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Cutting fluid application for titanium alloys Ti-6Al-4V and Ti-10V-2Fe-3Al in a finish turning process

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Abstract

Superalloys such as titanium alloys are classified as hard to machine. Cutting tools and cutting fluids (coolants) are under constant development to improve the machining of such alloys. Coolants remove heat and metal cuttings (chips) from the cutting zone and provide lubrication. Usage of coolant mitigates certain health and safety considerations whilst creating others. Prolonged exposure to coolant fluid and mist can cause health issues. Alternatively, the ignition of dry titanium chips can cause a fire. These risks must be mitigated. For this paper titanium alloys Ti-6Al-4V and Ti-10V-2Fe-3Al were machined, studying the effect of three coolant application conditions in finish turning. The conditions were through-tool delivery of emulsion coolant at 60 bar pressure (known as TT), flood delivery of emulsion coolant and cutting dry with no coolant.

Tool wear tests assessed the surface speed at which 15 minutes' tool life could be achieved. It was found that dry turning could be run at between 70 and 80 percent of the speed achieved for TT. The flood condition could achieve 88 to 92 percent of the speed achieved for TT. Dry cutting performed well regarding tool wear, considering the reduction of resource usage and reduced environmental impact. A weakness of dry and flood turning was that chips formed problematic tangled structures.

Individual turned Ti-10V-2Fe-3Al samples had their microstructure analysed. For a sample machined under dry conditions some sub-surface damage metrics were worsened whilst other were improved, compared to samples turned using coolant. No evidence was seen of a burned surface. Recommendations for future work include taking more samples for microstructure analysis.

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Keywords: titanium; turning; coolant; cutting fluid; dry machining; wear; surface integrity

1. Introduction

Titanium-based alloys are known as superalloys because of their excellent in-service properties such as temperature resistance and fatigue resistance [1]. However, low thermal conductivity and high chemical reactivity when heated make titanium alloys hard to machine [2]. To enhance machining productivity, use of cutting fluids (coolants) is commonplace for titanium [3]. Coolants remove heat and metal cuttings (chips) from the cutting zone. A coolant jet can break up chips and avoid damage to the cutting tool. Coolants also provide a lubrication role. The removal of heat and available oxygen has two-fold benefits: to reduce chemical reactions between titanium and cutting tools, and to mitigate the risk of titanium fires. Coolant use introduces a list of drawbacks however, from the health and environment perspective [4]. Chemical

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contents vary, with prolonged exposure to certain fluids and their mists increasing the risk of dermatitis and respiratory illness for machine operators. Special procedures must be followed in the case of spills and disposal, due to the environmental hazard posed. These benefits and drawbacks of coolants must be weighed up by manufacturers.

This study investigates the consequences for chip formation, tool wear rates and machined microstructure when running a titanium turning process with different coolant supply configurations. Dry machining is investigated. Further reading about typical practices and observations in microstructure analysis and surface integrity investigation can be found in the literature [5]. This study builds on recent research work of interest [6, 7], in particular through examining the machined microstructure and by testing alloy Ti-10V-2Fe-3Al.

2. Experimental work

2.1. Trials configuration

As displayed in Figure 1, three coolant conditions were tested via three experimental stages. The flood and through tool options utilized Houghton Hocut 795B emulsion coolant at 7% concentration. The two alloys tested were Ti-6Al-4V and Ti-10V-2Fe-3Al, both in the mill annealed condition and in bar form. Bars had a starting diameter of 160mm.

Turning was carried out on the bar outer diameters, the radial depth of cut was consistent with finish turning at 0.3mm. The feed rate was 0.1mm/rev and surface speeds were between 100 and 200m/min. The NC lathe used was a Mori Seiki NT5400, with a HydraJet WP10-1000 external coolant supply unit fitted.

The cutting inserts used were Sandvik Coromant uncoated cemented carbide CNGG 120408-SGF H13A. The tool holder was a C6-PCMNN-00115-12HP which supplies coolant through the holder (known as "through-tool" or TT) then through three fixed nozzles of approximately 1mm diameter, aimed at the insert rake face. Pressure gauges indicated that the TT coolant pressure was 60 bar at the external supply unit, and 50 bar when entering the tool holder.

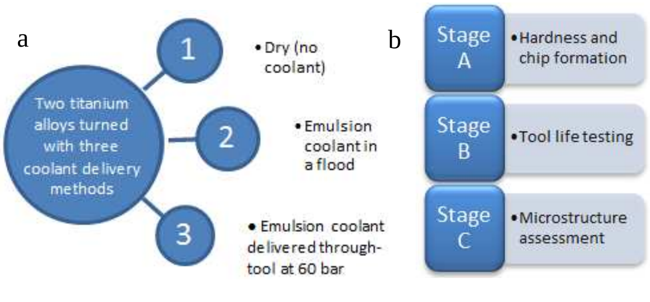

Fig. 1. (a) machining conditions; (b) experimental stages.

2.2. Material hardness and chip formation

Both titanium alloys were tested for hardness. Nine indentations were made on each bar and the results averaged.

Single-pass turning tests were carried out for each titanium alloy using dry, flood and TT coolant delivery options, to see the effect of coolant delivery on chip breaking. Chips were collected for each pass then photographed.

2.3. Tool life testing

Five tool wear tests were carried out for each of the six alloy / coolant delivery combinations. Each test consisted of turning titanium for 15 minutes then measuring the size of average and maximum flank wear scars on the cutting insert with a toolmaker's microscope. Insert edges were run at various surface speeds until an edge was found to be worn out. Lower surface speeds lead to lower levels of tool flank wear, whilst higher speeds cause greater wear. These tests evaluated a quantity known as "V15", which is the surface speed corresponding to 15 minutes' tool life. 15 minutes was selected as a tool life which is broadly representative of industrial practice.

The coolant flowrates were measured by filling a bucket for 30 seconds, then transferring the fluid volume from the bucket to measuring jugs. Results were averaged over three such tests for both flood and TT delivery.

To mitigate risks during dry machining, which combines titanium with heat and oxygen, a fire extinguisher was kept by the machine tool. No incidents of note occurred.

2.4. Microstructure examination

After tool life testing, surface sections were turned on the Ti-10V-2Fe-3Al bar using new inserts and all three coolant delivery methods at 0.3mm radial depth, 125m/min speed and 0.1mm/rev feed. Samples of these sections were then extracted using wire electrode discharge machining, depicted in Figure 2. The samples were sent to be analysed for machining-induced damage. Samples were mounted in polymer, ground, polished, etched and examined using a Leica light microscope and scanning electron microscopy system (Carl Zeiss Evo LS25). Various near-surface features were observed which are considered to represent damage to the material microstructure. They may have a negative effect on the in-service life of a machined component if no further surface processing is done.

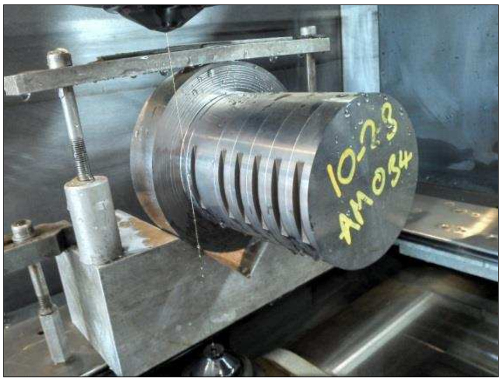

Fig. 2. Extraction of turned samples for microstructure evaluation.

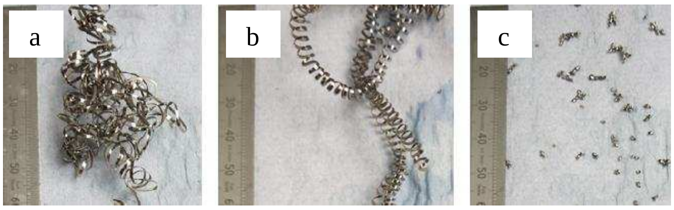

Fig. 3. Titanium cuttings. (a) dry cutting; (b) flood; (c) 60 bar through tool.

3. Results and discussion

3.1. Material hardness and chip formation

Hardness measurement revealed that the mean Rockwell C hardness for the Ti-10V-2Fe-3Al bar was 36 HRC, whilst for the Ti-6Al-4V bar it was 29 HRC. These measurements are within the anticipated range for the materials.

The screening exercise carried out for chip-breaking revealed a significant variation in morphology with coolant application method, characterised in Figure 3. The absence of a directed high-speed coolant jet in the case of dry and flood cutting meant little pressure was exerted on the chip, so it formed unbroken tangling nest-like structures. These structures are problematic for machining with no human intervention as they cause damage and fail to clear from the cutting zone. Dry cutting would be a more feasible prospect if the chip nesting problem could be overcome, for example by putting more pronounced chip breaking geometry on the cutting insert.

3.2. Tool life testing

The tool failure criteria were set to 0.25mm average and 0.5mm maximum of flank wear. Figure 4 shows the outcome of varying the surface speed for the case of turning Ti-10V-2Fe-3Al with flood coolant. From linear interpolation it can be seen that the measured flank wear crosses the failure thresholds just above 150m/min, so V15 for this case is 150m/min. V15 has been evaluated to the nearest 5m/min, suitable to the precision of the method employed. V15 values are compiled for all six material / coolant supply combinations in Table 1, coolant flowrates are also tabulated. Comparing the two alloys, the similar or lower V15 speeds found for Ti-10V-2Fe-3Al are consistent with a higher measured material hardness.

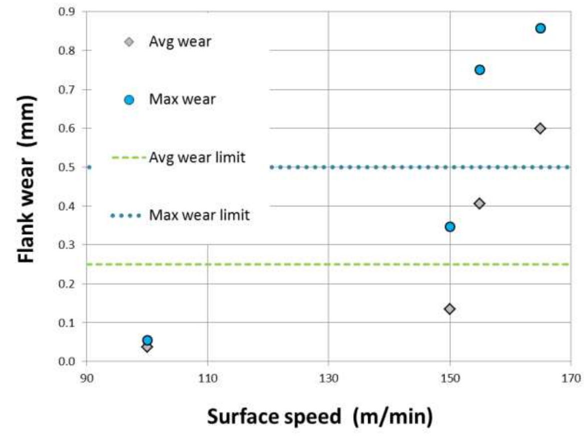

Fig. 4. Tool life data for Ti-10V-2Fe-3Al turned with flood coolant.

Table 1. V15 surface speed for two alloys with three coolant conditions.

Delivery method	Coolant flow rate (l/min)	V15 for Ti-6Al-4V (m/min)	V15 for Ti-10V-2Fe-3Al (m/min)
Dry	None	135	120
Flood	19.2	155	150
60 bar TT	16.5	170	170

It was found that for both titanium materials, the dry turning V15 surface speed was between 70 and 80 percent of the V15 achieved for TT coolant delivery. The flood condition achieved a V15 at 88 to 92 percent of V15 for TT. Dry cutting was considered to have performed well regarding tool wear rates, considering that a sump with hundreds to thousands of litres of emulsion coolant is required to run the flood and TT options. With dry cutting there is no requirement to purchase coolant and water, to fill and monitor the machine sump or to drain and dispose of coolants. Comparing flood versus TT coolant delivery, the TT option breaks chips better and achieves a higher surface speed, based on a lower coolant flowrate.

3.3. Microstructure examination

Examples of machined Ti-10V-2Fe-3Al microstructure samples are displayed in Figures 5 and 6. The bottom half of each image shows the etched titanium grain structure. The machining process causes the microstructure to be transformed near the surface, arrows in the figures point to the damage features created. The size of these features was evaluated using image measurement software. When cutting dry some near-surface metrics were worsened compared to when using emulsion coolant whilst others were improved, as is shown in Table 2. Based on a few samples it wasn't possible to get a generalized comparison of the effect of coolant on these damage features. However from examination of the micrograph images no evidence was seen of a burned surface. A heavily-deformed layer can be observed in Figure 6b, with grain and grain boundary features still visible within it. This layer occurred for wet cutting also.

Other tests which could be applied to compare these samples include chemical analysis and micro-hardness profiling.

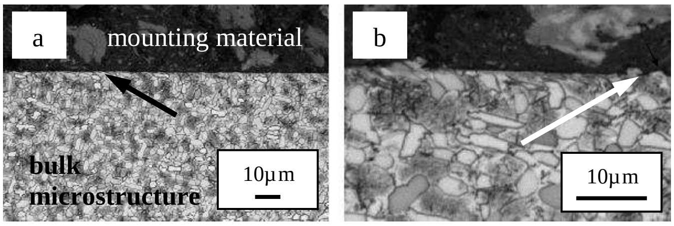

Fig. 5. Ti-10V-2Fe-3Al cut dry: (a) surface deformation; (b) surface tearing.

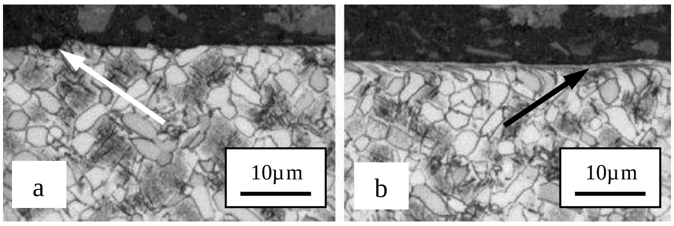

Fig. 6. Ti-10V-2Fe-3Al cut dry: (a) grain pull-out; (b) heavy deformation.

Table 2. Microstructure damage results for turned Ti-10V-2Fe-3Al.

Delivery method	Deformation depth (µm)	Tearing (µm)	Grain pull-out (µm)	Re-deposit material (µm)
Dry	3.5	1.5	1.5	None
Flood	4.5	<1	1	2
60 bar TT	3	1.5	None	None

4. Conclusions

This study was focussed on the effect of dry, flood and 60 bar through-tool emulsion coolant application in turning of titanium Ti-6Al-4V and Ti-10V-2Fe-3Al, specifically in terms of chip formation, tool wear and microstructure examination. The main conclusions arising were as follows:

- The absence of a directed high-speed coolant jet led to unmanaged, nesting metal cuttings (chips) in the case of dry and flood cutting;
- For an equivalent turning insert life of 15 minutes, dry cutting could be run at between 70 and 80 percent of the surface speed achieved for through-tool coolant. Flood cutting could be run at 88 to 92 percent of the surface speed achieved for through-tool coolant.
- Flood coolant offered no clear advantages over through-tool delivery, whereas removal of the coolant to cut dry offers numerous potential operational, environmental and health benefits. The fire risk must be mitigated when machining titanium without coolant.
- A small microstructure study of machined samples was encouraging in support of dry titanium cutting. Some microstructure damage metrics were worsened compared to when using emulsion coolant, whilst others improved.

Ideas for future work include studying the temperature of the cutting zone and of chips produced when cutting dry, to further address fire risks. Additionally, taking more machined samples for microstructure analysis and doing a near-surface chemical analysis on these is recommended.

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