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MACHINABILITY IMPROVEMENT IN END MILLING TITANIUM ALLOY TI-6AL-4V

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ABSTRACT

This paper presents the results of an investigation of machinability improvement in end-milling of Titanium Alloy Ti-6Al-4V through workpiece preheating. End milling tests were conducted on the Vertical Machining Centre with full immersion cutting. Titanium alloy Ti-6Al-4V bar was used as the workpiece. Machining was performed with a 20 mm diameter end-mill tool holder fitted with one uncoated WC-Co carbide insers. Induction coil heating was utilized during end milling under preheated conditions. Flank wear has been considered as the criterion for tool failure and the wear was measured using a Hisomet II Toolmaker's microscope. Tests were conducted until an insert was rejected when an average flank wear greater than 0.30 mm was recorded. Cutting force and torque measurements were conducted using the Kistler Rotating Cutting Force Dynamometer. Vibration during cutting was captured using an online vibration monitoring system. The results lead to the conclusion that workpiece preheating significantly increases the tool life of uncoated WC-Co carbide inserts in end-milling of Titanium Alloy Ti-6Al-4V.

1.0 Introduction

Titanium alloys are used widely in the aerospace, chemical and ship building industries because of their superior mechanical as well as heat resistant and corrosion resistant properties. Titanium alloys, however, are materials that are extremely difficult to machine. During the machining of titanium alloy, tool wear progresses rapidly because of the high cutting temperature and strong adhesion between the tool and the work material, owing to their low thermal conductivity and high chemical reactivity (Komanduri, 1982; Komanduri and Turkovich, 1982).

For these alloys, machining productivity is limited by tool wear which indirectly represents a significant portion of the machining costs as such they are known as difficult-to-cut materials. However, by properly selecting the tool material and cutting conditions an acceptable rate of tool wear may be achieved and thus lowering the total machining cost (Kishawya, Becze and McIntosh, 2004). The performance of a cutting tool is normally assessed in terms of its life. Wear criteria are usually used in assessing tool life. Mostly, flank wear is considered, since it largely affects the stability of the cutting wedge and consequently the dimensional tolerance of the machined work surface (Turnad *et al*., 2007).

The use of workpiece preheating (hot machining) as a technique for improving machining operations has been under consideration since the late 19th century. Metals tend to deform more easily when heated, thus enhancing machining. The principle behind hot machining is increasing difference in hardness of the cutting tool and workpiece, leading to a reduction in the component forces, improved surface finish and longer tool life (Krabacher and Merchant, 1951). Amin and Talantov (1986) studied the influence of the furnace method of preheating of workpiece on the machinability of titanium alloy BT6 (Russian Standard) and found that all the vertical cutting force component decreases with the increase in the preheating temperature but the radial and the axial components sharply increase to their peak values at a particular temperature. Ozler *et al* (2000) used gas flame heating to improve the machinability of austenitic manganese steel. They considered heating temperature as one the variables in line with other cutting parameters namely, cutting speed, feed and depth of cut while hot turning of austenitic manganese steel under a liquid petroleum gas flame. The effects of surface temperature and other cutting parameters on tool life were studied rigorously and an expression for tool life prediction using a factorial regression method was developed. Wang *et al* (2002) performed LAM using a YAG continuous solid laser on Al_2O_3 particle reinforced aluminum matrix composite (Al_2O_3p/Al). The result of their study showed that in the machining of an Al_2O_3p/Al composite the cutting force was reduced by 30-50%, tool wear was reduced by 20-30 % and the machined surface quality was improved in laser assisted machining as compared to conventional cutting. Tosun and Ozler (2002) studied hot machining in turning high manganese steels using a liquid petroleum gas flame under different cutting conditions of feed rate, depth of cut, cutting speed and surface temperature. A mathematical model for tool life was obtained from the experimental data using a regression analysis method. In addition, the tool life was estimated using artificial neural network (ANN) with back propagation (BP) algorithm.

The main objective of this study is to investigate the effect of workpiece preheating with high frequency induction heating on improvement of tool life of uncoated WC-Co inserts during the end milling of a titanium alloy Ti-6Al-4V. Tool wear, vibration and cutting force were investigated during the experiments.

2.0 Experimental Set-up and Procedure

The workpiece material used in all experiments was alpha-beta titanium alloy Ti-6Al-4V. The microstructure consisted of both coaxial and columnar alpha phase and inter-granular beta phase. The composition (in wt %) and its mechanical properties of the alloy are presented in Table 1 and Table 2 respectively.

Table 1: The Composition of Titanium Alloy Ti-6Al-4V

Chemical Composition (wt %)					
Al	V	$C_{(max)}$	$Fe_{(max)}$	$N_{2\,(max)}$	$O_{2\,(max)}$
5.5 – 6.76	3.5 – 4.5	0.08	0.25	0.05	0.2

Table 2: The Mechanical Properties of Titanium Alloy Ti-6Al-4V

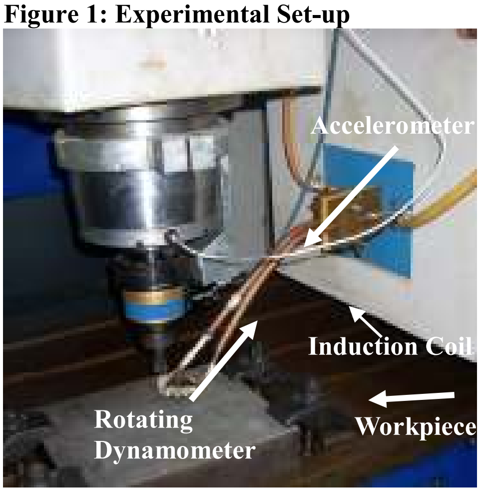
Ultimate Tensile Strength (MPa)	Elongation (%)	Elastic Modulus (GPa)	Hardness (HV0.5)
897	10	114	320

End milling tests were conducted on the Vertical Machining Centre (VMC ZPS, Model: MLR 542) with full immersion cutting. A titanium alloy Ti–6Al–4V bar was used as the work-piece. Machining was performed with a 20 mm diameter end-mill tool holder fitted with one insert. Sandvik uncoated tungsten carbide inserts were used in the experiments. All of the experiments were run under room temperature and preheated conditions. High frequency induction heating was utilized to run the preheated machining. Selected cutting conditions for the experimentation are presented in Table 3.

Table 3: Cutting Condition for Experimental Work

Cutting Parameters	Values
Cutting speed (m/min)	70
Feed (mm/tooth)	0.088
Axial depth of cut (mm)	1
Radial depth of cut (mm)	20 (full immersion)
Preheating temperature (^{0}C)	Room temperature, 315, 450, 650

Figure 1: Experimental Set-up



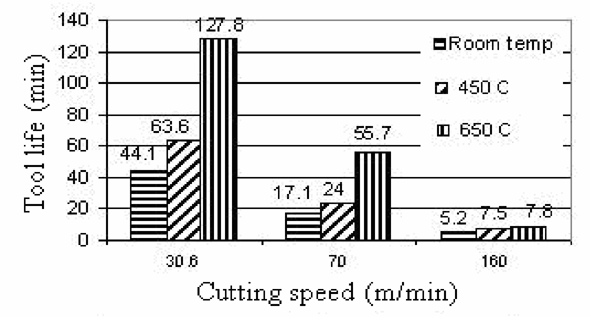
The experimental set up for the machining is presented in Figure 1. Flank wear has been considered as the criteria for tool failure and the wear was measured under a Hisomet II Toolmaker's microscope. Tool life experiments were stopped when an average flank wear achieved exceeded 0.3 mm.

3.0 Results and Discussions

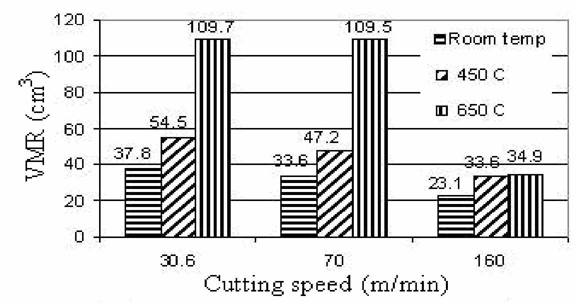
3.1 Tool life

The effects of cutting speed on tool life and metal removal are presented in Figure 2. Figure 2(a) clearly reflects that an increase in cutting speed considerably decreases the values of tool life in all cutting conditions (room temperature and preheated conditions). It is related to the increase in mean shear-zone and the maximum tool face temperature with the increase in the cutting speed (Boothroyd and Knight, 1989). It is also attributed to higher wear rate when the temperature increases (Shaw, 1984). At the highest cutting speed of 160 m/min, the tool life is abruptly reduced under all the three conditions of preheating. Hence, it abruptly deteriorates the tool life. It is also affirmed that there are substantiated reductions of tool life when the cutting speed is increased from 30.6 to 160 m/min. In the range from 30 m/min to 70 m/min tool life decreased by 61.2% and by 56.4%, and in the range from 70 m/min to 160 m/min by 11.1% and 86 % for room temperature and preheated machining at 650 ^{0}C. Furthermore, Figure 2(a) also reflects that an increase in preheating temperature increases the tool life. For instance, at a cutting speed of 30 m/min, an increase in tool life was 2.9 times, and at cutting speed of 70 m/min an increase in tool life was found to be 3.26 times when cutting at 650 ^{0}C compared to cutting at room temperature conditions. It is due to the fact that the preheating leads to a reduction of the strength of the work material layer, which facilitates lower cutting forces with less work done. Preheating also leads to higher ductility of the work material which leads to higher chip-tool contact length, and lower stress acting on the tool. Softer workpiece reduces the stress acting on the tool, and it is responsible for reducing tool wear and increasing the tool life.

Figure 2(b) illustrates the effects of cutting speed and preheating temperature on the volume of metal removal (VMR). An increase in cutting speed eventually decreases the VMR. It is attributed to the fact that an increase in cutting speed decreases the tool life, as shown in Figure 2(a). These facts appeared in all cutting conditions. For instance, with preheating at 650 ^{0}C, a decrease of VMR from 109.7 cm^3 to 34.9 cm^3 (68.2% reduction) was noticed at the cutting speed range from 30.6 to 160 m/min.



(a). Tool life vs Cutting speed



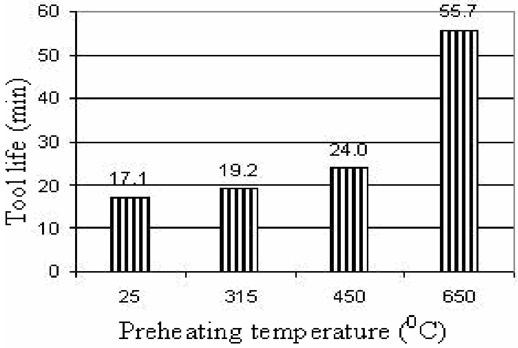
(b). VMR vs Cutting speed

Figure 2: Effects of Cutting Speed at Different Preheating Temperature On: (a). Tool Life, (b). VMR (Feed = 0.088 mm/tooth, axial DOC = 1 mm)

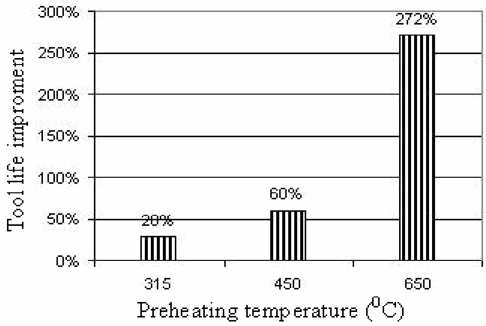
At the highest cutting speed of 160 m/min, the value of VMR for all the temperature conditions are relatively low compared to those at lower cutting speeds. It is attributable to the high heat generated at this cutting speed. An increase in cutting speed results in an increase in the temperature on the tool face, which leads to an increase in the rate of diffusion wear of the tool. Furthermore, under extremely rapid cutting speed, breakdown of the cutting tools easily occurs because of the plastic deformation of the tool at the cutting edge. Thus, it can be concluded that a cutting speed of 160 m/min falls to an extreme condition in cutting of Ti-6Al-4V alloy with uncoated WC-Co inserts. It is suggested from the Figure 2 that preheating does not appreciably give benefits in increasing tool life when machining is operated at a cutting speed of 160 m/min and above. For instance, preheating at 650 ^{0}C gives only 7.8 min in tool life with a cutting speed of 160 m/min, compared to that of 55.7 min with a cutting speed of 70 m/min. Moreover, preheating at a high cutting speed does not have appreciable influence on improving the VMR.

Figure 3 presents the effects of preheating temperature on tool life and tool life improvements at a constant cutting speed of 70 m/min. The results show that preheating was found to have substantial effects on improving tool life. However, up to a preheating temperature of 315 ^{0}C, there was practically no improvement in tool life. But, as the temperature was increased, a significant improvement was initiated due to sufficient heating which was occurred in the suppression of chatter/vibration and lowering the cutting force. In the experiments, there is evidence in increasing tool life up to 272 % with preheating at 650

^{0}C. The result certainly confirms that induction coil heating has been successfully proved as a method in enhancing the life of the cutting tools.



(a). Tool life vs Preheating Temperature



(b). Tool life improvement vs Preheating temperature

Figure 3: The Effects of Preheating Temperature on: (a). Tool Life, (b). Tool Life Improvement (V=70 m/min, axial DOC = 1 mm, Feed = 0.088 mm/tooth)

The feed is considerably sensitive in affecting the tool life. An increase in feed significantly decreases the tool life under both room temperature and preheated machining as shown in Figure 4. Reduction of tool life was 62.4 % as recorded when increasing feed value from 0.05 to 0.15 mm/tooth in room temperature machining, whereas a reduction of 83.5 % was detected in cutting with preheating at 450 ^{0}C. These reductions are related to the fact that an increase in feed increases the undeformed chip thickness, and then eventually increases the tangential cutting force. Furthermore, an increase in cutting forces increases the dynamic loads on the cutting edge which leads to lower tool life. The effect of preheating on tool life at the highest feed rate of 0.15 mm/tooth is least significant. It is related to the fact that high feed substantially increases the tool wear rate due to high impact loading and preheating is insufficient to reduce this effect.

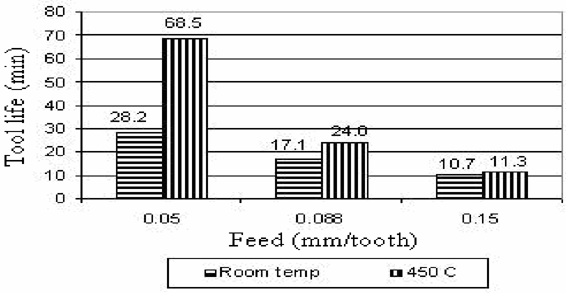
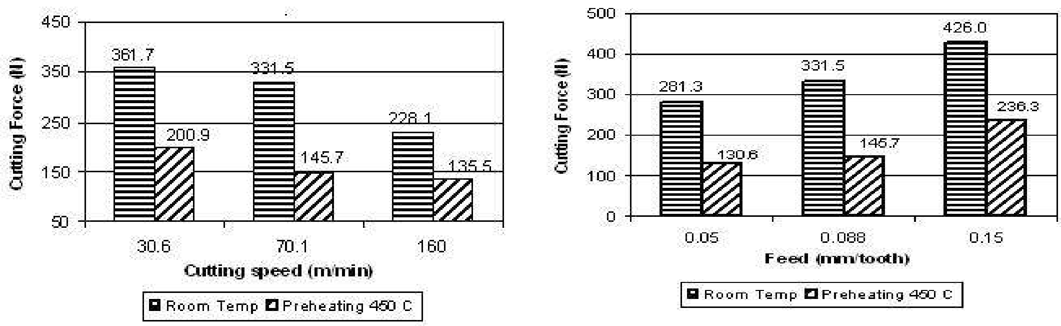


Figure 4: Effects of Feed on Tool Life (V=70 m/min, axial DOC = 1 mm)

3.2 Cutting Force

The effects of cutting speed on cutting force are comparably presented in Figure 5(a). The figure affirms that an increase in cutting speed substantially decreases the resultant cutting force, which occurred in both room temperature and preheated conditions. For instance, an increase in a cutting speed ranging from 30.6 to 160 m/min substantially reduces the resultant cutting force in 36.8 % and 32.5 % for room temperature and preheated machining, respectively. Cutting force are very sensitive to feed and drastically rises with the increase of feed as can be seen the curves in Figure 5(b). This general trend of the soaring of cutting forces as the feed increases is similar for both the room temperature and preheated end milling. It is noticeable from Figure 5 that there is an increase in cutting force in 51.4 % and 81.1 % when increasing feed ranging from 0.05 to 0.15 mm/tooth in room temperature and preheated machining, respectively. The figure also reflects that preheating substantially reduces the cutting force during cutting. This is attributable to the yield strength of the workpiece material dropped at the elevated temperature during the preheated end milling which eventually reduces the shear stress and thus contributes to lessen the cutting forces. Preheated machining also apparently helps to ease the chip flow, which reduces frictional forces in the rake and flank faces of the tool. Figure 6 illustrates the effect of preheating temperature on cutting force. It is undoubtedly accomplished that an increase in preheating temperature substantially decreases the resultant cutting force.



(a). Cutting Force vs Cutting speed *(b). Cutting Force vs Feed*

Figure 5: Effects of Cutting Speed and Feed on Cutting Force

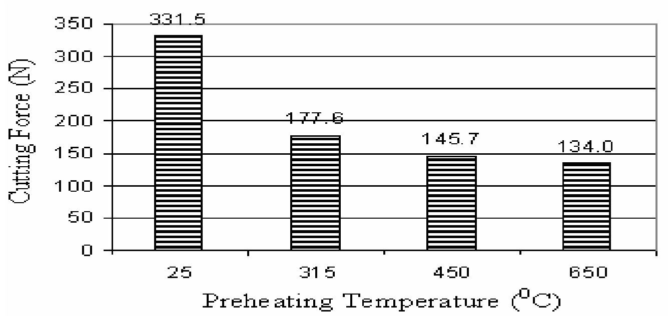
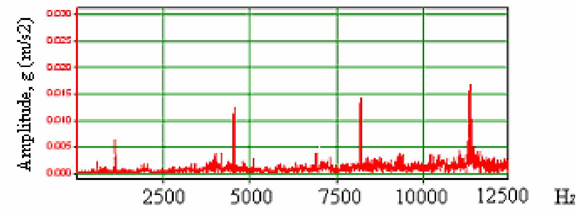


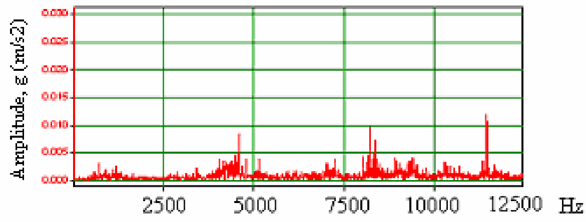
Figure 6: Effect of Preheating on Cutting Force (V=70 m./min, d= 1 mm, Feed = 0.088 mm/tooth)

3.3 Vibration/Chatter

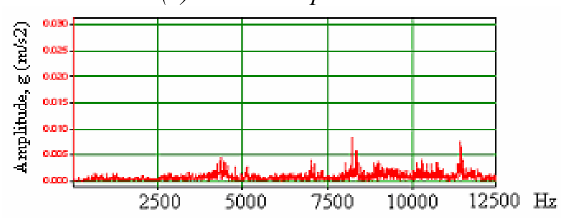
Preheated machining has a very great effect on end milling in terms of vibration and chatter as can be seen from the FFT diagram of acceleration amplitudes vs. frequency in Figure 7. It may be observed from the figure that there are four main peaks of amplitude in the range of 0 – 12,500 Hz. These peaks are eventually used to observe the effects of preheating on amplitude.



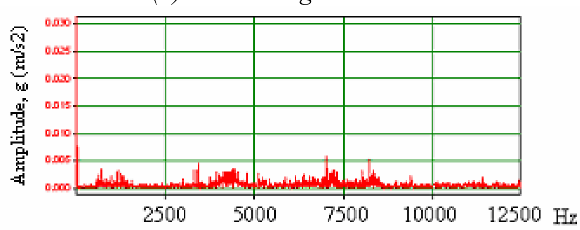
(a). Room temperature



(b). Preheating at 315 ^{0}C



(c). Preheating at 450 ^{0}C



(d). Preheating at 650 ^{0}C

Figure 7: FFT Output of End Milling (Cutting speed: 70 m/min, axial depth of cut: 1 mm, feed: 0.088 mm/tooth)

Table 4: Acceleration Amplitudes of Vibration and the Percent Reduction

Frequency Range (Hz)	Maximum acceleration amplitude (m/s^2)						
	RT	315 ^{0}C	Reduction (%)	450 ^{0}C	Reduction (%)	650 ^{0}C	Reduction (%)
0 – 2,500	0.006	0.003	50	0.002	66.7	0.001	83.3
2,500 – 5,000	0.012	0.009	25	0.005	58.3	0.003	75
7500 – 10,000	0.014	0.010	28.6	0.008	42.9	0.005	64.3
10,000 – 12,500	0.017	0.012	29.4	0.007	58.8	0.002	88.2

The maximum acceleration amplitude for room temperature and preheated machining along with the percentage of reductions are presented in Table 4. Compared to room temperature amplitude, decreased acceleration of amplitude ranging from 25 to 50 %, 42.9 to 66.7 %, and from 64.3 to 88.2 % are appreciably attained when employing preheated machining at 315, 450 and 650 ^{0}C, respectively.

It is suggested that preheated machining can be employed successfully to reduce the vibration/chatter in machining. Reducing chatter during cutting essentially reduces the bouncing effect on the tool tips, and accordingly reduces the tool wear rates. Figure 8 shows the effects on preheating temperature on the reduction of acceleration amplitude during preheated machining. It may be observed that preheating considerably reduces the maximum acceleration amplitude during cutting. As the preheating temperature is increased, the maximum acceleration of vibration substantially decreases. It is suggested that the induction method is useful in reducing the vibration in end milling of titanium alloy.

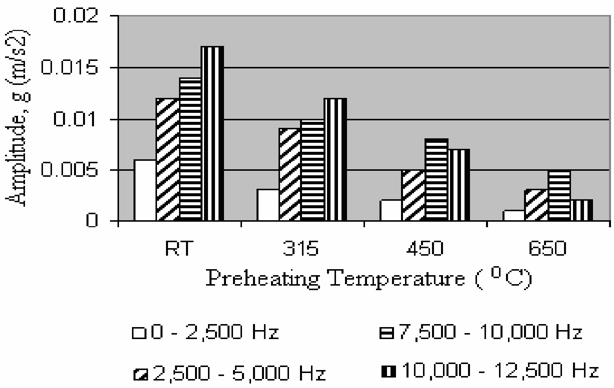


Figure 8: Effect of Preheating Temperature on Acceleration Amplitude of Vibration (inserts: uncoated WC-Co)

4.0 Conclusion

The following specific conclusions have been drawn on the work:

1. High frequency induction heating has been proven to be a successful preheating method in the improvement of the machinability of titanium alloy Ti-6Al-4V.
2. Preheating helps in substantially increasing tool life during end milling of titanium alloy Ti-6Al-4V using uncoated WC-Co inserts. A range of cutting speed from 30 m/min to 70 m/min tool life decreased by 61.2% and by 56.4%, and in the range from 70 m/min to 160 m/min by 11.1% and 86 % for room temperature and preheated machining at 650 ^{0}C.
3. Preheating appreciably lowers the cutting force. An increase in cutting speed ranging from 30.6 to 160 m/min substantially reduces the resultant cutting force in 36.8 % and 32.5 % for room temperature and preheated machining respectively.
4. Preheated machining is beneficial in reducing vibration/chatter in machining which leads to a reduction of tool wear rates, hence increases the tool life.

5.0 Acknowledgement

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