https://doi.org/10.20965/ijat.2016.p0647

Paper:

Ultra-Low-Frequency Vibration Assisted Machining of Ti-6Al-4V Alloy

Tatsuya Sugihara† and Toshiyuki Enomoto

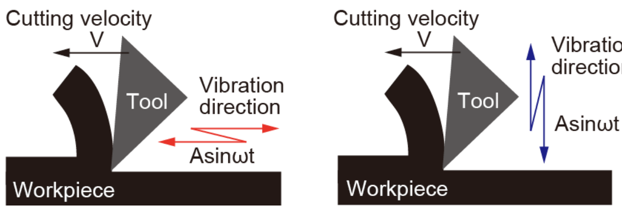
Osaka University
2-1 Yamada-oka, Suita, Osaka 565-0871, Japan
†Corresponding author, E-mail: t-sugihara@mech.eng.osaka-u.ac.jp
[Received February 1, 2016; accepted May 19, 2016]

As titanium alloys such as Ti-6Al-4V provide several benefits, including high-temperature strength and high corrosion resistance, the demand for such materials has rapidly increased, particularly in the aircraft industries. On the other hand, they are known to be among the most difficult-to-cut materials due to their mechanical and chemical properties, which make tool life extremely short. In order to solve this problem, this paper proposes a new cutting method employing ultra-low-frequency (ULF) vibration. ULF vibration ranges from less than 1 Hz to approximately 10 Hz and is generated by using a numerically-controlled machine tool axis and an NC program. The results of turning experiments showed that the developed method significantly reduces crater wear in the machining of Ti-6Al-4V, even under dry machining conditions. Moreover, the mechanism that ULF vibration affects and the effect of actual cutting time and non-cutting time in each individual vibration period on the amount of crater wear were investigated. As a result, it was found that the developed process is a promising method for achieving high performance dry machining of titanium alloys.

Keywords: cutting process, vibration assisted machining, tribology

1. Introduction

Ti-6Al-4V is one of the most important alloys of the titanium alloys because it has unique properties such as high specific strength and high corrosion resistance. Therefore, the demand for such materials has rapidly increased, particularly in the aircraft industries. On the other hand, titanium alloys are known to be among the most difficult-to-cut materials due to their mechanical and chemical properties. Consequently, they make tool life extremely short, especially under dry machining and high speed machining conditions [1–3]. Accordingly, various studies have been done, such as the ones on cryogenic machining [4, 5] and high pressure coolants [6, 7]. However, these techniques require costly additional devices and equipment, and dry machining without the use of any cutting fluid has recently become desirable to reduce en-



(a) Cutting velocity direction (b) Feed direction

Fig. 1. Classification of vibration assisted machining.

vironmental load and production costs [8, 9].

To overcome this situation, we have proposed a new cutting method focusing on vibration assisted machining (VAM). In VAM, small-amplitude vibration is applied to a cutting tool or workpiece material to enhance cutting performance and numerous studies regarding VAM have been conducted. Generally, conventional VAM can be classified into two types: vibration in the direction of cutting velocity (cutting velocity direction, **Fig. 1(a)**) and vibration in the direction of tool-feed (feed direction, **Fig. 1(b)**) [10, 11]. In either case, it is known that various advantages can be obtained when the usual continuous contact between the cutting tool and the workpiece material is replaced by intermittent cutting [10, 12]. To realize intermittent cutting through the application of vibration in the cutting velocity direction, cutting speeds have to satisfy the condition of $\omega A > V$, where ω is the angular vibration frequency, $2A$ is peak-to-peak amplitude and V is cutting speed. Therefore, this kind of vibration machining typically uses ultrasonic vibration and is only applied to ultra-precision machining at very low cutting speeds [13–15]. In addition, an advanced VAM process in the cutting velocity direction, know as elliptical vibration cutting, has been developed and successfully put to practical use [16–18]; nevertheless, the application of this method is also limited to ultra-precision machining for the same reason described above. On the other hand, in the case of vibration in the feed direction, various vibrations, including those ranging from dozens of Hz to dozens of kHz, have been employed [12, 19-23], resulting in the improvement of surface integrity [19] and discrete chip formation [20–22]. However, the application is still limited to conditions with relatively low machining efficiency with low feed rate, since the undeformed chip thickness has to be less

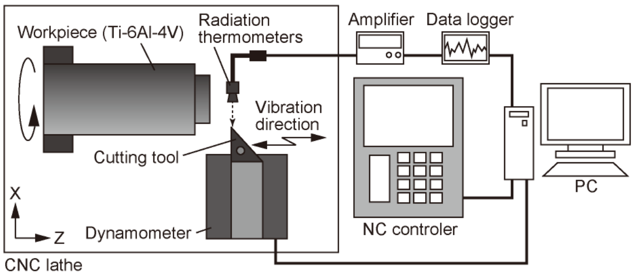


Fig. 2. Setup of experiment.

Table 1. Cutting conditions.

Workpiece	Ti-6Al-4V alloy (Initial diameter: 100 mm)	
Tool	Cemented carbide P10, KW10 DCGW11T302 (Non-coated) (KYOCERA Corp.)	
Tool geometry	Rake angle Clearance angle	0 degrees 10 degrees
Cutting speed	100 m/min	
Depth of cut	1 mm	
Feed rate	0.10 (mm/rev)	
Cutting fluid	Dry	

than 2A to realize intermittent cutting with discrete chip formation.

In order to solve the above mentioned issues of conventional vibration assisted machining and to achieve high performance dry machining of titanium alloys, this paper presents a new cutting method employing ultra-low-frequency (ULF) vibration ranging from less than 1 Hz to approximately 10 Hz in the feed direction generated by using a numerically-controlled machine tool axis and an NC program. A series of turning experiments was carried out to show the performance of ULF vibration on the dry machining of Ti-6Al-4V alloy, and the mechanism that ULF vibration affects and optimum vibration conditions were experimentally investigated.

2. Ultra-Low-Frequency Vibration Assisted Machining

In conventional VAM, vibration is generated by adding devices such as a piezoelectric or magnetorestrictive actuator [13, 14, 20], or a linear motor [21]. In contrast to these methods, ULF vibration is directly generated by using a numerically-controlled machine tool axis and an NC program without any devices. **Fig. 2** shows the setup of the experiment. As shown in this figure, turning experiments employing a WC-Co cemented carbide cutting tool (KYOCERA Corp., KW10 DCGW11T302: ISO P10-type, uncoated tool) were conducted on Ti-6Al-4V alloy. **Table 1** lists the cutting conditions. Vibration in the feed direction was applied to the Z-axis of a CNC lathe (DMG MORI SEIKI CO., LTD; DuraTurn 2050). A dynamometer (Leptrino Co., Ltd., MFS085CA152US) was set up under the cutting tool holder to measure three components of the cutting forces, and a radiation thermometer (Japan Sensor Corp., FTK9-R220R-2.5B11) was set up on the tip of the cutting tool to measure the tool surface temperature. The NC controller was connected to a PC via a PCMCIA-LAN card, and position feedback data was measured by using servo tuning software (FANUC corp., FANUC SERVO GUIDE) to detect the actual position of the tool during the machining process.

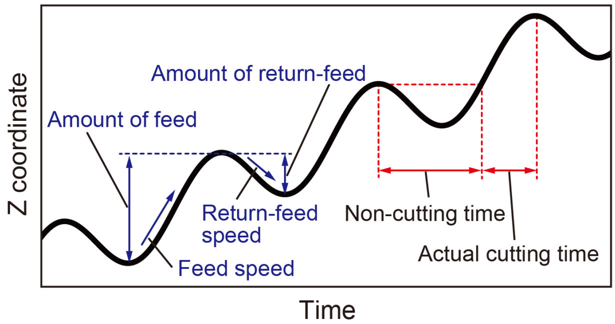


Fig. 3. Typical movement of cutting tool in ULF vibration assisted machining.

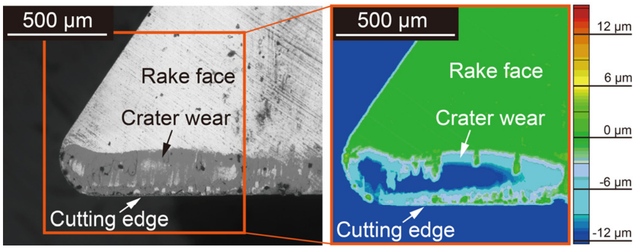
Figure 3 shows a typical movement of a cutting tool in ULF vibration assisted machining. As shown in this figure, the developed process consists of actual cutting time and non-cutting time in each individual vibration; this realizes intermittent cutting in turning operations. The vibration waveforms, including the actual cutting time and non-cutting time, can be controlled freely by changing four input parameters in the NC program: amount of feed, speed of feed, amount of return feed and speed of return feed. A similar method has been proposed by Smith et al. to provide chip breaking in turning operations [22]. We utilized this method to achieve high performance dry machining of titanium alloys.

3. Performance of Ultra-Low-Frequency Vibration Assisted Machining

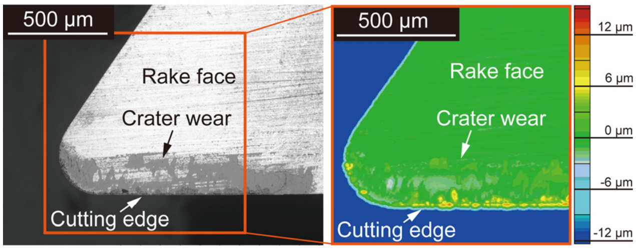
3.1. Effect on Tool Wear

In order to clarify the effect of the proposed method, dry machining experiments on Ti-6Al-4V alloy were conducted. In these experiments, the actual cutting time and non-cutting time in each vibration period were 0.15 sec and 0.40 sec, respectively.

Figure 4 shows SEM images and 3-D geometries of the tool rake face after 100 m of cutting. As shown in **Fig. 4(a)**, in the case of conventional machining without vibration, there was severe crater wear and the maximum depth of the crater wear was approximately 15 μm. On the other hand, **Fig. 4(b)** confirms that, when ULF vibration was imparted, the maximum depth of the crater wear of the tool rake face was significantly reduced from 15 μm (obtained with the conventional tool) to 3 μm even under the dry cutting condition. Although it has been recognized that the application of low and high frequency



(a) Conventional machining without vibration



(b) ULF vibration assisted machining

Fig. 4. SEM images and 3-D geometries of tool rake face after dry cutting for 100 m: (a) Conventional machining, (b) ULF vibration machining.

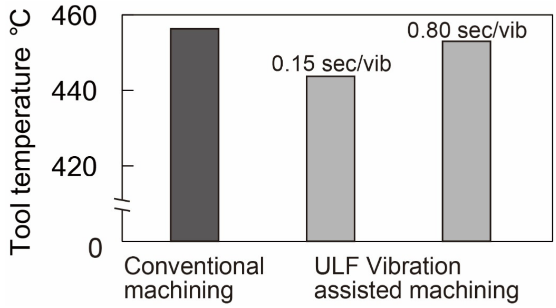


Fig. 5. Maximum temperature of tool surface.

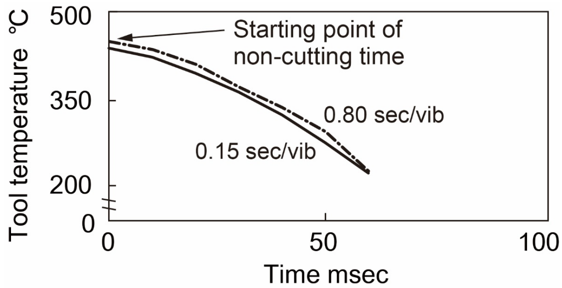


Fig. 6. Transition of tool surface temperature during non-cutting time.

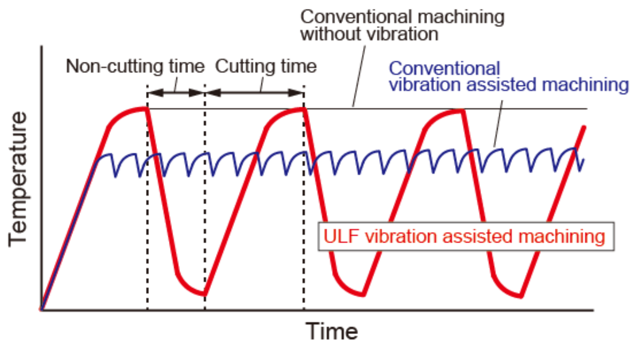


Fig. 7. Expected temperature transition: conventional machining without vibration, conventional VAM and ULF vibration assisted machining.

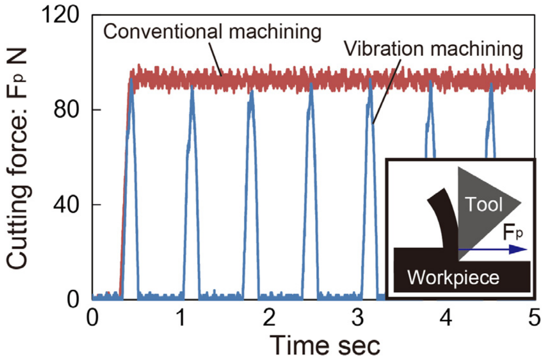
vibrations improves various parameters in metal cutting, the advantages of the vibration assisted machining are mainly explained as resulting from the effects of the penetration of cutting fluid into the tool-chip interface during non-cutting time [20, 23]. In contrast, these results show that the proposed method can significantly decrease the amount of the crater wear even without the use of cutting fluids.

3.2. Effect on Cutting Temperature

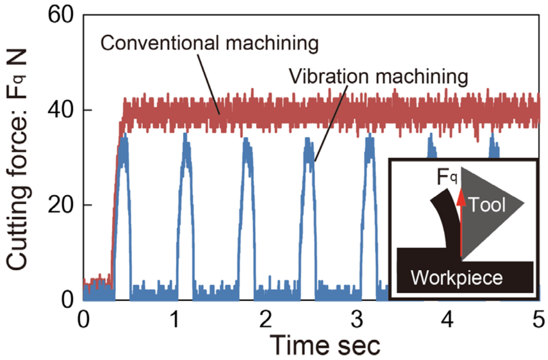
In order to identify the mechanism of the suppression of the tool wear in ULF vibration assisted machining, the cutting temperature was evaluated. As shown in **Fig. 2**, a radiation thermometer (Japan Sensor Corp., FTK9-R220R-2.5B11) was set up on the tip of the cutting tool and the temperature of the cutting tool surface was measured at the moment the tool was released from the workpiece. In these experiments, two different actual cutting times, 0.15 sec/vib and 0.80 sec/vib, were selected. The non cutting time was set to 0.40 sec/vib.

Figure 5 shows the maximum temperature of the tool surface with and without vibration, and this figure indicates that there was little difference among the three conditions, while the vibration with the actual cutting time of 0.15 sec/vib slightly reduced the tool surface temperature. This can be attributed to the fact that ULF vibration has a relatively long actual cutting time compared to that of conventional low frequency vibration assisted machining and the cutting temperature reaches peak temperature in conventional machining during each individual vibration. On the other hand, **Fig. 6** shows the transition of the tool surface temperature immediately after the tool was released from the workpiece in ULF vibration assisted machining. As this figure shows, the temperatures in both vibration conditions rapidly decreased during the non-cutting time suggesting that the elevated temperature, was cooled to close to the atmospheric temperature in each individual vibration period without the use of cutting fluid because the non-cutting time of ULF vibration assisted machining was long enough for the tool surface temperature to be cooled.

Figure 7 shows the expected temperature transition during the machining process. It has been reported that conventional vibration assisted machining, which employs low frequency vibration ranging from dozens to thousands of Hz, has the effect of reducing the peak cutting temperature compared with conventional machining without vibration [21, 22]. In contrast to this, it is supposed that ULF vibration can sufficiently decrease the tool surface temperature due to the heat dissipation into the atmosphere and tool substrate during non-cutting time, leading to the suppression of thermal wear.



(a) Cutting force in horizontal direction: F_p



(b) Cutting force in vertical direction: F_q

Fig. 8. Cutting forces in conventional and ULF vibration assisted machining.

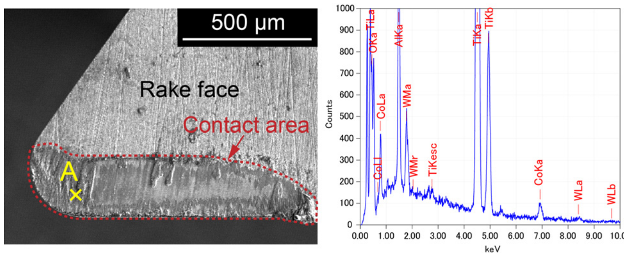


Fig. 9. SEM with energy-dispersive X-ray analysis of tool rake face after conventional machining (Left: SEM image Right: EDX analysis at point A).

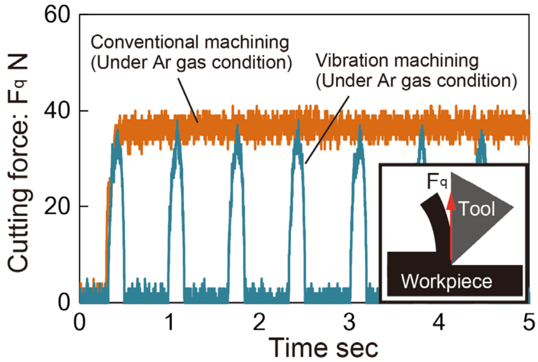


Fig. 10. Cutting forces in vertical direction in conventional and ULF vibration assisted machining under inert gas condition.

3.3. Effect on Cutting Force

In order to evaluate the effect of ULF vibration on the cutting forces, three components of the cutting forces were measured using a dynamometer (Leptrino Co., Ltd., MFS085CA152US) which was set up under the cutting tool holder (**Fig. 2**). When the cutting forces were measured, the depth of cut was set to 0.5 mm to avoid chatter vibration.

Figure 8 shows the cutting forces in the horizontal (F_p) and vertical directions (F_q), respectively. As shown in **Fig. 8(a)**, there are no significant differences in the peak values of F_p between the conventional and vibration assisted machining (actual cutting time: 0.15 sec/vib, non-cutting time: 0.40 sec/vib). On the other hand, **Fig. 8(b)** indicates that ULF vibration slightly decreases the peak values of F_q compared with the conventional machining. Since the rake angle of the tool is 0°, F_q can be regarded as the component perpendicular to the tool rake face, which is strongly influenced by the frictional properties at the tool-chip interface. This result suggests that the friction between the tool surface and the workpiece material decreased due to the vibration. It has been reported that the frictional properties can be improved by the application of conventional low frequency vibration, and the reason was mainly explained as resulting from the penetration of cutting fluids into the tool-chip interface during non-cutting time [20, 23]. In contrast, the results show that ULF vibration can reduce friction even under dry machining conditions.

3.4. Effect on Generation of Oxide Film

Figure 9 shows SEM with energy-dispersive X-ray analysis (SEM-EDX) of the tool rake face at point A after the conventional machining without vibration. As shown in this figure, titanium and aluminum, which are the base materials of Ti-6Al-4V, were detected at the tool-chip contact area of the rake face. This suggests that the Ti-6Al-4V alloy severely adhered to the surface of the cutting tool due to the high cutting temperature and high chemical affinity of the titanium alloy. In addition, it is supposed that the adhesion layer leads to diffusion and adhesive wear, as is generally well known [2, 24], since tungsten and cobalt, which are the base materials of the tool, were also detected at the same point. Furthermore, the peak of oxygen, which can be seen in the figure, indicates that the adhesion layer generated on the rake face was covered with oxide film. Moreover, Sasahara et al. have pointed out that a low-frequency vibration of 50 Hz generates a lubricant film on tool rake face and decreases the friction in 70%Cu-30%Zn Brass and medium carbon steel machining [25]. Therefore, it is expected that ULF vibration assisted machining also promotes the generation of the oxide film on the adhesions of Ti-6Al-4V alloy on the tool rake face during non-cutting time, resulting in the suppression of the crater wear and F_q, as described in the previous section.

In order to evaluate whether ULF vibration has the effect of generating the oxide film or not, dry cutting experiments under inert gas conditions were conducted. During the machining operation, argon gas at a pressure of

0.4 MPa was discharged from two nozzles set on the tool rake face side and tool flank face side. Other cutting conditions were the same as those listed in **Table 1**. **Fig. 10** shows the cutting force in the vertical direction (F_q), under the argon gas condition. As shown in this figure, the peak value of F_q in the vibration assisted machining was substantially coincident with that in the conventional machining, in contrast to the results in the atmospheric environment (**Fig. 8**). This result clearly shows that the ULF vibration promotes the oxidization of the surface of the adhesion layer on the tool rake face during non-cutting time, leading to the suppression of the crater wear.

4. Optimization of Vibration Conditions

Since ULF vibration assisted machining contains non-cutting time during the machining process, the machining efficiency, e.g. material removal rate, is lower than that in the conventional machining without vibration at the same cutting speeds. Therefore, optimization of the vibration conditions is important to the achievement of both high performance and high efficiency machining in the dry machining of titanium alloys. In this chapter, the effect of the actual cutting time and non-cutting time in each individual vibration period on the amount of crater wear are investigated with a view to optimizing the vibration conditions.

4.1. Influence of Actual Cutting Time

Figure 11 shows the relationship between the actual cutting time in each individual vibration period and the amount of the crater wear with three different non-cutting times (0.40, 0.50, and 0.60 sec/vib) after 100 m of dry machining. As shown in this figure, the amount of crater wear increased in proportion to the increase in the actual cutting time, and the amount of wear in the vibration assisted machining became nearly equal to that in the conventional machining when the actual cutting time was set to 0.8 sec/vib. This is probably because when the actual cutting time in each individual vibration period increases, tribological and thermal behaviors in the vibration assisted machining become closer to those in the conventional machining without vibration. In addition, the oxide film generated while the tool was released from the workpiece might be removed during the actual cutting time, resulting in the increase in diffusion and adhesive wear.

On the other hand, **Fig. 11** also shows that there is no significant difference in the amount of the crater wear even when the non-cutting time increased.

4.2. Influence of Non-Cutting Time

Figure 12 shows the relationship between the non-cutting time in each individual vibration period and the amount of the crater wear with three different actual cutting times (0.10, 0.15 and 0.30 sec/vib) after 100 m of dry machining. When the actual cutting time was set to 0.10 sec/vib, non-cutting time was set to over 0.40 sec/vib, but not under 0.40 sec/vib due to the limitation of the servo

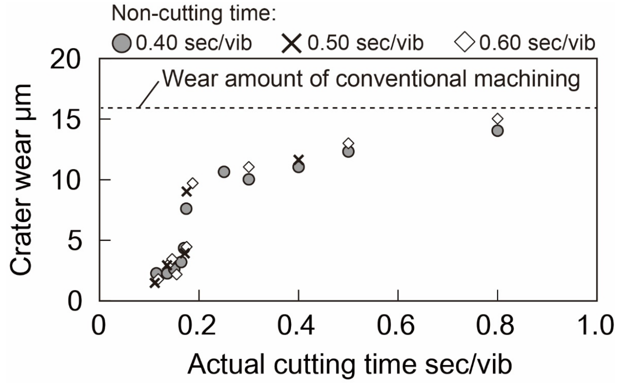


Fig. 11. Relationship between actual cutting time and amount of crater wear.

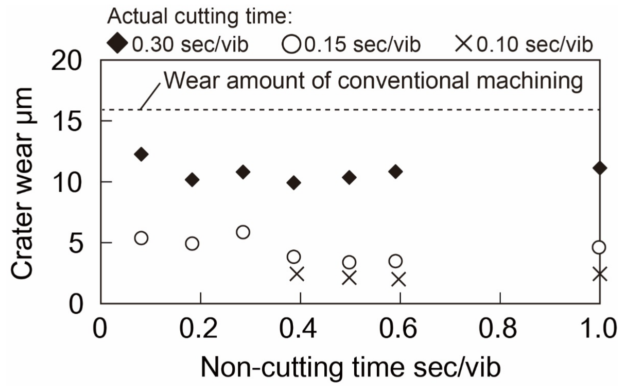


Fig. 12. Relationship between non-cutting time and amount of crater wear.

performance. In contrast to the situation in **Fig. 11**, there was no significant difference in the amount of the crater wear even when the non-cutting time was changed. It was also found that the wear amount depended on only the length of the actual cutting time. This might be attributed to the fact that the tool surface temperature can decrease sufficiently in a relatively short non-cutting time because the temperature is drastically reduced immediately after the tool is released from the workpiece, as shown in **Fig. 6**. Moreover, it is supposed that the oxide film on the adhesion layer also formes instantaneously during the non-cutting time since Ti-6Al-4V alloy oxidizes easily at high temperature.

These results indicate that ULF vibration assisted machining can suppress crater wear in the dry machining of titanium alloys, even when the non-cutting time is shortened to a certain degree. This leads to the increase of the material removal rate in the proposed machining process. **Fig. 13** compares the amount of crater wear in conventional machining without vibration and ULF vibration assisted machining employing one of the optimized vibration conditions (actual cutting time: 0.15 sec/vib, non-cutting time: 0.10 sec/vib), after 100 m of dry machining. This figure confirms that the application of ULF vibration suppresses the crater wear by more than 65%, while reducing the decrease in cutting efficiency by approximately 40%, as compared with conventional machining without

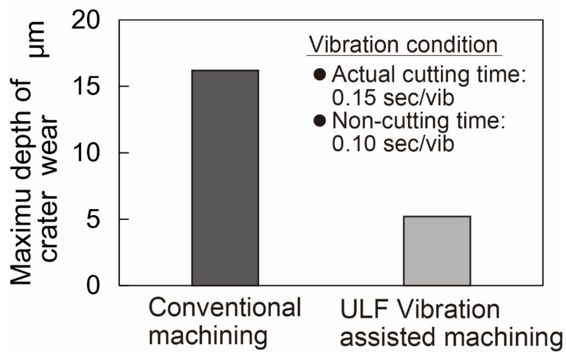


Fig. 13. Relationship between non-cutting time and amount of crater wear.

vibration at the same cutting speed. These results indicate that the developed process has great potential to achieve high performance dry machining of titanium alloys.

5. Conclusion

In this study, a new cutting method employing ultra-low-frequency vibration (ULF) generated by an NC program was developed in order to achieve high performance dry machining of titanium alloys. The findings of the study are as follows:

(1) The application of ULF vibration is significantly effective in reducing crater wear in the dry machining of titanium alloys.

(2) ULF vibration suppresses crater wear resulting from the effect of reducing tool surface temperature and generating oxide film on the adhesion of the workpiece material while the tool is released from the workpiece.

(3) The performance and efficiency of ULF vibration machining strongly correlate with the actual cutting time and non-cutting time in each individual vibration.

References:

[1] E. O. Ezugwu, J. Bonney, and Y. Yamane, "An overview of the machinability of aeroengine alloys," J. Mater. Process. Technol., Vol.134, pp. 233-253, 2003.

[2] A. Krämer, D. Lung, and F. Klocke, "High performance cutting of aircraft and turbine components," AIP Conf. Proc., Vol.1431, No.425, pp. 425-432, 2012.

[3] A. Pramanik, "Problems and solutions in machining of titanium alloys," Int. J. Adv. Manuf. Technol., Vol.70, No.5, pp. 919-928, 2014.

[4] Z. Y. Wang and K. P. Rajurkar, "Cryogenic machining of hard-to-cut materials," Wear, Vol.239, pp. 168-175, 2000.

[5] S. Y Hong, I. Markus, and W. Jeong, "New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V," Int. J. Mach. Tools Manuf., Vol.41, pp. 2245-2260, 2001.

[6] L. N. López de Lacalle, J. Pérez-Bilbatua, J. A. Sánchez, J. I. Llorente, A. Gutiérrez, and J. Albóniga, "Using High Pressure Coolant in the Drilling and Turning of Low Machinability Alloys," Int. J. Adv. Manuf. Technol., Vol.16, No.2, pp. 85-91, 2000.

[7] E. O. Ezugwu, R. B. Da Silva, J. Bonney, and Á. R. Machado, "Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies," Int. J. Mach. Tools Manuf., Vol.45, No.9, pp. 1009-1014, 2005.

[8] F. Klocke and G. Eisenblätter, "Dry cutting," CIRP Annals, Vol.46, No.2, pp. 519-526, 1997.

[9] P. S. Sreejith and B. K. A. Ngoi, "Dry machining: Machining of the future," J. Mater. Process. Technol., Vol.101, No.1-3, pp. 287-291, 2003.

[10] D. E. Brehl and T. A. Dow, "Review of vibration-assisted machining," Prec. Eng., Vol.32, pp. 153-172, 2008.

[11] B. Lauwers, F. Klocke, A. Klink, A. E. Tekkaya, R. Neugebauer, and D. Mcintosh, "Hybrid processes in manufacturing," CIRP Annals, Vol.63, No.2, pp. 561-583, 2014.

[12] J. B. Mann, Y. Guo, C. Saldana, W. D. Compton, and S. Chandrasekar, "Enhancing material removal processes using modulation-assisted machining," Tribol. Int., Vol.44, No.10, pp. 1225-1235.

[13] T. Moriwaki and E. Shamoto, "Ultraprecision Diamond Turning of Stainless Steel by Applying Ultrasonic Vibration," CIRP Annals, Vol.40, No.1, pp. 559-562, 1991.

[14] E. Shamoto and T. Moriwaki, "Ultaprecision Diamond Cutting of Hardened Steel by Applying Elliptical Vibration Cutting," CIRP Annals, Vol.48, No.1, pp. 441-444, 1999.

[15] M. Yoshimaru, H. Koresawa, H, Narahara, and H. Suzuki, "Processing Micro Reactor by Non-Rotational Cutting Tool with Ultrasonic Vibration," Int. J. Autom. Technol., Vol.3, No.5, pp. 602-609, 2009.

[16] E. Shamoto and T. Moriwaki, "Study on Eliptical Vibration Cutting," CIRP Annals, Vol.43, No.1, pp. 35-38, 1994.

[17] S. Amini, E. Shamoto, N. Suzuki, and M. J. Nategh, "FE Analysis of One-Directional and Elliptical Vibration Cutting Processes," Int. J. Autom. Technol., Vol.4, No.3, pp. 252-258, 2010.

[18] Y. Wang and E. Shamoto, "Elliptical Vibration Cutting of Hardened Steel with Large Nose Radius Single Crystal Diamond Tool," Int. J. Autom. Technol., Vol.8, No.6, pp. 820-826, 2014.

[19] A. Schubert, A. Nestler, S. Pinternagel, and H. Zeidler, "Influence of ultrasonic vibration assistance on the surface integrity in turning of the aluminum alloy AA2017," Materialwissenschaft und Werkstofftechnik, Vol.42, No.7, pp. 658-665, 2011.

[20] Y. Guo, J. B. Mann, H. Yeung, and S. Chandrasekar, "Enhancing Tool Life in High-Speed Machining of Compacted Graphite Iron (CGI) Using Controlled Modulation," Tribol. Lett, Vol.47, No.1, pp. 103-111, 2012.

[21] K. Okamura, H. Sasahara, T. Segawa, and M. Tsusumi, "Low-frequency Vibration Drilling of Titanium Alloy," JSME Int. J. Ser. C, Vol.49, pp. 76-82, 2006.

[22] S. Smith, B. Woody, W. Barkman, and D. Turshy, "Temperature control and machine dynamics in chip breaking using toolpaths," CIRP Annals, Vol.58, No.1, pp. 97-100, 2009.

[23] W. Moscoso, E. Olgun, W. D. Compton, and S. Chandrasekar, "Effect of Low-Frequency Modulation on Lubrication of Chip-Tool Interface in Machining," Trans. ASME, Vol.127, pp. 238-244, 2005.

[24] D. Jianxin, L. Yousheng, and S. Wenlong, "Diffusion wear in dry cutting of Ti-6Al-4V with WC/Co carbide tools," Wear, Vol.265, No.11-12, pp. 1776-1783, 2008.

[25] H. Sasahara, G. Jin, M. Jin, and M. Murakawa, "Effect of Vibration and Atmosphere in Vibration Cutting Process (On 50 Hz Vibration Cutting)," Trans. Jpn. Soc. Mech. Eng. Ser. C, Vol.70, No.694, pp. 1843-1848, 2005.

Name:
Tatsuya Sugihara

Affiliation:
Assistant Professor, Department of Mechanical Engineering, Graduate School of Engineering, Osaka University

Address:
2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

Brief Biographical History:
2012 Assistant Professor, Osaka University

Main Works:
- "Improving anti-adhesion in aluminum alloy cutting by micro stripe texture," Precision Engineering, Vol.36, pp. 229-237, 2012.
- "Crater and flank wear resistance of cutting tools having micro textured surfaces," Precision Engineering, Vol.37, pp. 888-896, 2013.
- "On-machine tool resharpening process for dry machining of aluminum alloys employing LME phenomenon," Precision Engineering, Vol.40, pp. 241-248, 2015.

Membership in Academic Societies:
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Precision Engineering (JSPE)
- Japan Society for Abrasive Technology (JSAT)

Name:
Toshiyuki Enomoto

Affiliation:
Professor, Department of Mechanical Engineering, Graduate School of Engineering, Osaka University

Brief Biographical History:
1990 Joined RICOH Company, Ltd.
2004 Associate Professor, Osaka University
2010 Professor, Osaka University

Main Works:
- "A Newly Developed Polishing Pad for Achieving High Surface Flatness Without Edge Roll Off," CIRP Annals, Vol.60, pp. 371-374, 2011.
- "Spiral-Structured Fixed-Abrasive Pads for Glass Finishing," CIRP Annals, Vol.62, pp. 311-314, 2013.
- "A New Surgical Grinding Wheel for Suppressing Grinding Heat Generation in Bone Resection," CIRP Annals, Vol.63, pp. 305-308, 2014.

Membership in Academic Societies:
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Precision Engineering (JSPE)
- Japan Society for Abrasive Technology (JSAT)
- International Academy for Production Engineering (CIRP)