assisted turning of Ti6Al4V. When the shape of the chips was examined, it was observed that the chips are serrated and have the irregular shape. It can be said that vibration causes serration and irregular shape of chips. The chips were not broken off because of the fast intermittent mechanism and the workpiece/tool material properties. It was also observed that the results were consistent with the literature study [27].

CONCLUSIONS

In this study, surface properties and chip morphology were investigated in ultrasonic-assisted turning. The results can be summarized as follows:

1. It was observed that average surface roughness was reduced by 11% in ultrasonic-assisted turning compared to conventional turning.

2. Ultrasonic-assisted turning method generated less deformation on the surface, so it was obtained that the surface deformation hardening effect is less dominant than conventional turning and the hardening effect remains on the surface of the cross-section. However, it should be noted that the measured hardness difference was about of 30-40 HV only.

3. The generated chip with UAT method was continuous, serrated and irregular.

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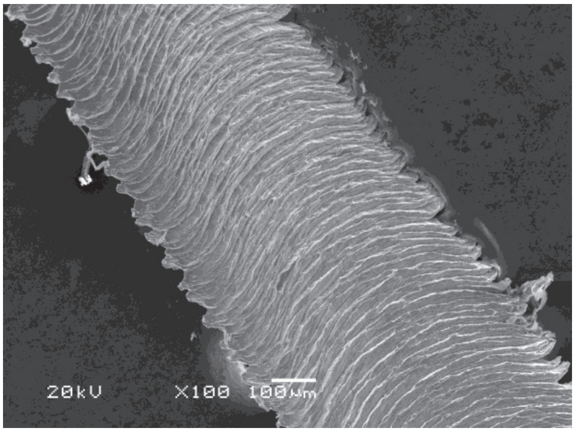

Figure 4. SEM image of the conventional machined Ti6Al4V chip
(Interior region, cutting speed=40 m/min)

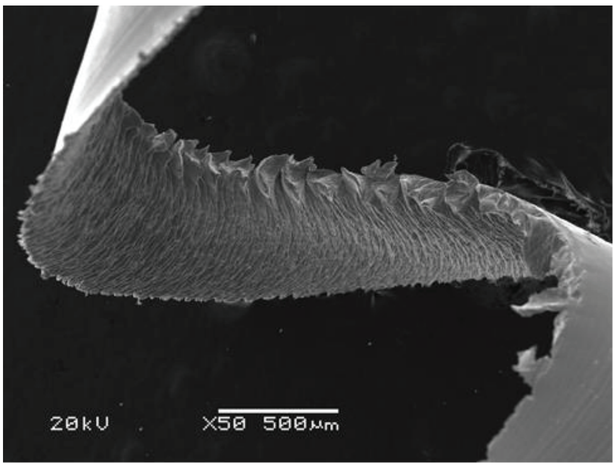

Figure 5. SEM image of the ultrasonic-assisted machined Ti6Al4V chip
(External region, cutting speed=40 m/min)

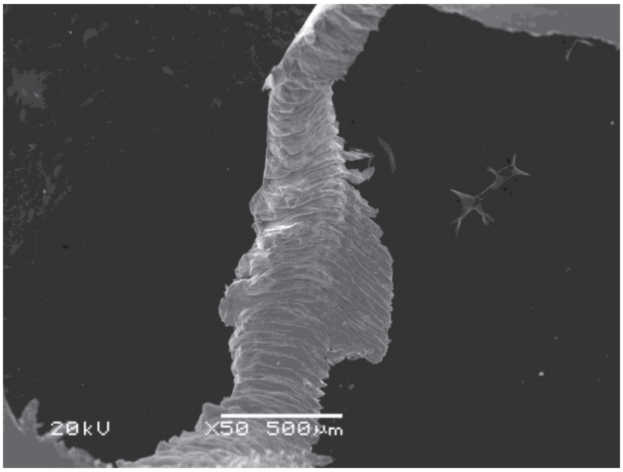

Figure 6. SEM image of the ultrasonic-assisted machined Ti6Al4V chip
(Interior region, cutting speed=40 m/min)

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