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Procedia Engineering 132 (2015) 577 – 584

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Investigation of cutting tools and working conditions effects when cutting Ti-6Al-4V using vegetable oil-based cutting fluids

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Abstract

Power consumed in metal cutting is typically converted into heat near the cutting tool edge. Cutting fluids are then provided to a cutting zone in order to improve the tribological characteristics of machining processes and to dissipate the generated heat. The use of conventional cutting fluids however has lately been questioned due to the adverse impact on the environment and human health. Therefore, trends are directed to various alternatives such as vegetable oils (VOs). VOs offer a combination of good biodegradability and high lubricity, eco-friendly and compatibility with additives, low toxicity and volatility, high flash points and high viscosity indices. This paper details preliminary experimental results when turning Ti-6Al-4V. The impact of VO-based cutting fluids, cutting tool materials and working conditions were investigated. Two sets of experimental plans were designed comprising 25 and 27 tests with analysis of variance (ANOVA) employed to evaluate the effect of process variables on Ra and tool flank wear. In general, surface roughness Ra ranged between 0.56 µm and 1.81 µm and statistical analysis showed that the main contributing factor for Ra is feed rate having a high Percentage Contribution Ratio (PCR) of 94.4%. Noticeable increase in tool tip flank wear was recorded when higher cutting speeds were used.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: Turning; Cutting fluids (CFs); Vegetable oils; Working Conditions; Ti-6Al-4V.

1. Introduction

The generation of heat during a cutting process due to the incessant contact between cutting tools and workpiece is inevitable. Analytical evaluation of cutting temperature was presented by Trigger and Chao in 1950 [1]. They

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Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.535

computed the average tool-chip interface by considering the mechanism of heat generation during the metal cutting process. It was concluded that the tool-chip interface temperature is composed of plastic deformation associated with the chip formation at the shear zone in addition to friction between the chip and tool face along the contact region [1]. This stimulated the need for a cutting fluid (CF) to improve the dissipation of the generated heat, lubricate chip-tool interface and estrange chip from the cutting zone. The use of cutting fluids in a cutting process is anticipated to enhance tool life and produce a better quality product. However conventional cutting fluids have a negative health and environmental impact. For example, mineral-oil based cutting fluids are disposed inappropriately and generate pollutants such as carbon dioxide which enter the atmosphere thus contributing to global warming. They can damage the soil and water resources causing skin and respiratory problems. Therefore, a demand has been seen for alternatives such as biodegradable fluids [2].

The growing demand for biodegradable products has opened up an opportunity for vegetable oil based cutting fluids as an alternative to conventional CF counterparts [3]. Lubricity is a major advantage of vegetable oil based cutting fluids due to the minor polar charge on the VO which draws the vegetable oil's molecule to a metallic surface and makes it tenacious enough to resist being wiped off [4]. Consequently, frictional energy is reduced and thus heat generation is minimised. Triglycerides of vegetable oils are known to provide thick, strong and durable lubricant films. These strong lubricating films give vegetable oils a greater capability to absorb pressure and high load carrying capacity [5, 6]. Vegetable oil based CFs are also a superior coolant due to their high heat conductivity (0.17 W/m·K) [7], compared to 0.125 W/m·K for mineral oils [8], which is essential for removing heat from cutting zones. Biodegradability of VO based cutting fluid (susceptible to biochemical breakdown by the action of a microorganism) is one of the major advantages over conventional CFs with high degradation rate especially in an anaerobic condition [3, 9]. A biodegradation test was carried out in the dark at 20–25 °C for 28 days and found that a vegetable-oil based, synthetic ester and rapeseed oil had 100 % biodegradability, whereas an alternative type of cutting oil had 20–30 % biodegradability [3, 9]. 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, titanium alloys are less resistant to stress and therefore they may not retain original shape post machining as a result of high forces. Additionally, without a coolant, titanium alloys are more susceptible to reacting with atmosphere gases which can also adversely affect their mechanical properties.

Ramana et al. [10, 11] investigated the effect of using different cutting fluids on surface finish when turning Ti-6Al-4V. Dry, palm oil and a mixture palm oil with boric acid were used as cutting fluids. A reduction in average surface roughness was obtained when the palm oil was used compared with dry cutting (Ra was 3.56μm and 3.84μm respectively). Lowest surface roughness results were obtained using CVD coated tool at 79m/min cutting speed, 0.206mm/rev feed rate and 1mm depth of cut. Rahim and Sasahara [6] studied the strength of using the palm oil and synthetic ester in minimum quantity lubricant (MQL) when drilling Ti-6Al-4V at 100m/min cutting speed and 0.1 mm/rev feed rate. The results showed that the use of palm oil MQL resulted in lower cutting force of 1954 N compared with 2318 N for synthetic ester with no impact on tool life (314 seconds for both CFs). This was attributed to the formation of thin boundary lubrication film which led to a reduction in friction in tool–workpiece interface. Tool wear was also evaluated when grooving Ti-10V-2Fe-3Al using different cutting fluid application methods including vegetable oil (MQL) at rake face (RF) with carbon dioxide (CO2-snow) at flank face (FF), carbon dioxide (CO2-snow) at (RF) & (FF) and a conventional oil/water emulsion (6%) [12]. Trials were performed at a range of cutting speeds (12.5 - 300 m/min) and constant feed rate and depth of cut of 0.1mm/rev and 0.3mm respectively. Results showed that the tool wear was marginally reduced when the vegetable oil MQL mixed with CO2-snow was employed. Lower flank wear of 0.08mm was reported when the VO/CO2 mixture was used while the use of only CO2 and conventional oil/water emulsion produced 0.09mm and 0.12mm wear respectively. Additionally, the use of vegetable oil MQL when turning Ti-6Al-4V was investigated to evaluate tool life / tool wear rate [13]. Experiments were performed at 120m/min, 0.1 mm/rev and 1.2mm cutting speed, feed rate and depth of cut respectively. The flank wear rate was observed to be minimum in the case of vegetable oil MQL (Vb= 0.01mm/min) with a corresponding rise in tool life compared with 0.04mm/min for dry cutting. Surface hardness and average surface roughness were also measured on Ti-6Al-4V specimens cut using palm oil MQL, dry and flood cutting [14]. Minimum Ra (0.89 μm) was obtained when palm oil was used with a corresponding surface hardness of 332 HV while dry cutting produced Ra of 3.25μm. Praiarone et al. [15] investigated the performance of vegetable oil MQL, flood and dry milling and turning of titanium aluminide. Responses involved flank wear, tool life and surface roughness. Lower flank wear, higher tool life and lower average surface roughness (0.1 μm, 80 min, 0.5 μm respectively) were achieved when milling using vegetable oil MQL. However, tool life in relation to wet/flood turning of titanium aluminide was increased to 45 min compared to 40 min for both dry and MQL. It can be obviously concluded that the use of VOs cutting fluids is still in growing phase in the metal cutting industry. Additionally, although there are several researches investigating the use of vegetable oils in machining of titanium alloys, only limited investigations considered the variation of cutting tool materials/coatings and their effect on the quality of the machined surface.

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

Nomenclature

CFs Cutting Fluids
VO Vegetable Oil
Ra Average surface roughness
PCR Percentage Contribution Ratio
CVD Chemical Vapour Deposition
PVD Physical Vapour Deposition
α Cutting tool clearance angle
X_n Insert included angle
r_ε Insert nose radius

2. Experimental Work

All experiments were performed on a Graziano Tortona Centre lathe. The Ti-6Al-4V Grade 5 workpiece samples were 30 mm diameter, 330 mm long and were mounted between the spindle chuck and a centre. Workpiece materials were supplied by Titanium Metal UK Limited, West Bromwich, UK. Phase 1 involved the variation of cutting speed, feed rate and depth of cut each at three levels as seen in Table 1 and only Hocut3450 cutting fluid and H10F cutting tool were used throughout the 27 tests. While Phase 2 involved the variation of two control factors namely cutting fluid and cutting tool, each at 5 levels and at constant cutting speed, feed rate and depth of cut of 75m/min, 0.15mm/rev and 0.75mm respectively (25 tests). Five different indexable tool inserts with constant nose radius (r_ε=0.8mm), insert included angle (X_n=80˚) and clearance angle (α=0˚) were used and all were supplied by Sandvik, UK. Additionally, four soluble VO based cutting fluids and one mineral-oil based cutting fluid were investigated. Table 2 shows details of tools and cutting fluids used throughout this work. The selection of vegetable oil based cutting fluids was made based on the different properties and characteristics inherent by each of the oils. Vasco 1000 was described as delivering highest possible tool life and surface finish on titanium. HOCUT 3450 was described as having high lubricity performance and antiwear properties designed to giving superior surface finish and extending tool life. Super Synth 4 has good inhibition against corrosion of a wide range of metals giving protection to both workpiece and machined parts. All vegetable oil based cutting fluids benefited from environmental impact characteristics. The mineral oil “Castrol Cooledge” was chosen as a reference for comparison against all vegetable oils.

Table 1. Process variables and their corresponding levels for Phase 1

Factor	Level 1	Level 2	Level 3
Cutting speed (m/min)	28	75	120
Feed rate (mm/rev)	0.1	0.15	0.2
Depth of cut (mm)	0.5	0.75	1

Table 2. Process variables and their corresponding levels for Phase 2

Factor	Level 1	Level 2	Level 3	Level 4	Level 5
Cutting fluids	Hocut 3450	Vasco 1000	Coolant NE250 H	Super Synth 4	Mineral oil based CF
Cutting tools	Uncoated carbide, (H13)	PVD (TiAlN coated carbide), (GC1105)	Uncoated fine grain carbide, (H10F)	CVD coated carbide, (S05F)	Mixed ceramic (titanium & alumina), (CC650)

Each test had a cutting length of 100mm and a new tool insert was used. Cutting fluids were applied to the cutting zone through a single flexible hose. The cutting fluids supplied to the machining zone had a 5% concentration vegetable oil when mixed with water (as recommended by the VO suppliers). Concentration was regularly checked using a refractometer. 3D surface topography assessment was carried out using an Alicona Infinite Focus G4 optical scanner, having a resolution down to 10 nm. The scanning area was 13mm x 4mm in axial and circumferential directions respectively. Scans were obtained using 200 nm and 7 µm vertical (Z direction) and lateral (X and Y) resolutions respectively. Average surface roughness was measured using Talylor Hobson Surtroni 3+, having a resolution of 0.01µm. All measurements conformed to ISO4287 and ISO4288 using 0.8mm cut-off and 4mm evaluation length. Three Ra readings (at the beginning, middle and end of the cut) were recorded and an average was then computed, see Fig. 1. Flank wear was also assessed using a stereoscope (Leica EZ4D) in conjunction with Leica LAS EZ software.

3. Results and Discussion

The obtained results will be shown in two different phase. Phase 1 includes results from work to investigate the influence of cutting conditions (cutting speed, feed rate and depth of cut) on surface roughness. Results from Phase 2 are then presented which includes analysis of surface roughness when using various cutting fluids and tools. Additionally, sample tool wear measurements will be presented. Fig. 2 shows the main effects plot for average surface roughness results. In general, Ra ranged between 0.56 µm and 1.81 µm and statistical analysis (ANOVA results are shown in Table 3) showed that the main contributing factor for Ra is feed rate having a high PCR of 94.4%. Average surface roughness results for all experiments conducted at 0.2mm/rev feed rate was 1.55 µm while it was only 0.65 µm for experiments carried out at 0.1 mm/rev. The relatively small error level (4.9%) associated with the average surface roughness evaluation was within the acceptable levels (up to 15%), suggesting that all important variables had been considered and measurements accurately performed.

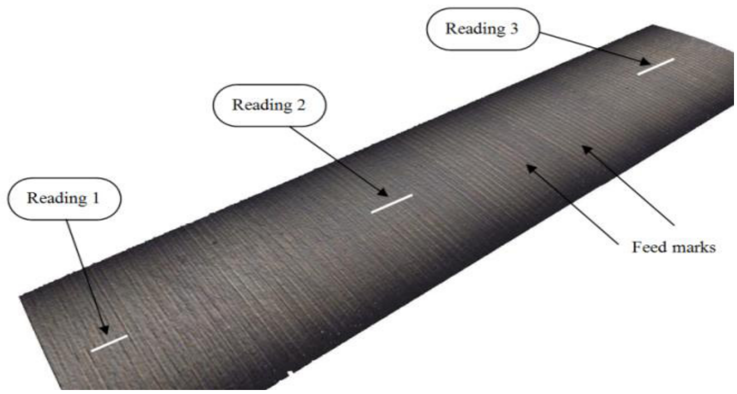

Fig. 1. 3D scan for a cut surface including the locations of surface roughness measurement

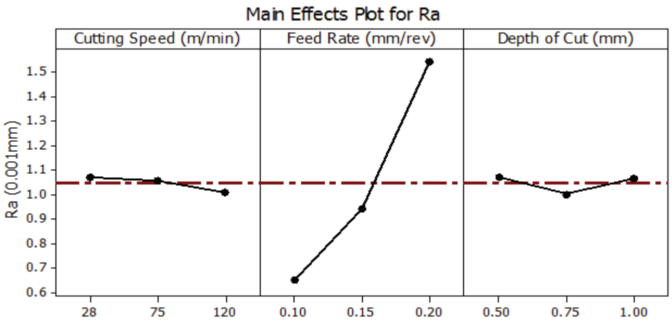

Fig. 2. Main effects plot for average surface roughness results (Ra) – Phase 1

Table 3. ANOVA results for average surface roughness (Ra) – Phase 1

	DF	SS	MSS	Exp SS	F	P	PCR
Cutting Speed	2	0.0177	0.00885	0.009287	1.05	0.368	0.23
Feed Rate	2	3.74028	1.87014	3.731867	222.28	0*	94.40
Depth of Cut	2	0.02691	0.013455	0.018497	1.6	0.227	0.47
Error	20	0.16827	0.008414				4.90
Total	26	3.95316					

DF = Degrees of freedom
SS = Sum of squares
Exp SS = Expected sum of squares
* Significant at the 5% level
F = F-test value
P = Probability
PCR = Percent contribution ratio

Fig. 3 shows part of Phase 2 results which present Ra versus cutting tools (except for ceramic which was withdrawn from the analysis due to unexpected premature failure resulted in reducing the depth of cut to 0.5 mm). The average surface roughness for all cutting tools was below the threshold for critical applications (e.g. Ra 1.6 µm for aerospace components). TiAlN PVD coated carbide tools (GC1105) produced the overall lowest average Ra of 0.72 µm owing inherently to its superior mechanical properties such as thermal stability and high hardness of 2800 HV [16]. The thermal stability may have resulted in maintaining its precision during cutting. The highest overall average Ra of 0.97 µm was achieved by the coarse grain carbide tools (H13A). Ceramics possess low fracture toughness (4.0 MPa.m1/2) and mechanical fatigue hence its instant failure when exposed to high stresses.

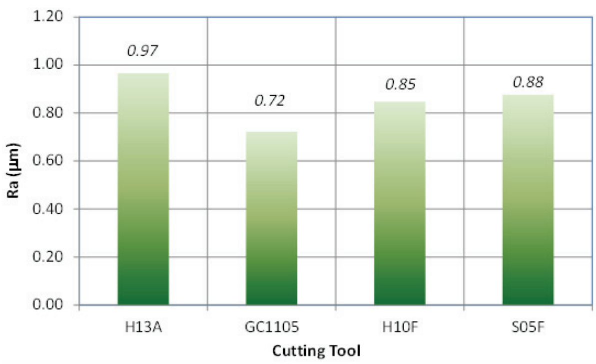

Fig. 3. Ra results versus cutting tools (Phase 2)

Fig. 4 shows the effects of cutting fluids on the average surface roughness. Relatively marginal variation of the average roughness values was observed between the tested fluids (0.15 µm). This could be attributed to a witnessed variation in the fluid flow rate during the experimentation in addition to an observed variation in the cutting fluid concentration. In general, NE250 H gave the highest average Ra of 0.93 µm compared to the mineral-oil based which gave the lowest average (0.78 µm). This similarity in the performance was not anticipated as Vegetable-oil based cutting fluids inherent higher lubrication and higher cooling effects in the cutting zone than mineral-oil based cutting fluids. VOs typically possess higher heat conductivity therefore dissipating the generated heat away from the tool/workpiece interface. Their higher lubrication capability also decreases the frictional forces contributing to this heat thus suffering less deformation. The results could be also ascribed to an observed increase in mineral oil concentration (up to 8% at the end of five tests) compared to limited rise for the counterparts (only up to 5.8%). Statistical analysis (ANOVA results are shown in Table 4) showed that cutting tool type/material was statistically significant on Ra having a high PCR of 44.5%. However, a relatively high error level (44%) associated with the average surface roughness evaluation was achieved suggestion that not all important variables had been considered.

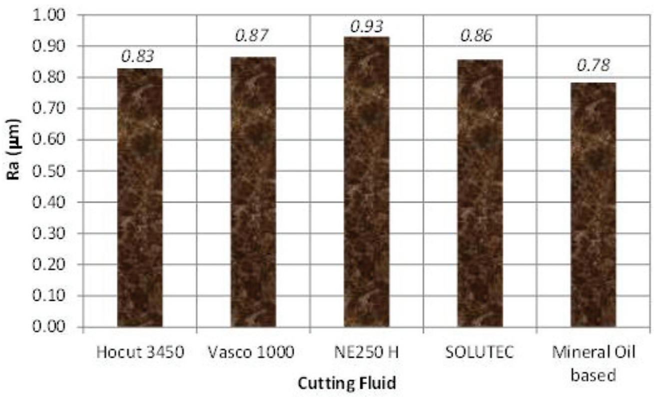

Fig. 4. Effect of cutting fluid on the average surface roughness results (Phase 2)

Table 4. ANOVA results for average surface roughness (Ra) – Phase 2

	DF	SS	MSS	Exp SS	F	P	PCR
Cutting Fluid	4	0.046191	0.011548	0.036228	1.16	0.376	11.44
Cutting Tool	3	0.150871	0.05029	0.140908	5.05	0.017*	44.50
Error	12	0.119551	0.009963				44.05
Total	19	0.316613			* Significant at the 5% level		

Fig. 5 shows average surface roughness results for all cutting tools when Hocut3450 cutting fluid was used. The mixed ceramic tool (CC650) demonstrated the poorest performance in relation to surface roughness (Ra of 1.63 µm). Ceramic inserts also suffered severe chipping prior to observed premature fracture which may have altered the tool geometries. This resulted in withdrawing the ceramic tools from the comparison following use with Hocut3450 and Vasco1000. Limited trials were then performed using ceramic tools at smaller depth of cut (0.5 mm). On the other hand, the lowest Ra 0.68 µm was recorded for the TiAlN PVD coated fine grain carbide with 6% cobalt (GC1105). Error bars added to the figure were relatively small suggesting that the measurements were performed accurately.

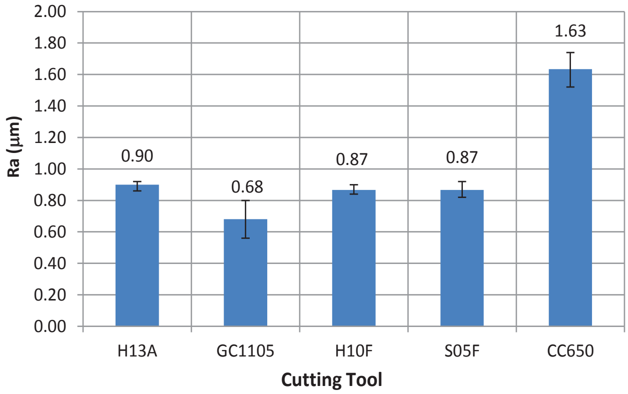

Fig. 5. Average surface roughness results versus all cutting tools using Hocut 3450 at 0.75 mm depth of cut (Phase 2)

Fig. 6 shows the effect of cutting speed on tool wear and discolouring on the tool tip. Marking or discolouring was hardly observed on any of the cutting tools used at low cutting speeds which can be attributed to the lower cutting temperature while significant discolouring and wear scars were seen on tool tips used at higher level of cutting speeds (120m/min). Fig. 7 shows the progress of the flank wear at 0.15mm/rev feed rate for various cutting speeds and depth of cuts. A typical rise in flank wear with increasing cutting speed can be seen on the cutting tools. Greater increase in flank wear was observed at larger depth of cuts (1mm) particularly at a high cutting speed (120m/min).

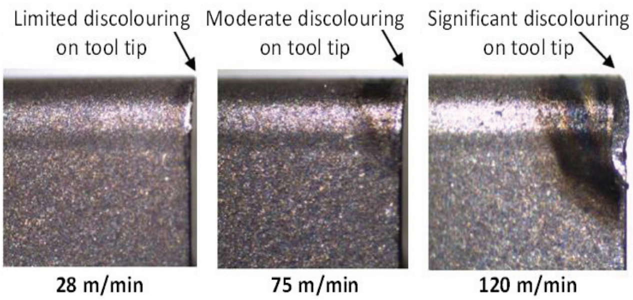

Fig. 6. Images for flank wear and discolouring on tool tips used at various cutting speeds and at 0.2mm/rev and 1mm feed rate and depth of cut respectively (Phase 1)

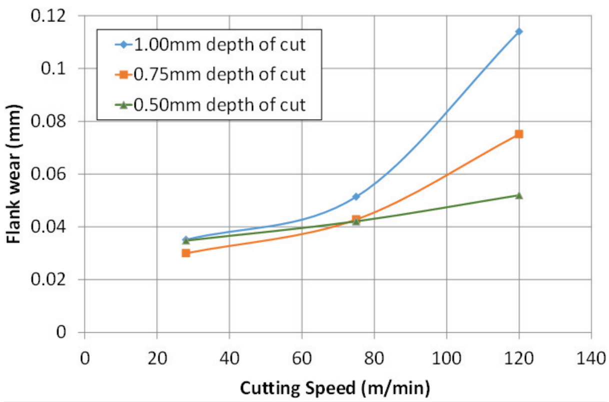

Fig. 7. Flank wear results at various cutting speed and depth of cut (constant feed rate of 0.15mm/rev was used), Phase 1

4. Conclusions

The work reported concerns the turning of titanium 6Al-4V. The following conclusions can be drawn:

- Ra ranged from 0.56to 1.81 μm and statistical analysis showed that the main contributing factor for Ra is feed rate having a high PCR of 94.4% (Phase 1). Better surface finish (lower surface roughness) could be obtained at optimum working conditions of 120m/min, 0.1mm/rev and 0.75mm cutting speed, feed rate and depth of cut respectively.
- Cutting tool material was the main contributing factor for Ra having a PCR of 44.5% while the variation in cutting fluid had no significant effect (Phase 2). The use of PVD TiAlN coated carbide tools resulted in relatively lower surface roughness compared to other cutting tools.
- The majority of mixed ceramic cutting tools tested at higher depth of cut level (1mm) experienced premature failure.
- Flank wear increased with higher cutting speeds particularly at high levels of depth of cut.

Acknowledgements

The authors would like to thank the department of mechanical and construction engineering at Northumbria University for technical support to carry out this research, the authors would also like to thank the Libyan government for financial support. The authors would also like to thanks Mr. Tom Sanderson for his technical support.

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