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CRYOGENIC ROTARY ULTRASONIC MACHINING OF TITANIUM ALLOYS

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ABSTRACT

Titanium alloys are utilized especially in applications that require a good combination of high strength, low mass and good corrosion resistance in aggressive environments. However, mechanical properties prejudge titanium alloys to hard machinability. Machining of titanium alloys is usually accompanied by cooling with liquids or gasses. One of the most effective cooling approaches is cooling by liquid nitrogen. Liquid nitrogen decreases temperature of tool, but also increases strength, hardness and brittleness of workpiece. One of the most suitable machining methods to machine hard and brittle materials is ultrasonic machining. In this article, rotary ultrasonic machining of titanium alloys under cryogenic conditions is analyzed.

KEY WORDS

Cryogenic machining, Rotary ultrasonic machining, Titanium alloys, Liquid nitrogen

INTRODUCTION

Commercial production of titanium began in the 1950s (Singh and Khamba, 2006). It has become an important material especially in spacecraft and aircraft, where it is primary applied to production of jet engines and airframe components. These components demand high geometric accuracy and low roughness of surface. Machining of titanium alloys is accompanied by high tool wear and low tool life. Worn tool cannot reach neither required accuracy, nor roughness. Rotary ultrasonic machining is able cost-effective machining hard machinable materials with relative high material removal rate and it also reaches high precision and low roughness. It makes rotary ultrasonic machining suitable for machining of titanium alloys, especially under cryogenic condition.

MATERIALS AND METHODS

Titanium has the highest strength-to-weight ratio of any metal. Therefore, titanium and its alloys have high utility in manufacturing sector. Also, titanium has excellent corrosion

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resistance. However, their properties prejudge titanium alloys to hard-machinability. They can reach value of yield strength up to 1400 MPa (Boyer, 1996; Peters and Leyens, 2009). Therefore, high cutting forces are required for machining of titanium. Higher cutting forces generate more process heat. Titanium alloys have poor thermal conductivity and it causes high temperature at the tool, because generated heat cannot be fast enough to be lead away by chips and it remains in tool-workpiece interface. This effect decreases tool life and increase tool wear.

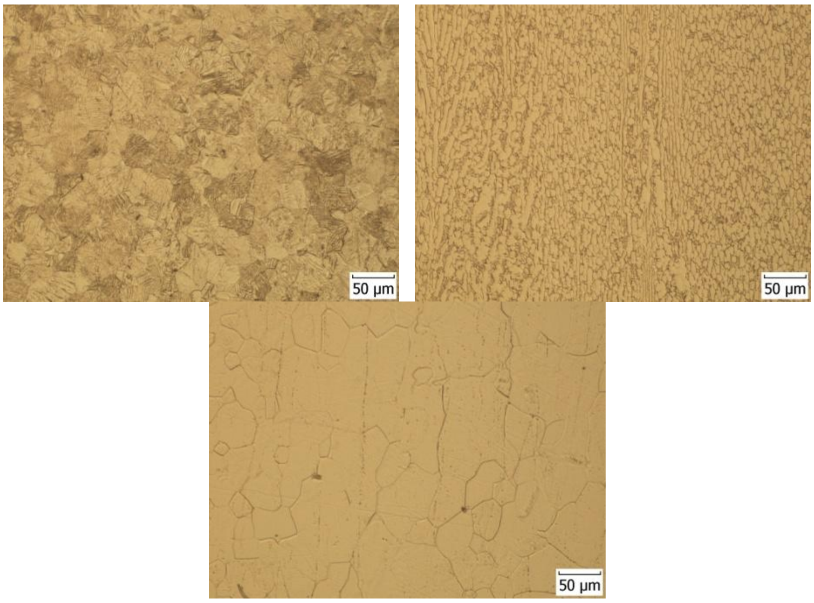
Pure titanium has two allotropic modifications. Alpha-titanium is present up to 882 °C and it is characterized by hexagonal close-packet (HPC) lattice. Over this temperature, up to melting point (1668 °C), beta-titanium is present, which is characterized by body centered cubic (BCC) lattice (Hong et al., 2001). However, we can affect resultant structure of titanium alloys at room temperature by adding alloying elements. Consequently, three structure types can be obtained at room temperature: alpha structure, alpha + beta structure, and beta structure. Beta-titanium alloys are characterized by higher mechanical properties and they can be heat-treatable. In comparison to other titanium alloys, beta-titanium alloys offer higher tensile strength due to deeper hardenability, increased fatigue strength and better forming properties (Machai and Biermann, 2011). In this article, the investigation of titanium alloy resultant phase to suitability to rotary ultrasonic machining under cryogenic condition is planned. There will be investigation of its influence to cutting forces, too. Representative of alpha-titanium alloys is Titanium Gr. 2. Alpha+beta-titanium alloys representative is Titanium Gr. 5. Finally, Titanium Gr. 19 is representative of beta-titanium alloys. Chosen titanium alloys and their chemical composition are recorded in Table 1. Chemical composition has been reached by EDX analysis.

CHEMICAL COMPOSITION AND PRESENT PHASES IN INVESTIGATED TITANIUM ALLOYS

Table 1

Material	Chemical composition [wt. %]						Phase
	Ti	Al	V	Cr	Zr	Mo	
Titanium Grade 2	100	-	-	-	-	-	α
Titanium Grade 5	89,96	5,81	4,23	-	-	-	α + β
Titanium Grade 19	73,12	3,39	8,08	5,98	4,62	4,80	β

Resultant microstructure is shown in Figure 1. To reach these microstructures, samples have been grinded by emery with granularity 600, then by emery with granularity 1200. After grinding, the polishing follows. To polishing the solutions that contain diamond abrasive are needed. Size of diamond particles are 9 µm, 6 µm, 3 µm and finally 1 µm. To highlight microstructure etching by Kalling´s etchant containing 10 ml of water, 3 ml of HNO_3 and 1,5 ml of HF for 5 to 10 seconds has been used. Microstructure has been observed by light microscope.



a) b) c)

Fig. 1 *Microstructure of titanium alloys: a) Grade 2, b) Grade 5, c) Grade 19*

To machine hard and brittle materials, one of the most suitable machining processes is unconventional method called Ultrasonic machining (USM). USM is a mechanical material removal process based on ultrasonic vibration of an abrasive particles carried in coolant. Application of USM brings many advantages. Workpiece is neither thermally nor chemically affected, and machined surface has low roughness (Thoe et al., 1998). Coolant in process circulates between a tool and the workpiece and it is primary used for removing of chips and for carrying of abrasive particles, not for cooling of the tool.

Rotary ultrasonic machining (RUM) is a hybrid machining process, which combines advantages of USM and diamond grinding. It achieves higher material removal rate than can be obtained by either diamond grinding or USM (Hu, 2002). In addition, it can reach higher precision and lower roughness compared to USM. RUM is cost-effective machining technology available for milling hard and brittle materials, like glass and ceramics. Even during machining such hard-machinable materials, it can reach superior surface finish, improved accuracy of holes, capability to drill deep holes, etc. In contrast with USM, RUM utilizes rotating tool with diamond abrasive bonded on active part of tool. There the coolant is also used, but in this case coolant does not carry abrasive particles. Primary application of coolant is also for removing of chips. Machining strategies of RUM are common plunging, and also face milling, as shown in Figure 2.

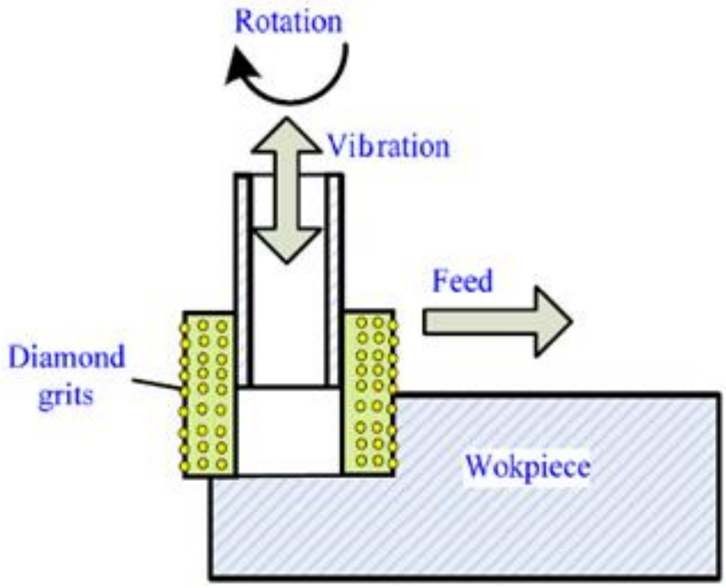


Fig. 2 *Illustration of rotary ultrasonic machining during side milling (Gong et al., 2010)*

ANTICIPATED RESULTS

A lot of researches based on increasing of tool life are focused on liquid nitrogen. For example, Yildiz and Nalbant (2008) ascribe the liquid nitrogen cooling approach the biggest impact on increased tool life, on improved surface roughness and on temperature control among all cooling strategies. Hong et al. (2001) applied small focused micro-jets of liquid nitrogen towards the tool tip, which cause increasing tool life in machining of Ti-6Al-4V up to five times. Umbrello et al. (2012) compared cryogenic cooling approach and dry machining, and they find out that turning with cryogenic cooling can reach as low roughness as grinding.

Application of liquid nitrogen is focused on the cooling effect, because temperature of liquefaction of nitrogen is – 196 °C (77 K). Lubrication effect of liquid nitrogen is insignificant. When any material is exposed to cryogenic temperatures, its mechanical properties will change. Its hardness and strength will be increased and material becomes more brittle. Especially materials with cubic lattice are susceptible to embrittlement. That also affects cutting forces. Therefore, mechanical properties of material under cryogenic conditions are important to know, especially impact strength is relevant. Velocity of heating of frozen material on atmosphere is another important attribute. Based on these facts, simulation of heating the sample for impact bending test has been investigated. Simulation has been created by ANSYS software. As shown in Figure 3, titanium sample reaches room temperature after few minutes after exposing surroundings. The highest amount of temperature has been absorbed at the beginning of heating. Development of temperature in first 150 seconds is shown in this figure. Uniform temperature of sample has been – 196 °C, temperature of surrounding has been + 20 °C. In this figure longitudinal sectioned sample is shown. Therefore, temperatures in the middle of the sample can be observed.

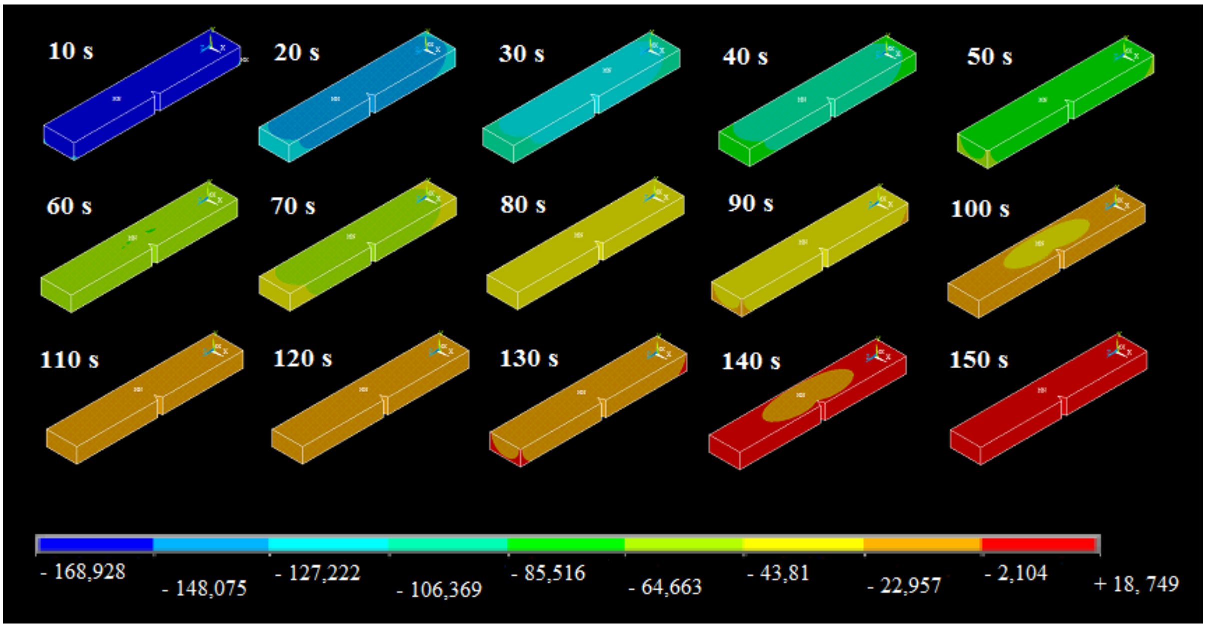


Fig. 3 *Development of temperature in time for frozen titanium sample*

Detail about development of specific temperatures in hottest and coldest places of frozen titanium sample in five minutes are shown in Table 2. Information in this table is based on simulation that was mentioned above. Temperature arises fast at the beginning. But with increasing of temperature of sample, velocity of heating is decreasing. Difference between surface temperature and core temperature is decreasing with exposing time and rising temperature. It is because heat drain is rising with rising of difference between temperature of sample and temperature of surrounds.

DEPENDENCE OF TEMPERATURE ON TIME DURING HEATING OF TITANIUM SAMPLE

Table 2

Time [s]	***10***	***20***	***30***	***40***	***50***	***60***	***70***	***80***	***90***	***100***
$\mathbf{T_{min}}$ [°C]	-169	-142	-118	-97	-80	-65	-52	-41	-32	-24
$\mathbf{T_{max}}$ [°C]	-145	-116	-94	-76	-61	-48	-37	-29	-21	-15

Time [s]	***110***	***120***	***130***	***140***	***150***	***160***	***170***	***180***	***190***	***200***
$\mathbf{T_{min}}$ [°C]	-17	-12	-7	-3	+1	+4	+6	+8	+10	+12
$\mathbf{T_{max}}$ [°C]	-9	-5	-1	+2	+5	+7	+9	+11	+12	+13

Time [s]	***210***	***220***	***230***	***240***	***250***	***260***	***270***	***280***	***290***	***300***
$\mathbf{T_{min}}$ [°C]	+13	+14	+15	+16	+16	+17	+17	+18	+18	+18
$\mathbf{T_{max}}$ [°C]	+14	+15	+16	+17	+17	+18	+18	+18	+19	+19

Figure 4 shows graph of dependence that was mentioned above in Table 2. Size of used sample for impact bending test is normalized: 10x10x55 mm. This sample has notch in the middle. Notch could be V or U shaped, and in this case, it is V shaped. Angle of notch is 45 ° and its depth is 2 mm (Tanaka and Bar, 1980). Surface of the sample has higher temperature than core of sample. Therefore, the highest temperature is on edges, and the lowest temperature is in the middle of the sample.

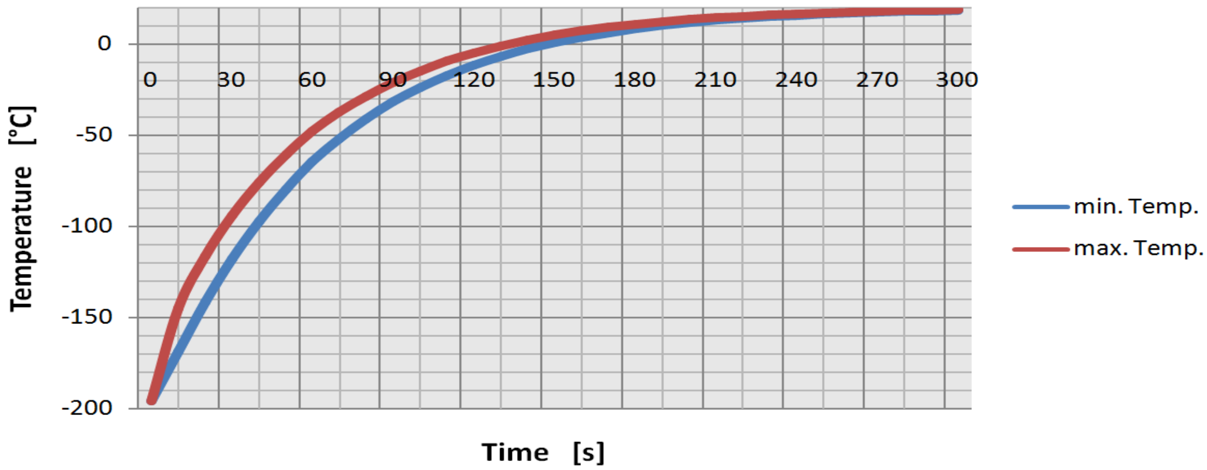


Fig. 4 *Graph of development of temperature in surface and core of titanium sample in five minutes*

CONCLUSION

It is commonly known that the machining of titanium alloys is performed at slow cutting speeds and it is accompanied by rapid tool wear. One of the most significant methods to increase tool life is utilizing of coolants. Cryogenic cooling has the biggest impact on increasing of tool life from all cooling approaches (Yildiz and Nalbant, 2008). Cryogenic cooling is utilized even in ultra-precision machining (Kakinuma et al., 2012).

Use of rotary ultrasonic machining is another way how to machine hard-machinable materials and to reach high quality of the machined surface. RUM is especially suitable for hard and brittle materials. Therefore, cryogenic cooling could enhance machining process.

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REFERENCES

1. SINGH, R., KHAMBA, J. S. 2006. Ultrasonic machining of titanium and its alloys: A review. *Journal of Materials Processing Technology*, 125-135.
2. BOYER, R. R. 1996. An overview on the use of titanium in aerospace industry. *Materials Science and Engineering* A 213 (1), 103-114.
3. PETERS, M., LEYENS, C. 2009. Titan und Titanlegierungen. *Wiley VCH*, Weinheim.
4. HONG, S. Y., MARKUS, I., JEONG, W. 2001. New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. *International Journal of Machine Tools & Manufacture* 41, 2245-2260.
5. MACHAI, C., BIERMANN, D. 2011. Machining of β-titanium-alloy Ti-10V-2Fe-3Al under cryogenic conditions: Cooling with carbon dioxide snow. *Journal of Materials Processing Technology* 211, 1175-1183.
6. THOE, T. B., ASPINWALL, D. K., WISE, M. L. H. 1998. Review on ultrasonic machining. *Tools Manufact*., **38**(4), pp. 239-255.

7. GONG, H., FANG, F. Z., HU, X. T. 2010. Kinematic view of tool life in rotary ultrasonic side milling of hard and brittle materials. *International Journal of Machine Tools & Manufacture*, 50, 303-307.
8. HU, P., ZHANG, J. M., PEI, Z. J., TREADWELL, C. 2002. Modeling of material removal rate in rotary ultrasonic machining: designed experiments. *Journal of Materials Processing Technology*, 129, 339-344.
9. YILDIZ, Y., NALBANT, M. 2008. A review of cryogenic cooling in machining processes. *International Journal of Machine Tools and Manufacture*, **48**(9), 947–964.
10. TANAKA, K., BAR, H. 1980. Impact bending test on steel at low temperatures. *The Japan society of mechanical engineers*, **23**(185), 1736-1744.
11. KOBRIN, P. A., SEMIATIN, S. L. 2001. Determination of interface heat-transfer coefficients for permanent-mold casting of Ti-6Al-4V. *Metallurgical and materials transactions B*, **32**B, 685-695.
12. UMBRELLO, D., MICARI, F., JAWAHIR, I. S. 2012. The effects of cryogenic cooling on surface integrity in hard machining: A comparison with dry machining. *CIRP Annals – Manufacturing Technology 61*, 103-106.
13. KAKINUMA, Y., KIDANI, S., AOYAMA, T. 2012. Ultra-precision cryogenic machining of viscoelastic polymers. *CIRP Annals – Manufacturing Technolog, 61*, 79-82.