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Machining Performance of Ti-6Al-4V Titanium Alloy Assisted by High Pressure Waterjet

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Abstract: The High Pressure Waterjet Assisted Machining (HPWAM) is a machining process that involves high pressure coolant being delivered at the cutting zone. This paper investigates the performance of conventional and HPWAM when machining Ti-6Al-4V titanium alloy. The evaluations were based on the tool life, wear mechanisms, surface profile and chip formation. The coolant pressures, cutting speed, feed rate and depth of cut were set at 11-20.3 MPa, 110m/min, 0.15 mm/rev and 0.5 mm respectively. The results showed that improved tool life as much as 195% can be achieved when machining Ti-6Al-4V with HPWAM due to better coolant access at the cutting zone. Surfaces generated when machining with HPWAM were generally acceptable with negligible physical damage. Long and continuous chip formations were observed when machining in conventional coolant supply corresponded to the low coolant pressure. Increasing coolant pressure significantly reduces the chip size, resulting in a reduction in the tool-chip contact and improvement in lubrication at the contact interfaces. This paper provides the understanding and correct use of HPWAM especially when machining Ti-6Al-4V alloy.

Key words: High Pressure Waterjet Assisted Machining % Coolant Pressure % Cutting Tool % Titanium Alloy % Surface Integrity

INTRODUCTION

The High Pressure Waterjet Asisted Machining (HPWAM) is the machining process that involves the high pressure coolant being delivered to the cutting region, generally within the range 0.5-360 MPa [1]. This is a hybrid process where dual action of machining and coolant pressure are used to remove the material during shearing action at the cutting zone [2]. The HPWAM consists of a piping components, motor and a specially designed tool holder installed in the machining system. The cutting fluid is first pumped by the motor from the coolant tank. The piping carries the coolant from the coolant tank to the tool holder. The tool holder delivers the coolant jet from the specially designed nozzle to the critical region in the secondary shear zone tool-chip interface [3]. There are many benefits of using HPWAM reported in previous studies [3-5]. Among the benefits are the HPWAM generally can provide better heat removal as compared to the conventional methods because of capability of coolant to penetrate deep into the cutting zone [3]. In addition, the penetration of high pressure

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coolant enables the coolant water wedge to be created at the tool-chip interface. The creation consequently reduces the tool-chip contact length, thereby eliminates the seizure effect between the cutting tool and chip. The tool is less susceptible to thermally-related wear mechanisms caused by the sliding chips because of the tool-chip contact time is shorter [4]. The HPWAM is reportedly capable to increase in productivity up to 700% and 500% when machining Iconel 718 and CK45 hardened steel respectively as compared to the conventional methods [4, 5].

The Ti-6Al-4V alloy is considered the most widely used titanium alloy in industry and accounted for about 60% of the total titanium production [6]. The alloy generally contains approximately 90% titanium, 6% aluminium, 4% vanadium and minor phases such as Iron, Carbon, Oxygen and Nitrogen [7]. This material generally has excellent mechanical properties, high corrosion resistance, high operating temperature and high strength-to-weight ratio. The Ti-6Al-4V being used widely in aerospace and marine applications such as in rocket motor cases, blades, disks and turbines [8].

The Ti-6Al-4V alloy is also known to be among the difficult-to-cut materials due to its mechanical properties and poor thermal conductivity [8]. Machining Ti-6Al-4V alloy normally consumeds an excessive concentration of temperature at the cutting interfaces, which, under severe conditions, which will cause various types of thermal damage on the cutting tool and the machined component [1-5]. Therefore, machining Ti-6Al-4V alloy is recommended to be undertaken under wet conditions to reduce the excessive cutting temperature and eliminate the possibility of surface deterioration [1-5]. The use of HPWAM is one of the possible alternatives to machine Ti-6Al-4V effectively. The objective of this paper is to investigate the HPWAM performance when machining Ti-6Al-4V titanium alloy. The evaluations are based on the tool life, wear mechanisms, surface profile and chip formations. The result of HPWAM is compared with the machining with conventional coolant to see the advantage of this hybrid technique in improving productivity of machining Ti-6Al-4V alloy.

MATERIALS AND METHODS

Machining tests were carried out on Colchester MASTIFF CNC machine in two different coolant environments: conventional coolant supply as illustrated in Figure 1(a) and High Pressure Waterjet Assisted Machining (HPWAM) as illustrated in Figure 1(b).

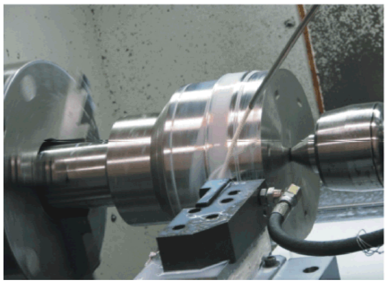
Fig. 1(a): Machining with conventional coolant supply

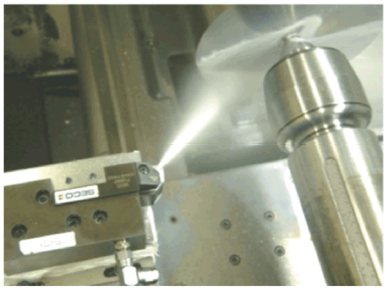
Fig. 1(b): High Pressure Waterjet Asissted Machining (HPWAM)


Fig. 2(a): Uncoated carbide inserts

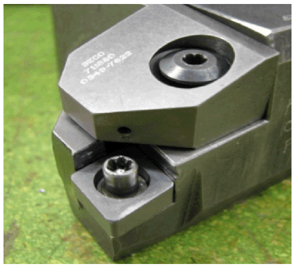
Fig. 2(b): The tool holder

The cutting speed, feed rate and depth of cut were kept constant at 110 m/min, 0.15 mm/rev and 0.5 mm respectively. The workpiece material used in this study is a commercially available Ti-6Al-4V alloy. The tests were performed using uncoated carbide inserts as shown in Fig. 2(a) with special tool holder designed for high pressure application as shown in Figure 2 (b). The properties of coolant, workpiece material and cutting tool used in this study are illustrated in Tables 1, 2 and 3 respectively.

Table 1: Physical Properties of Ti-6Al-4V Alloy

Tensile strength (MPa)	0.2% Proof stress (MPa)	Elongation (%)	Density (kg/m^3)	Melting point (°C)	Measured hardness (CI - 99%)* HV_{100}	Thermal conductivity at 20°C (W/m.°C)
900 to 1160	830	8	4430	1650	Min.= 297 Max. = 410	6.6

* CI: Confidence interval of 99 %, represented by the minimum (Min.) and maximum (Max.) values

Table 2: Properties of Uncoated Carbide 883 Grade Tool insert

ISO Designation	Chemical Composition (wt %)	Hardness (Knoop) GPa	Density (kg/m^3)	Heat Capacity J/kg.°C	Thermal conductivity W/m.°C	Grain size (µm)
CNMG 120412 – M1	93.8 % WC, 6% Co, 0.2% (Ta, Nb)C	13 (1760 HV)	14950	241	11	1.0

Table 3: General Properties of Coolant

Major Compo-sition	Concen-tration	Viscosity of coolant in oil phase (cSt)	Viscosity of coolant after mixed with water (cSt)	Average Surface Tension (mN/m)	pH
Fatty acid	6%	65	1	41.51	9.35

The tool wear is measured during each machining test with tool life criterion in accordance with ISO 8688-2 (maximum flank wear, V_{Bmax} of 0.3 mm). The surface finish is measured with a stylus type instrument (Surtronic 10) and the chips were collected after each machining test. The Scanning Electron Microscope (SEM) was then used in order to analyze the modes of tool wear, surface profile and chip formation after machining.

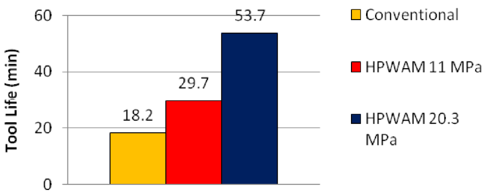

Fig. 3: Comparison of tool life recorded when machining Ti-6Al-4V alloy with various cutting conditions

RESULTS AND DISCUSSION

Tool Life: Figure 3 shows the comparison of tool performance between machining with conventional and the HPWAM. The overall results from Figure 3 show that machining Ti-6Al-4V alloy with HPWAM had a significant effect on tool life. The improvements of up to 195% is recorded when the coolant pressure is increased to 20.3 MPa when compared to machining with conventional coolant supply. At the conventional coolant supply, the coolant may have failed to effectively penetrate the cutting zone, resulting in a lower tool life. This is a general observation as shown in Figure 3 where the best recorded tool life when machining with conventional coolant just reaches 18 min, 63% lower than for HPWAM under 110 m/min cutting speed.

The inability of this coolant to perform at the conventional coolant supply is reflected in its low pressure as well as its properties, as shown in Table 3. The oil phase of this coolant has a very high viscosity of 65 cSt, as compared to water (1 cSt). The high viscosity of the oil phase of this coolant may imply the presence of large structural components inside the coolant's molecular structure [9]. Coolants with a large molecular size normally have poor interfacial penetration and are relatively ineffective as cutting lubricants. On penetrating into the spaces at the cutting interfaces, the coolant with a large molecular size can become lodged under the tight contact of the sliding boundary between tool-chip contact, which is a distance away from the tool edge [10].

Additionally, the amount of coolant lodged will be wiped out by the moving chip, which creates further difficulties for the diffusion of the coolant into the cutting region [11]. These difficulties combine with the high surface tension of coolant, i.e. 41.51 mN/m, promotes lower wettability properties due to the high attractive forces between the coolant molecules [12]. These phenomena render this coolant inefficient to provide adequate cooling and lubrication, resulting in lower tool performance at a conventional coolant supply.

The tool life is increased to 29.7 min as the machining with high pressure coolant is applied with 11 MPa. This accounts for about 63% improvement relative to machining with the conventional coolant supply. The tool life performance is further increased to 54 min when the coolant pressure is increased to 20.3 MPa. This result shows that high velocity flow of coolant at a high pressure has a significant effect in providing the adequate cooling and lubrication at the tool-chip interface, this leading to a better machining performance.

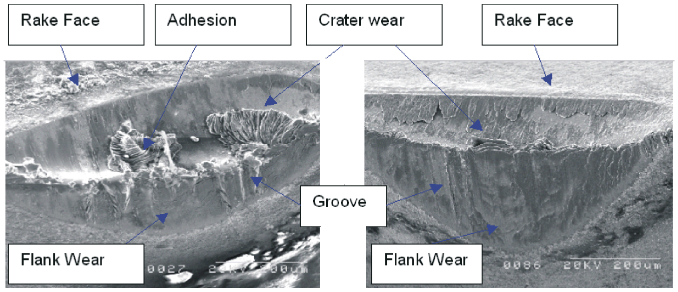

Fig. 4(a): Worn cutting tool after machining
Fig. 4(b): HPWAJ under a pressure of 11MPa

It is proven that there is a high resistance to flow without the coolant disintegration, if the coolant used has a high viscosity [13]. At the higher pressure of 11 MPa, the flow of coolant manages to give impact with sufficient momentum to create a larger gap with spaces for the coolant to penetrate further into the tool-chip and tool-workpiece interfaces. This enables closer contact of the coolant with the tool tip, which exposes the coolant to the higher cutting temperature. During penetration of the coolant into the tool-chip interface, the amount of fatty acid inside the coolant can be physically absorbed into the contact interface to form a relatively lower shear strength film [14]. This film, although extremely thin, is capable of reducing friction at the tool chip interface and preventing the re-welding of asperities on the back surface of the chip, thus reducing the wear rate of the cutting tool. This prevents friction in the areas affected by the lubricant film and minimises heat transfer to the cutting tool, thus prolonging tool life.

Wear Mechanism: Some samples of the tool wear when machining with conventional and HPWAM are shown in Figure 4. Almost all the worn surfaces showed similar characteristics with the failure modes being dominated by flank and crater wear. Flank wear occurs when the flank face of the cutting tool abrades against the workpiece material. Inside the flank wear region, an enlarged view of the flank face for the inserts shows that scratches, grooves and ridges appear across most of the observed area Figure 4(a). This suggests that abrasion by carbide grains was the dominant wear mechanism During machining, the greater cutting temperatures and stresses generated on the flank face caused the detachment of tungsten carbide particles from the bulk surface of the cutting tool. These particles subsequently flow between the tool's flank face and the newly-machined surface, causing microcutting or microploughing actions at the flank face surface. As the machining is prolonged, the sliding action became more pronounced resulting to the wider development of flank wear until it is displaced towards the nose region. During this stage, higher temperature and friction developed in a small area resulting in more abrasion occurring in a concentrated region. This resulted in tremendous wear at the nose region, accelerating beyond the 0.3mm rejection criterion within a short time [15].

The crater wear appears on the rake face of the tool as shown in Figure 4(a) and Figure 4(b). Crater wear is characterized by a wide crater formation at the rake face of a carbide tool where contact with the tool-chip interface takes place. An observation of these crater areas shows a thin layer of molten metal attached to the crater face of the cutting tool. The formation of this thin layer is attributed to the molten film of Ti-6Al-4V alloy that adherences to the rake face of the cutting tool results in adhesive wear occurring in some locations. Adhesion wear is attributed to the detachment of particles from the cutting tool as a result of the adhesive force from the sliding chip. During machining, individual grains of carbide structure are detached from the tool surfaces and carried away from the tool-chip interface by the sliding chip. As the machining continues, the high temperatures generated provide more substitutional grain detachment between at the tool-chip interface, which further weaken the areas of the cutting tool exposed to the high temperatures. With tribological sliding between the cutting tool and the chip, severe seizure takes place causing loss of the material at the tool’s rake face and increase in the depth of the crater wear [15].

Surface Profile: Figure 5 shows the variation of the surface roughness for various cutting conditions when machining with all the coolants being investigated. It shows that the average surface roughness based on the centre line average varies marginally between 0.7 µm and 0.8 µm, well within the rejection criterion of 1.6 µm.

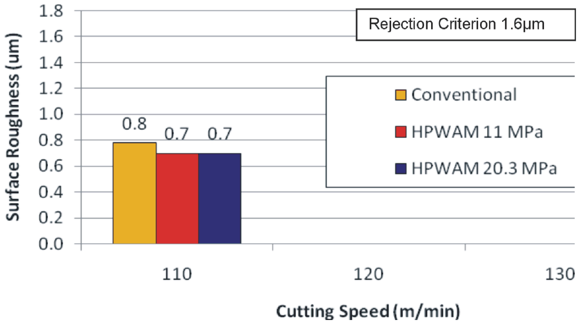

Fig. 5: Surface roughness variation recorded when machining Ti-6Al-4V alloy with all cutting conditions

Results from Figure 5 also indicate that machining with all cutting conditions considered had a negligible difference on the surface finish generated. Therefore, it can be established that the surface finish generated with both machining with conventional and HPWAM is not adversely affected by the cutting conditions investigated.

The relatively low surface roughness can be attributed to the fact that the introduction of coolant may cool the tool surfaces to prevent or reduce adhesion wear therefore maintaining the nose radius of the cutting tool for a longer period. The sharp edges of the cutting tool will act as the stress concentrators that enables the surface to be machined cleanly, thus resulting in the lower surface roughness values and better surface finish [16]. Such a low surface roughness reflects the ability of HPWAM to secure better dimensional accuracy whilst improving the fatigue strength of the machined component.

The surfaces generated after machining under conventional coolant supply are shown illustrated in Figure 6. It shows that the surfaces generated under all the investigated conditions were not adversely affected and were free from damage such as cracking, tearing and rupture. There is also no evidence of serious surface smears and chatter marks after machining the Ti-6A-4V alloy with various coolant grades. This evidence is reflected from the results for the surface roughness where low surface roughness is recorded for most of the cutting conditions.

For coolant in conventional coolant supply, the phenomenon of slight material side flow is evidenced as shown in Figure 6(a). Due to the inability of conventional coolant supply to reach the contact region, higher cutting temperatures are generated at the tool-chip interface which enhance thermal softening and improve the local ductility of the machined surface. When the cutting tool shears the metal, the relative motion between the tool and workpiece generates surface tearing leaving displaced marks in the direction opposite of the feed mark trails [17]. This severe surface damage would change the surface profile and average surface roughness values leading to the deterioration of the machined surface quality. This process is also reported to be accelerated by the development of nose wear in the tool edge [17].

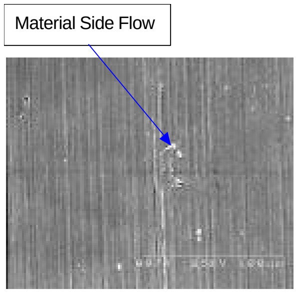

Fig. 6(a): Surfaces generated after machining under conventional coolant supply

Fig. 6(b): Surfaces generated after machining under HPWAM

Chip Formations: During machining with both conventional and high pressure coolant supply, two different forms of chip were produced: a long, tubular, chip-shape when machining under conventional coolant flow as shown in Figure 7(a) and a small, segmented, C-shaped chip when machining with 11 MPa and 20.3 MPa coolant pressures as illustrated in Figure 7(b) and Figure 7(c). The formation of continuous chips is attributed to the inability of the applied coolant to effectively break the chips [3]. Continuous and snarled chips are undesirable because they usually wrap themselves around the workpiece or get tangled around the tool holder, restricting coolant access to the cutting zone. This hinders the coolant's ability to provide better cooling and lubrication at the contact interfaces resulting in a temperature rise and leads to poor tool performance. Improved chip breakability was observed when HPWAM is applied. This can be attributed to the effect that the

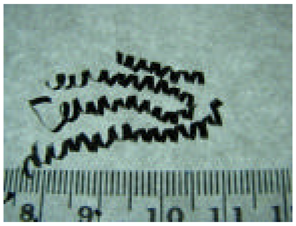

Fig. 7 (a): Chips generated under conventional coolant supply

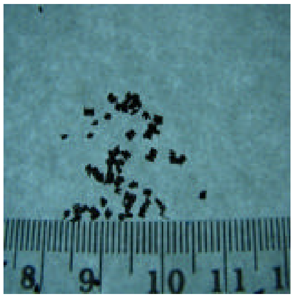

Fig. 7(b): Chips generated under HPWAM at 11 Mpa

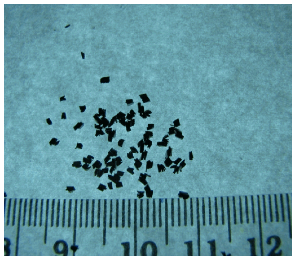

Fig. 7(c): Chips generated under HPWAM at 20.3 MPa

high-momentum jet of pressurised coolant exerts on the deformed chip [3]. In HPWAM, the stable flow of coolant tends to lift the chip up after passing through the deformation zone. Coolant volume fills the gap between the chip and the tool rake face, allowing the coolant to penetrate a smaller area of the chip. At a given supply power, a high-pressure coolant stream bends the chips upwards causing the breakage of the chips into smaller segments.

CONCLUSION

This study concludes that machining Ti-6Al-4V Titanium alloy under HPWAM gave better cutting performance of up to 195% improvement over machining with conventional coolant supply. The predominant wear mechanisms when machining under the cutting conditions are abrasive and adhesive wear. Surface roughness values recorded when machining Ti-6Al-4V alloy under the cutting conditions are generally below the 1.6 ìm rejection criterion. The HPWAM significantly reduces the chip size, resulting in a reduction in the tool-chip contact and improvement in lubrication at the contact interfaces. This paper provides the understanding and correct use of HPWAM especially when machining Ti-6Al-4V alloy. It can be suggested that the future work for this study should be focused more into the machining trials of HPWAM using different types of coolants.

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