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EFFECT OF CUTTING TOOLS AND WORKING CONDITIONS ON THE MACHINABILITY OF TI-6AL-4V USING VEGETABLE OIL-BASED CUTTING FLUIDS

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ABSTRACT

The cutting of titanium alloys is usually associated with low productivity, poor surface quality, short tool life and high machining costs. This is due to the excessive generation of heat in the cutting zone and difficulties in heat dissipation due to the relatively low heat conductivity of this metal. Cooling applications in machining processes are crucial, since many operations cannot be performed efficiently without cooling. Improving machinability, increasing productivity, and enhancing surface integrity and part accuracy are the main advantages of the use of cutting fluids (CFs). Conventional cutting fluids such as mineral oil-based, synthetic and semi-synthetic fluids are the most common types used in the machining industry. Although these cutting fluids can be beneficial, they pose a great threat to human health and to ecosystems. Vegetable oils (VOs) are being investigated as a potential source of environmentally favourable lubricants, due to a combination of biodegradability, good lubrication properties, low toxicity, high flash points, low volatility, high viscosity indices and thermal stability. The fatty acids of vegetable oils are known to provide thick, strong, and durable lubricant films. These strong lubricating films give the vegetable oil base stock a greater capability to absorb pressure and a high load carrying capacity. This paper details the main experimental results from an investigation of the impact of various vegetable oil-based cutting fluids, cutting tool materials and working conditions when turning Ti-6Al-4V. A full factorial experimental design was employed involving 24 trials to evaluate the influence of process variables on average surface roughness (Ra), tool wear and chip formation. In general, values of Ra varied between 0.5 µm and 1.56 µm and the Vasco1000 cutting fluid exhibited a level of performance comparable to other fluids in terms of surface roughness, while the uncoated coarse grain WC carbide tool achieved lower flank wear at all cutting speeds. On the other hand, all tools tips were subject to uniform flank wear during the cutting trials. Additionally, formed chip thickness (tc) ranged between 0.1 mm and 0.14 mm with a noticeable decrease in chip size when higher cutting speeds were used.

INTRODUCTION

The heat generated during a cutting operation is a summation of the plastic deformation involved in chip formation, the friction between tool and workpiece and that between the tool and chip. Plenty of this heat remains in the chip, but a portion is conducted into the tool and the workpiece. The high cutting temperature in machining always results in aggressive adhesion wear at the tool tip surface and the surface quality of machined components may deteriorate. In the absence of a cutting fluid, (CF) less heat is carried away from the cutting zone, resulting in an increase in tool and workpiece temperature. Thus a cutting fluid is used to cool and lubricate the cutting process, thereby reducing tool wear and enhancing tool [1]. Currently, several types of conventional cutting fluids are used such as synthetic, semi-synthetic and mineral/petroleum oil-based fluids. However, conventional fluids are involved in the ecological cycle with air, soil and water and their toxicity may damage the ecosystem. Particularly when CFs evaporate and are distributed as vapour and micro-particles, they may also cause serious problems in human health [2]. To cope with these problems, the necessity of using biodegradable fluids has recently been emphasized [3, 4].

The growing demand for biodegradable products has opened up an opportunity for cutting fluids based on vegetable oil (VO) as an alternative to conventional CF counterparts [5]. Lubricity is a major advantage of vegetable oil-based cutting fluids due to the minor polar charge on the VO which draws its molecules to a metallic surface and makes it tenacious enough to resist being wiped off [6]. Consequently, frictional energy is reduced and thus heat generation is minimised. VOs have a higher flash point (224˚C) than mineral oil-based fluids (130˚C) which reduces smoke formation and fire hazards. A higher flash point , allows such cutting fluids to be used in high-temperature conditions [7, 8]. Vegetable oils base stocks have a high natural viscosity (86 cP at 25˚C) as the cutting temperature increases. The viscosity of vegetable oils also drops more slowly than mineral oils. As the temperature falls, VOs remain more fluid than mineral oils, facilitating quicker drainage from chips and workpieces. The higher viscosity index of VOs ensures that they will provide more stable lubricity across the operating temperature range [9-11]. Vegetable oil-based CFs are also a superior coolant due to their high heat conductivity of 0.17 W/m·K [12] compared to 0.125 W/m·K for mineral oils [13] , which is essential for removing heat from cutting zones. The biodegradability of VO -based cutting fluids is one of their major advantages over conventional CFs with high degradation rates, especially in anaerobic conditions. A biodegradation test was carried out in the dark at 20–25°C for 28 days and it was found that vegetable oil-based, synthetic ester and rapeseed oil had 100 % biodegradability, whereas conventional cutting oil had only 20–30% biodegradability [5, 14]. Additionally, cutting titanium alloys can be difficult owing to their low thermal conductivities (e.g. 6.7 W/m·K for Ti-6Al-4V), relatively low Young's modulus compared with steel alloys and high chemical reactivity at elevated temperatures. Low thermal conductivity impedes the dissipation of the heat generated during the cutting process, which can be harmful to the cutting tool and workpiece. Due to their relatively low Young's modulus (110 GPa) [15] , titanium alloys are less resistant to stress and, therefore, they may not retain the original shape post-machining as a result of the high forces used. Furthermore, without a coolant, titanium alloys are more susceptible to reacting with atmospheric gases, which can also adversely affect their mechanical properties.

Bermingham et al. [16] evaluated five different cutting strategies, including dry, flood (mineral oil-based), minimum quantity lubricant (MQL) VOs, laser-assisted milling (LAM), and MQL/LAM when milling Ti-6Al-4V at a cutting speed of 69 m/min. A higher tool life of 28 minutes was obtained when MQL/LAM and MQL were used compared to flood (9 min), dry (4 min) and LAM (5 min). In addition, MQL VOs produced lower average tool wear (40 µm) relative to MQL/LAM (50 µm), while others achieved tool wear levels above the limit of 200 µm. The performance of palm oil (MQL) and synthetic ester cutting fluids has also been examined when drilling Ti-6Al-4V at a cutting speed of 100m/min with a 0.1 mm/rev feed rate [17]. The results showed that the use of palm oil (MQL) resulted in a lower cutting force of 1954 N compared with 2318 N for a synthetic ester with no impact on tool life (314 seconds for both CFs). This was attributed to the formation of a thin boundary lubrication film which led to a reduction in friction in the tool–workpiece interface. Surface roughness was also evaluated when turning Ti-6Al-4V using different cutting fluid application methods, including dry, palm oil VOs and a mixture of palm oil with boric acid [18]. A reduction in average surface roughness was obtained when the palm oil was used compared with dry cutting (values of Ra were 3.56µm and 3.84µm respectively). The lowest surface roughness results were obtained using a chemical vapour deposition (CVD) coated tool at a cutting speed of 79 m/min with a 0.206 mm/rev feed rate and a depth of cut of 1mm. Additionally, the use of vegetable oil MQL when turning Ti-6Al-4V has been investigated to evaluate tool life and wear rate [19] . Experiments were performed at 120 m/min, 0.1 mm/rev and 1.2 mm cutting speed, feed rate and depth of cut respectively. The flank wear rate was observed to be at a minimum in the case of the vegetable oil MQL (Vb = 0.01 mm/min) with a corresponding increase in tool life compared with 0.04mm/min for dry cutting. Surface hardness and average surface roughness have also been measured on Ti-6Al-4V specimens cut using palm oil MQL, dry and flood cutting [20]. Minimum Ra values were obtained when palm oil was used, with a corresponding surface hardness of 332 HV, while dry cutting produced an Ra value of 3.25 µm. Three cooling modes, including MQL (VOs), flood, and dry cooling have also been investigated during the turning of Ti-6Al-4V at different cutting speeds (90, 120, and 150 m/min) utilizing PVD coated cermet tool [21]. Lower surface roughness of 1.90 µm was achieved when turning using VOs (MQL), whereas values of 2.12 µm, 2.08 µm respectively were obtained when using dry and flood cooling modes. Also, MQL outperformed the other methods in terms of flank tool wear at a cutting speed of 150 m/min. In addition, it was observed that VOs decreased average cutting temperature by 26.6%, 17.9% and 17.5% compared to the dry condition at cutting speeds of 90, 120 and 150 m/min respectively. It can be concluded that the use of VO cutting fluids is at an early stage in the metal cutting industry. Additionally, although there are several research programmes are investigating the use of vegetable oils in the machining of titanium alloys, only a few studies have considered the effect of different cutting tool materials and coatings on the quality of the machined surface.

Therefore, this work aims to investigate the effect of various cutting tool materials and coatings and four different vegetable oil-based cutting fluids on surface finish and tool wear when turning Ti-6Al-4V alloy.

EXPERIMENTAL METHODS

All turning trials were carried out on a Graziano Tortona Centre lathe. The Ti-6Al-4V Grade 5 workpiece samples were 28 mm in diameter and 330 mm long and were mounted between the spindle chuck and the tailstock. Workpiece materials were supplied by Titanium Metal UK Limited, West Bromwich, UK. The tests involved differences in cutting fluids, cutting tools and cutting speeds as shown in Table 1 whereas a feed rate of 0.1 mm/rev and depth of cut of 0.75 mm were kept constant. Three different indexable tool inserts were supplied by Sandvik, UK with: 1. constant nose radius (r_ε=0.8 mm); 2. insert included angle (X_n=80˚); and 3. clearance angle ($\alpha = 0$˚). Table 2 shows main properties details of the cutting tools used throughout this work. Additionally, four soluble VO-based cutting fluids were investigated. The selection of vegetable oil-based cutting fluids was based on their different properties and characteristics. Vasco 1000 is described by the manufacturer as delivering the highest possible tool life and surface finish on titanium. HOCUT 3450 is described as having high lubricity performance and anti-wear properties designed to give superior surface finish and to extend tool life. SOLUTEC is said to have a good inhibition against corrosion for a wide range of metals giving protection to both workpiece and machined parts.

All of the vegetable oil-based cutting fluids are said to have favourable environmental impact characteristics, and the properties of all tested fluids are depicted in Table 3. Each test involved a cutting length of 100 mm and a new tool insert was used. Flood cooling mode was selected to supply cutting fluids to the cutting zone through a single flexible hose at a constant flow rate of 0.9 l/min. The cutting fluids supplied to the machining zone had a 5% concentration of vegetable oil when mixed with water, as recommended by the suppliers. The concentration was regularly monitored using a refractometer. The average surface roughness (Ra) of Ti-6Al-4V bars was measured using an Alicona Infinite Focus G4 optical scanner, which has a resolution down to 200 µm employing 10 magnification factors. The scanning area was 5 mm x 1 mm in the axial and circumferential directions respectively. Scans were obtained using 599 nm and 5.40 µm vertical (Z direction) and lateral (X and Y) resolutions respectively. Selected illumination parameters including values of the exposure time and contrast of 166 µs and 0.7 respectively.

All measurements confirmed to ISO 4287 and ISO 4288 using 0.8 mm cut off and 1 mm evaluation length. Three readings of Ra (at the top, middle and bottom) were recorded at each side of the bars and the average was then computed as shown in Figure 1. Chip thickness was also measured using a digital micrometer. 3D surface topography and tool flank wear were also assessed using the Alicona Infinite Focus G4 optical scanner.

TABLE 1. PROCESS VARIABLES AND LEVELS

Factor	Level 1	Level 2	Level 3	Level 4
Cutting fluid	Vasco1000	Hocut 3450	NE250H	SOLUTEC
Cutting tool	Coated carbide (PVD) GC1105	Coated carbide (CVD) S05F	Uncoated carbide H13A	
Cutting speed (m/min)	120	175		

TABLE 2. PROPERTIES OF THE CUTTING TOOLS

Cutting tool	Density (g/cm^3)	TRS (N/mm^2)	Average grain size (µm)	Hardness (HRA)
Uncoated	15000	2690	3	93
PVD	14750	2550	>3.5	92.8
CVD	14950	2350	>3.5	92.5

TABLE 3. PROPERTIES OF THE CUTTING FLUIDS

Fluid (Pure oil)	Density (at 20°C)	Viscosity (at 40° C)	Flash point
Vasco1000	0.95 g/cm^3	56 mm^2/s	180° C
Hocut 3450	0.94 g/cm^3	55 mm^2/s	176° C
NE250H	0.97 g/cm^3	38 mm^2/s	200° C
SOLUTEC	0.98 g/cm^3	30 mm^2/s	195° C

RESULTS AND DISCUSSION

1. Surface Roughness

Figure 1 presents values of Ra versus cutting tools at cutting speeds of 120 and 175 m/min. The average surface roughness for all cutting tools was below the threshold for critical applications (e.g. Ra 1.6 for machined aerospace parts). The uncoated coarse grain WC carbide tool (H13A) produced the overall lowest average values of Ra of 0.55µm and 0.51µm at 120 and 175 m/min respectively. This is due to its superior combination of high hot hardness and toughness properties. The CVD coated carbide tool (S05F) demonstrated the poorest performance in relation to surface roughness (values of Ra of 0.62 µm and 0.60 µm respectively), whereas TiAlNi PVD coated carbide tool outperformed the CVD tool, achieving overall average values of Ra of 0.61 µm and 0.55 µm at cutting speeds of 120 m/min and 175 m/min respectively. This could attributed to its peculiar mechanical properties, including thermal stability, a low friction coefficient of 0.5 and high hardness of 2300 HV [22].

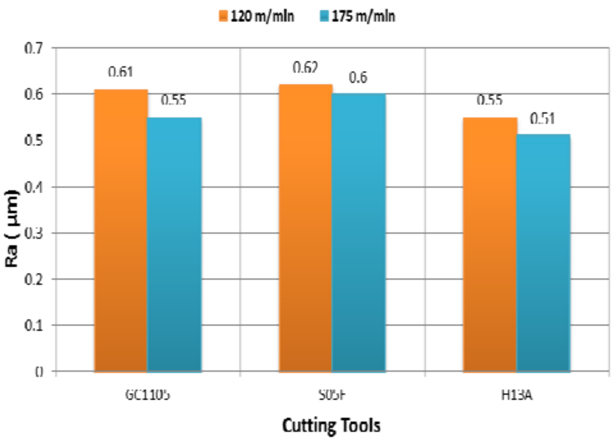


FIGURE 1. Ra RESULTS VERSUS CUTTING TOOLS AT CUTTING SPEEDS OF 120 AND 175 m/min

Figure 2 shows the performance of the cutting tools in terms of average surface roughness. It is seen that the values of Ra of the machined bars decreases with increased cutting speed. This is due to the fact that high spindle speed is associated with a higher cutting temperature; increasing the softening of the workpiece material and then reducing the cutting forces and hence leading to a better surface finish. These findings are consistent with the most of a recent report [23] for the turning of Ti-6Al-4V. Overall, all tested tools showed similar trends in a reduction of Ra values at higher cutting speeds. However, the results exhibited a sharp drop in Ra values at higher speed by 6 % when using physical vapour deposition (PVD) coated tools, whereas coarse grain WC uncoated carbide and CVD coated tools show a gradual decline by 4% and 2% respectively. This could be attributed to the discernible differences in their mechanical and physical properties. Some feed marks were also observed, which might be due to the plastic flow of the material during the cutting process which is known to result in higher surface roughness.

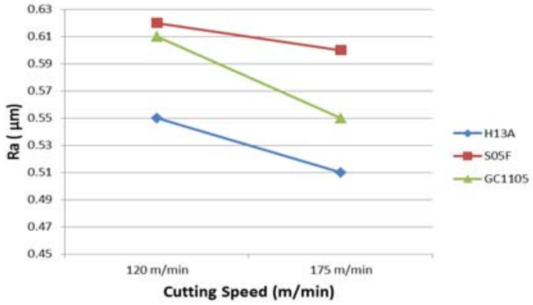


FIGURE 2. Ra PERFORMANCE OF VARIOUS CUTTING TOOLS AT CUTTING SPEEDS OF 120 AND 175 m/min

Figure 3 illustrates the effect of cutting fluids on the average surface roughness at cutting speeds of 120 and 175 m/min. Lower Ra values were obtained at all working conditions using Vasco1000. This shows that Vasco1000, which has a VO content of 45% possesses better cooling and lubricating properties which impart an excellent surface finish compared to the other fluids. On the other hand, NE250H and SOLUTEC demonstrate higher Ra values at the higher cutting speed of 175 m/min, while NE250H only displays inferior performance in terms of surface roughness at the lower cutting speed of 120 m/min. In addition, only a marginal variation of Ra values (0.03 µm) was recorded between Hocut 3450 and Vasco1000, probably because of the similarity in their physical and chemical characteristics

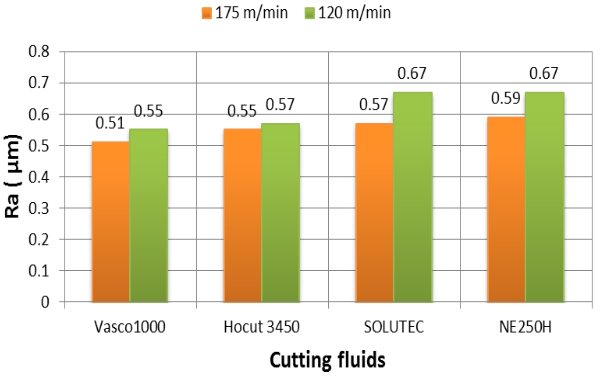


FIGURE 3. Ra RESULTS OF VARIOUS CUTTING FLUIDS AT CUTTING SPEEDS OF 120 AND 175 m/min

Figure 4 presents the overall Ra performance of all tested fluids at the cutting speed of 120 and 175 m/min. In general, all cutting showed similar trends in the reduction of Ra values from lower to higher cutting speeds. However, there were sharp falls in Ra values at the higher cutting speed when SOLUTEC and NE250H cutting fluids were employed, whereas a gradual drop in Ra values was recorded when using Vasco1000 and Hocu3450. It was observed that the disparity between the poor results using NE250H and the good results obtained with

Vasco1000 in terms of surface roughness can be explained in terms of the relative inefficiency of the former coolant due to its low content of VO base stock in the fluid and difficulties in heat dissipation at higher cutting speed conditions.

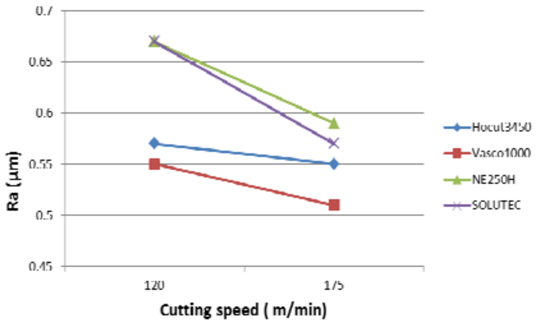


FIGURE 4. Ra PERFORMANCE OF VARIOUS CUTTING FLUIDS AT CUTTING SPEEDS OF 120 AND 175 m/min

2. Tool Wear

Figure 5 shows the performance of all tested cutting tools in terms of flank wear at cutting speeds of 120 and 175 m/min. It is clear that, as cutting speed increased, flank wear also increased correspondingly. This is mainly due to the heat generated at the cutting zone, confirming that cutting speed has the largest influence on tool wear. A typical rise in flank wear with increasing cutting speed can be seen on all tested tools. Additionally, it was observed that all tools tips were subject to uniform flank wear. In general, the coarse uncoated WC carbide tool (H13A) produced lower flank wear (50.34 and 97.18 µm respectively) compared to other tools while CVD coated tool exhibited highest flank wear values (118.19 and 141.83 µm) at cutting speed of 120 and 175 m/in respectively. In addition, PVD TiAlNi carbide tool outperformed the CVD tool in terms of flank wear under all cutting conditions. It was observed that adhesion is the dominant wear mechanism of the CVD coated tool at the higher cutting speed when SOLUTEC and NE250H cutting fluids were used.

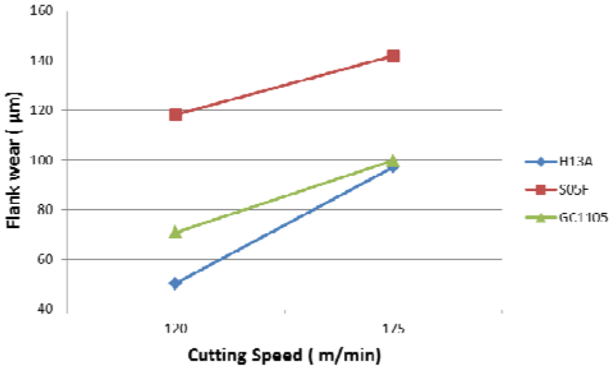


FIGURE 5. FLANK WEAR PERFORMANCE OF VARIOUS CUTTING TOOLS AT CUTTING SPEEDS OF 120 AND 175 m/min

Figure 6 represents the flank wear performance of all tested fluids at cutting speeds of 120 and 175 m/min. It is clearly shown that flank wear rises when cutting speed is increased with all cutting fluids. Hocut3450 cutting fluid achieved lower flank wear of 50 µm and 100.80 µm at cutting speeds of 120 and 175 m/min respectively. The poorest results of 68.29 µm and 105 µm were obtained by the foamy cutting fluid (SOLUTEC). This is mainly due to its lower content of VO base stock which led to insufficient heat dissipation and consequently higher flank wear. Additionally, all fluids showed a typical rise in flank wear values from lower to higher cutting speeds. However, Hocut 3450 shows a sharp increase in flank wear of 50% with the increase in cutting speed. This could be attributed to its chemical and physical properties.

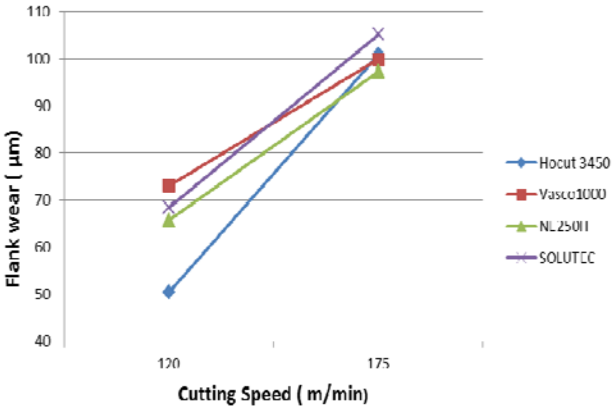


FIGURE 6. FLANK WEAR PERFORMANCE OF VARIOUS CUTTING FLUIDS AT CUTTING SPEEDS OF 120 m/min AND 175 m/min

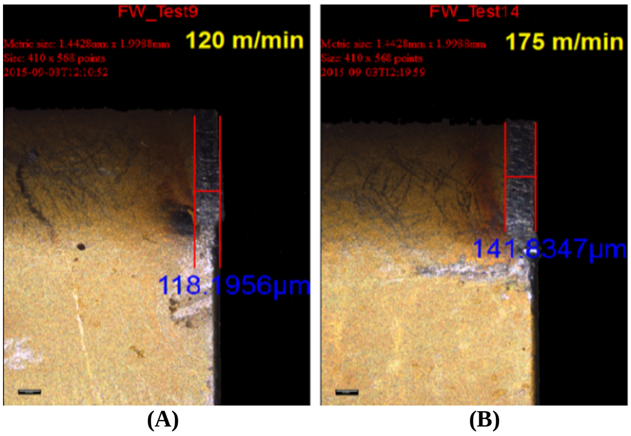
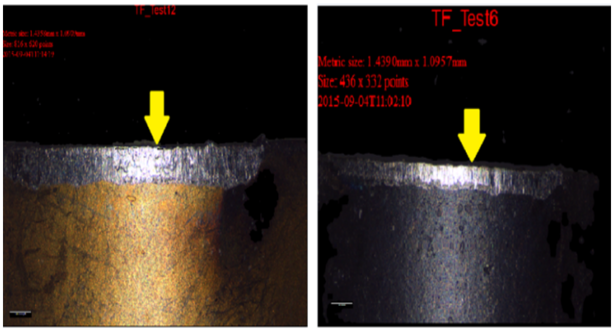
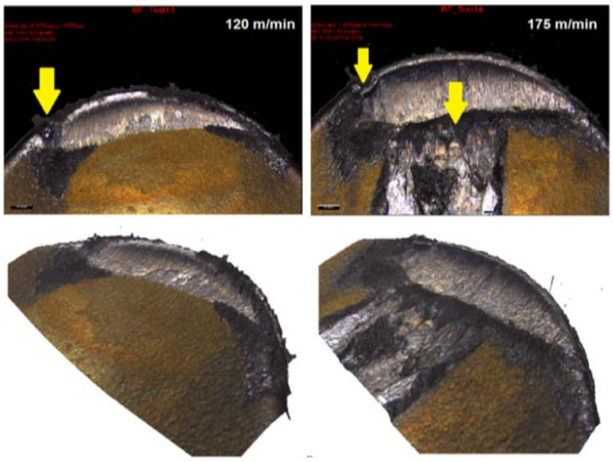


FIGURE 7. IMAGES OF FLANK WEAR ON CVD TOOL TIPS AT CUTTING SPEEDS OF (A) 120 m/min (B) 175 m/min



(A) (B)

FIGURE 8. IMAGES OF ABRASION MARKS ON TOOL TIPS AT CUTTING SPEED OF 175 m/min (A) CVD COATED TOOL (B) UNCOATED TOOL



(A) (B)

FIGURE 9. 2D AND 3D IMAGES OF ADHESION WEAR ON CVD TOOL TIPS AT CUTTING SPEEDS OF (A) 120 m/min (B) 175 m/min

3. Chip Formation

Figure 10 demonstrates chip thickness versus cutting fluids at cutting speeds of 120 and 175 m/min. In general, chip thickness (t_c) ranged between 0.1 mm and 0.14 mm, It can be seen that as cutting speed increased, chip thickness decreased. At low cutting speed, due to a large contact area on the rake face and small shear plane angle (Φ), thick chips are generated. The increase in cutting speed for a given feed rate increases the shear angle; very thin chips are then produced due to heat as well as by the reduction in material strength. It appears that there are no significant differences among the cutting fluids in terms of chip thickness, as the measured values are close to each other.

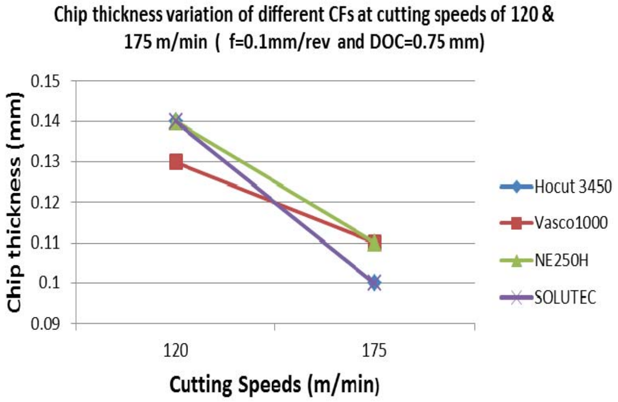


FIGURE 10. CHIPS THICKNESS VERSUS CUTTIING FLUIDS AT CUTTING SPEEDS OF 120 m/min AND 175 m/min

Figure 11 illustrates chip thickness ratio (R_c) versus cutting fluids at cutting speeds of 120 and 175 m/min. The chip thickness (R_c) ratio was calculated based on the orthogonal cutting model in turning operations (i.e. the ratio of un-deformed chip thickness t_0 to deformed chip thickness t_c, $R_c = t_0/t_c$). The un-deformed thickness was considered as equal to feed rate (0.1 mm/rev) and actual thickness was measured using a digital micrometer. In general, values of R_c varied between 0.7 and 1. It can be seen that a high value of chip thickness ratio leads to a higher degree of shear plane angle Φ, which in turn leads to low shear strain in the chip and reduced cutting power. When the cutting speed is increased, the region of plastic deformation becomes smaller. We observed that as the cutting speed increased, the chip thickness ratio also increased when turning Ti-6Al-4V.

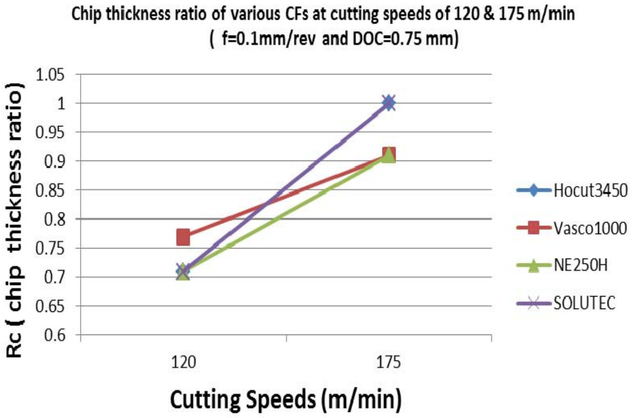
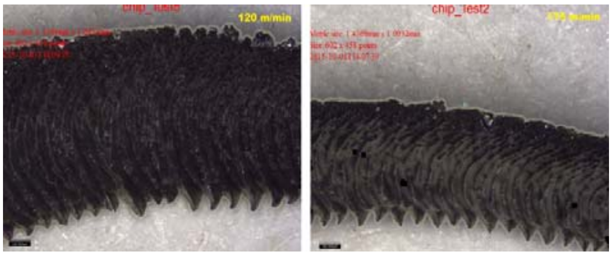


FIGURE 11. CHIP THICKNESS RATIO VERSUS CUTTING FLUIDS AT CUTTING SPEEDS OF 120 m/min AND 175 m/min



(A) (B)

FIGURE 12. IMAGES OF FORMED CHIPS OF Ti-6Al-4V AT CUTTING SPEEDS OF (A) 120 m/min (B) 175 m/min

CONCLUSION

Based on the results and discussion presented in this work, the following conclusions can be drawn:

1) A combination of VO cutting fluid (Vasco 1000) high cutting speed (175 m/min), low feed rate (0.1mm/rev), and low depth of cut (0.75mm) is helpful for achieving the minimal Ra (0.51 µm) during the turning of Ti-6Al-4V.
2) The uncoated carbide tool shows superior performance for a better surface finish.
3) Values of Ra decrease with increased cutting speed when turning Ti-6Al-4V, whereas flank wear increases with increased cutting speed.
4) Adhesion is a dominant wear mechanism of the CVD coated tool at the higher cutting speed of 175m/min.

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NOMENCLATURE

CFs	Cutting fluids
VO	Vegetable oil
Ra	Average surface roughness
CVD & PVD	Chemical & Physical Vapour Deposition
α	Cutting tool clearance angle
Xn	Insert included angle
$r\varepsilon$	Insert nose radius
t_0	Un deformed chip thickness
t_c	Deformed Chip thickness
R_c	Chip thickness ratio

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