Investigation of Selected Cooling Techniques for Milling of Ti-6Al-4V

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ABSTRACT

Weight and space limitations in aerospace industries have led to an interest in the application of titanium in aircraft structures and aircraft engines. Titanium's low thermal conductivity, segmentation of the chips and extreme reactivity at high temperatures cause a focused heat load on the cutting edge. These properties give titanium its characteristic of being difficult to machine, particularly when high performance machining parameters dictate elevated cutting speeds. This leaves the need to investigate cooling strategies to maintain or improve tool life. The reduction of chip/tool contact area and time leads to a decreased heat transfer and tool wear. In this work the application of external compressed air jet cooling (dry cutting), flood cooling and focused high pressure internal cooling strategies are studied. An investigation of the benefits under finishing operations, typically used for thin wall components, is conducted to determine the advantages of the cooling techniques under each respective cooling strategy. The main evaluating parameter is the flank face wear, which is measured optically. The measurements give an indication of the performance of the respective cooling technique. In the presented paper the experimental results are analysed and discussed.

1 INTRODUCTION

Titanium has a remarkably high strength-to-weight ratio leading to an increased demand for its use. Aerospace industries utilise this phenomenon to substitute steel with Ti-6Al-4Vin numerous applications. Structural lightweight components in aerospace applications mean large thin walled parts with a high mechanical strength requirement [1, 2]. Combined with titanium's strength properties, this alloy benefits from high operating temperature capability, corrosion resistance and good compatability with composite materials [3].

Machining challenges for titanium can be subdivided into thermal and mechanical tool demands. Titanium is exceptionally reactive at high temperatures during machining [3, 4, 5]. The tool face temperature is a function of the cutting speed (v_c) and exposure time to this thermal load. Titanium's low thermal conductivity leads to the heat generated concentrating in the cutting zone [6]. The fast moving segmented chips have a short contact length with the tool tip generating temperatures up to the region of 1100°C [3, 5]. This scenario causes complex tool wear mechanisms such as adhesion, diffusion and oxidation [7].

In this study various cooling and lubrication strategies were explored in order to design and develop innovative cooling techniques.

2 OVERVIEW OF SELECTED COOLINGSTRATEGIES AND TECHNIQUES

There are several cooling strategies that can be employed during machining. The most common and extensively studied strategies are dry cutting, flood cooling and high pressure cooling. With each of these strategies, coolant application techniques vary considerably. The strategy and technique used depends on the material and parameters surrounding the machining process.

Dry cutting involves reliance on the natural environment for cooling such as radiation and air convection and specifically no use of cooling fluid or lubrication directly onto the cutting zone. Included in this category of cooling is vaporisation of cryogenic coolants, as well as thermo-electric cooling systems, acting from under the insert. Dry cutting supplemented by an external supply of compressed air is also common practice, as was done in this case. The main reason for dry machining is the benefit to the environment and operators [8].

Flood cooling, best described as an uninterrupted flow of an abundant quantity of coolant, removes chips by a flushing action. With flood cooling, thermal shock on milling tools are minimized and the ignition of chips eliminated [3]. This method is often a benchmark for experiments due to its extensive use in standard machining application.

High pressure cooling demonstrates the possibility of improvements in tool life when machining Ti-6Al-4V with cemented carbide (coated and uncoated) tools at higher cutting speeds. The thought pattern behind this statement is visible in the trend shown in Figure 1. The figure illustrates notable tool life enhancement under high pressure through spindle cooling (HPTSC), compared to flood cooling methods. Particular attention to the greater potential of the HPTSC over flood cooling should be noted, specifically at higher cutting speeds. Tool life usually increases with higher coolant pressures [9] as the cutting speed increases, as a result of cutting temperature decrease by improved heat transfer. At a cutting speed of 110 m/min the highest pressure of 203 bar yields approximately double the tool life compared to 110 bar pressure and an approximate three times increase in tool life compared to flood cooling. However, a cutting speed of 120m/min has a variance in tool life of less than 5% between 203 bar and 110 bar cooling pressure, compared to 110 m/min. A difference of such a small magnitude is statistically perceived as insignificant.

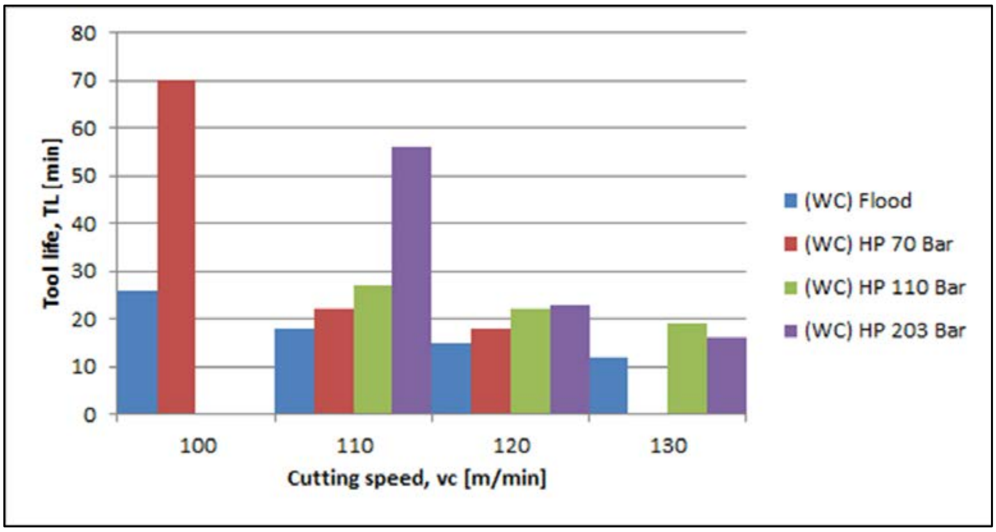

Figure 1: Tool life when machining titanium alloy with uncoated tungsten carbide (WC) under different cooling strategies [9]

When coated tungsten carbide cutting tools are used, improvements in flank wear under the concept of HPTSC are realised, as shown in Figure 2. Experiments indicated that the multi layered coating performance was the worst and showed no benefit from pressurised cooling or HPTSC. However, uncoated inserts showed clear benefit from HPTSC, yielding considerably lower values of uniform wear during the earlier part of the insert's life. The single layer coated insert performed better than the other inserts both under pressurised flood cooling as well as HPTSC. In the case of the single layer coated insert, the coating contributes towards a more robust process where the influence of cooling technique is not as prominent as with uncoated tools [10, 11, 12].

HPTSC can extend the life of the uncoated and single layered coating carbide inserts, approximating a linear flank wear. It is realised that under HPTSC the trend of the wear becomes more uniform. This is beneficial, as the wear became predictable and accurate change over time can be estimated or determined.

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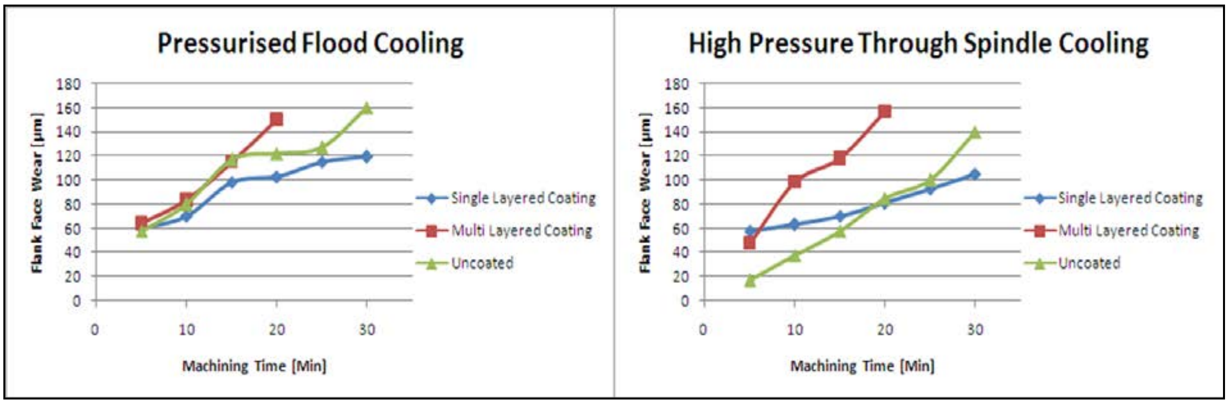

Figure 2: Performance of single layered coated, multi layered coated, and uncoated inserts (70 Mpa) (V_c = 120m/min, f_z= 0.076mm/z, a_p= 1mm, a_e = 10mm) [10]

The application of gas cooling with pressurised air with a small amount of emulsion coolant injected into the air stream was also investigated in previous work. Initial turning tests comparing conventional flood with the gas cooling were promising, but multi-nozzle pressurised flood cooling in milling tests proved to be superior to the gas cooling. Cryogenic cooling using liquid nitrogen, contained and focused on the cutting insert only, allowing the work piece to heat up, was also explored, indicating potential for the concept [10].

The conclusion made from this overview is that HPTSC has large potential specifically referring to the increased tool life at higher cutting speeds, as illustrated in Figure 1, and the linear flank wear in Figure 2. The inclusion of coating has an influence on the outcomes under HPTSC and the application of single layer coating is preferred in previous investigations [10], demonstrated graphically in Figure 2. It is clear that this is a complex phenomenon, worthy of being investigated comprehensively before it can become a standard industry practice. This paper reports work investigating focused nozzle direction and diameter, as used in HPTSC.

3 DESIGN OF FOCUSED HIGH PRESSURE THROUGH SPINDLE TECHNIQUE MODIFICATION

As a consequence of the benefits discussed in the overview, HPTSC produces favourable results. This encouraged the development of modification techniques for applying focused HPTSC. The design focused the jet of coolant on the chip and cutting tool interface, as depicted in Figure 3.

The envisioned result of the design technique is to improve the chip removal rate and reduce cutting temperatures. The anticipated outcome will enable the use of higher cutting speeds for machining titanium and improve the present HPTSC technique, leading to the benefits of reduced welding effect, contact length, material stickiness and temperature.

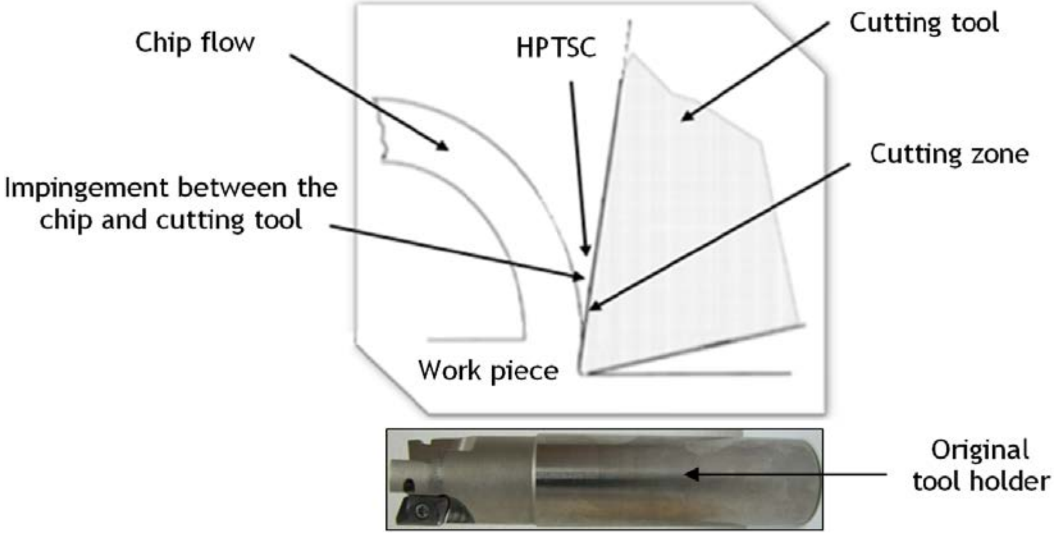

Figure 3: High pressure through spindle cooling (HPTSC) contact with insert and formed chip and original tool holder

The focused HPTSC techniques will impinge under the forming chip, into the cutting zone, and hydraulically force the chip away from the cutting edge. Both the hydraulic action impinging on the cutting zone, potentially removing heat, and the simultaneous "lifting of the chip", reducing contact length between tool and chip, transfer heat away thus decreasing the thermal load on the tool, demonstrated in Figure 3.

The new focused design techniques incorporated two changes to an existing tool holder, presented in Figure 3 by the original tool holder, namely adjusted HPTSC and the new focused HPTSC. A focus point was determined with the intent of the intensive HPTSC techniques contacting the cutting tool before the heat zone, indicated by "HPTSC" in Figure 3

The focus point was common for both technique changes. The adjusted HPTSC technique design, shown in Figure 4, reduces the original flushing hole diameter from 3mm to 0.5mm. This was obtained by plugging the original hole and then spark-eroding a 0.5mm replacement hole. The objective of the reduced diameter is to focus the original HPTSC jet improving its chip and heat removal capability.

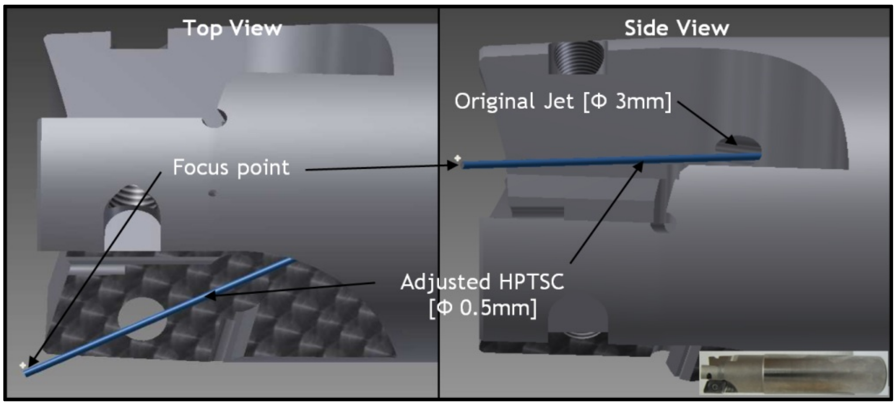

Figure 4: Adjusted high pressure through spindle cooling technique

The new focused HPTSC technique, using a spark eroded hole with a diameter of 0.5mm, is directed at the focus point through a point 0.2mm above the flat surface of the tool flute, indicated in Figure 5. This will reduce the distance travelled by the HPTSC jet. The reduced travel decreases the expansion of the jet diameter, increasing cooling capacity and the flushing action of the jet.

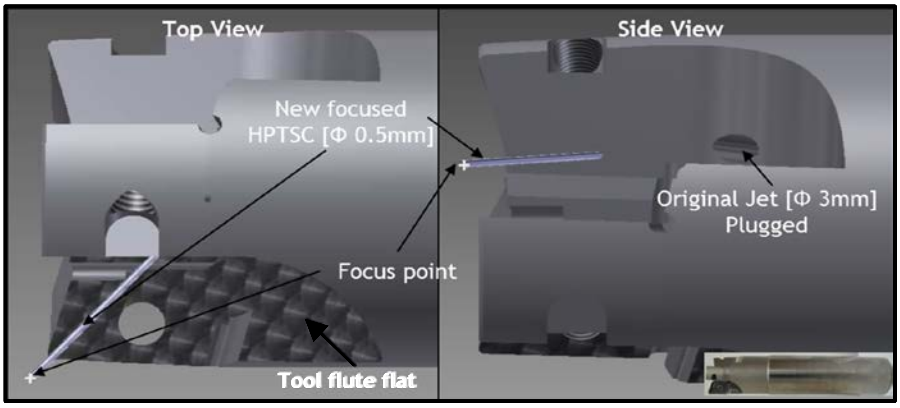

Figure 5: New focused high pressure through spindle cooling technique

The adjusted HPTSC jet diameter of contact, increased due to expansion of the jet, will be larger than that of the new focused HPTSC jet, allowing greater flushing of produced chips. In contrast to the adjusted HPTSC jet, the new focused HPTSC jet has a concentrated cooling capacity. Both these attributes of flushing and concentrated cooling are favourable and a combination of the two techniques is eligible. This combination of modified HPTSC techniques is discussed in the following section.

4 EXPERIMENTAL SETUP

All experiments used peripheral milling of Ti-6Al-4V, conducted on a Hermle C40 CNC milling centre. Machining was done using a Mitsubishi 25mm diameter tool holder fitted with a VP15TF coated carbide insert (code: Mitsubishi XPMT13T3PDER-M2), shown in the original tool holder Figure 3.

The three cooling strategies for the experiments were as follows: Dry cutting, flood cooling and HPTSC. Under HPTSC, three technique modifications were tested at a pressure of 70 bars. For each experiment, a cut made along the width of a block of Ti6Al4V, 330mm in length, constitutes a single pass machined to constrained cutting parameters, indicated in Table 1. After every second pass, a measurement of the insert's flank wear was made using an optical microscope. This was continued until the wear reached the selected limit value for the wear bandwidth. The wear bandwidth for the experiments is chosen as 300µm. This value was picked as a point for evaluation and comparison of the cooling strategies and techniques presented in this paper. Each experiment was repeated three times.

Table 1: Experimental cutting conditions

Axial depth of cut (DOC)	a_p	2 mm
Radial DOC	a_e	0.65 mm
Cutting speed	v_c	150 m/min
Feed rate	f_z	0.375 mm/tooth

The first sets of experiments commenced under dry cutting conditions, aided by an external stream of compressed air at ambient temperature. The air blowing action intended to prevent the welding, re-cutting of chips and chip ignition. The second set of experiments used flood cooling, applied separately to aid the removal of chips. There was no use of the HPTSC in the first and second sets of experiments.

The next four sets of experiments used HPTSC modifications from the design changes discussed. The HPTSC modification techniques are graphically represented in Figure 6. The first of the four experiments implement the HPTSC original (MI), using the original design of the tool with through spindle coolant.

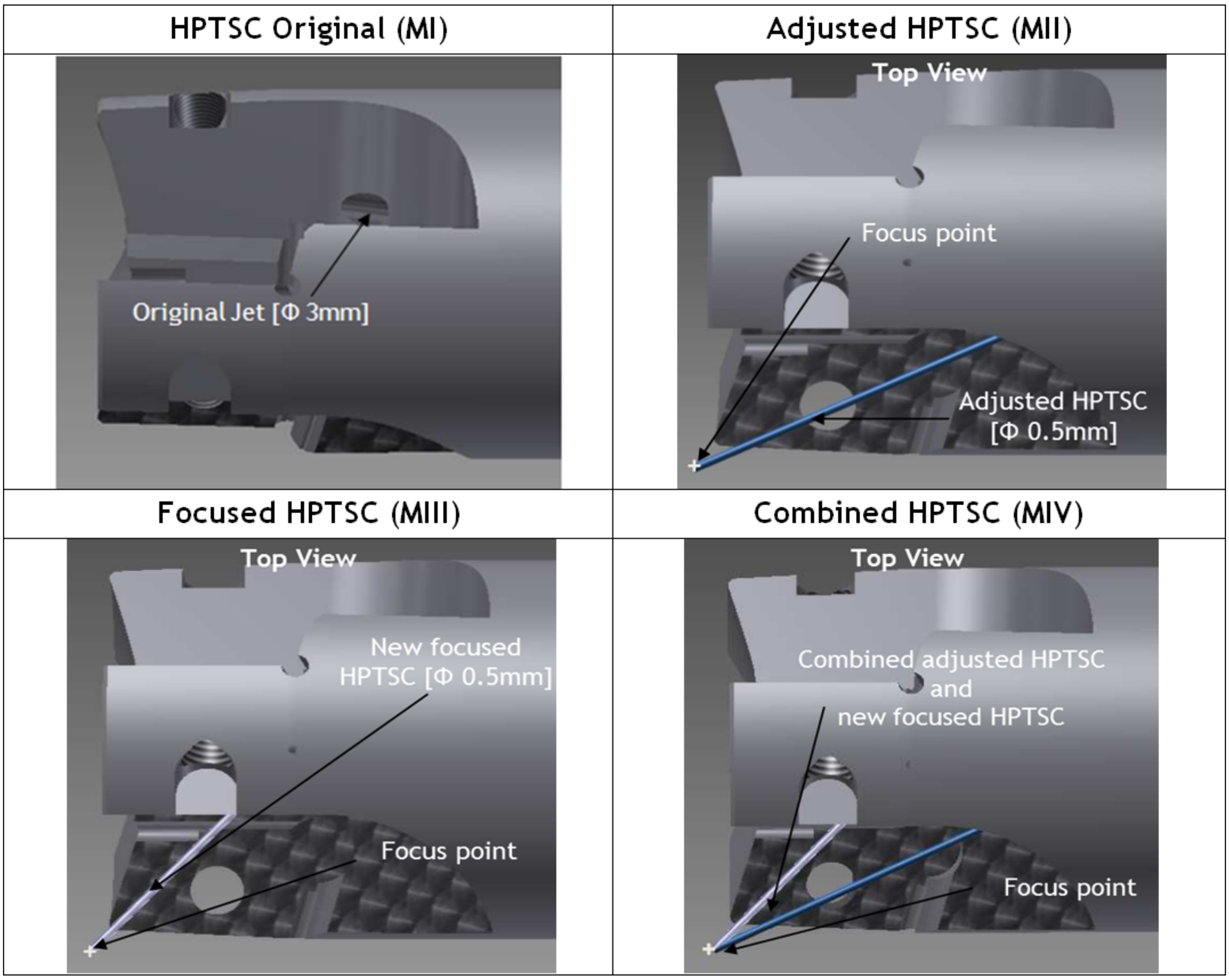

Figure 6: HPTSC modification configurations

The remaining technique modification configurations consist of the adjusted HPTSC (MII), focused HPTSC (MIII) and a combined HPTSC (MIV). The third modification (MIV) combines the benefits of both MII and MIII designs. (Figure 6)

5 DISCUSSION

In these experiments the performance of an insert is judged by machining time before the set designated tool failure wear limit occurs. The number of cuts made by an insert is an accurate indication of the amount or capability of material removal of the insert under the different cooling strategies. One cut is the equivalent of one revolution of the cutter body due to the attachment of a single insert during each experiment. The wear (µm) on the inserts was measured periodically and the number of cuts calculated for each period. The experimental results presented are displayed in a graph of flank wear as a function of the machining time determined from the number of cuts (Figure 7).

For this study, the criterion for tool failure was determined by the flank wear bandwidth. The tool rejection criterion used, was flank wear of 300µm. Under this criterion, the focused HPTSC modification techniques and flood cooling varied between 5500 and 7500 cuts before 300µm was reached. This corresponds to a machining time of approximately 3 to 5 minutes. On the other end of the scale, dry cutting removes material for up to 55000 cuts over a period of 27 min before the set failure limit. This shows remarkable improvements in cutting time and reduced wear. Consequently material removal increased significantly.

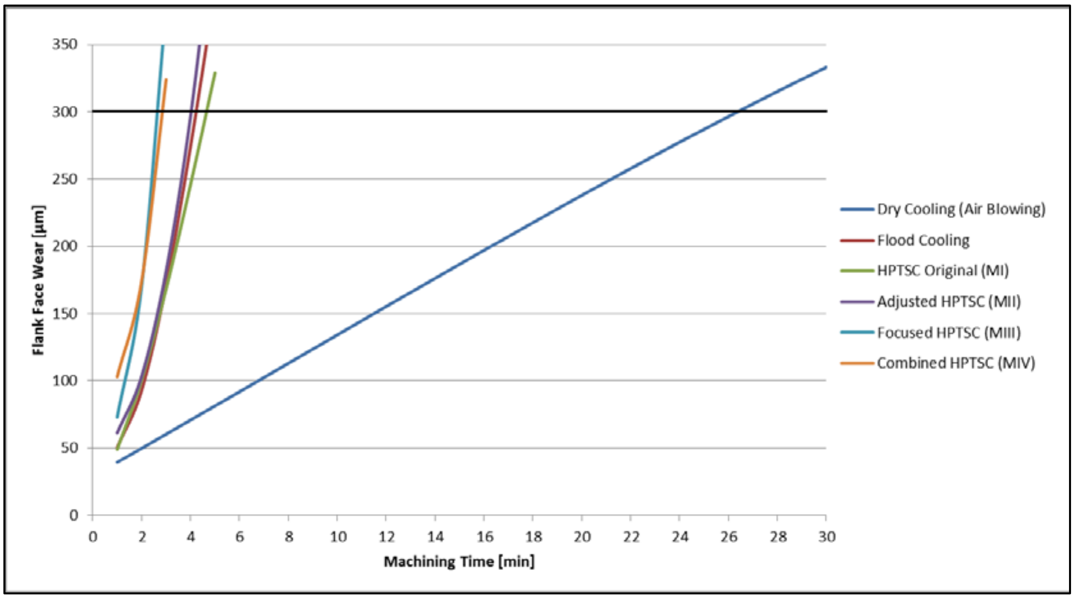

Figure 7: Flank face wear progression using different cooling strategies and techniques for milling Ti6Al4V

The performance of dry cutting under external compressed air cooling proved to be superior to all coolant jet design modifications used with focused high pressure cooling as well as flood cooling. This is attributed to the fact that the cutting parameters are for finishing procedures, under thin wall machining, and the heat generated aids the cutting process. Under roughing procedures the heat generated is considerably larger than that of finishing procedures.

In all cases the heat generated softens the material at the cutting zone, reducing the mechanical load on the insert. Simultaneously the thermal load on the tool surface also softens the tool material, accelerating tool wear mechanisms such as adhesion, diffusion and oxidation, apart from mechanical abrasion. The normal result is a larger softening effect on the tool than of the titanium work material causing accelerated tool wear at increasing cutting speeds. In this case, however, it appears that the cooling effect of the ambient compressed air stream was just enough to cool the tool material sufficiently for an extended life, while allowing the work material to heat up adequately to soften and contribute to an exceptional tool life.

In contrast to dry cutting, the focused high pressure cooling and flood cooling tend to cool the work material down and harden the surface being machined. This increases the mechanical load on the insert. When machining titanium with high feed rates, it is recognised that mechanical loading is the major mechanism of failure [2, 3, 10]. Therefore the hardening of the work material drastically decreases the tool life as a consequence of the increased mechanical load. This is evident in Figure 7 under all focused and flood cooling strategies.

6 CONCLUSION

The intention of the cooling modifications was to reduce the thermal load by aiding the removal of the heat generated at the cutting zone. Greater mechanical loading occurs from increased feed rates. The cutting speed, being the most influential parameter when tool life is concerned, increased the thermal load and caused surface hardening of the work material. This, together with the high mechanical load, rapidly decreased the tool life when the HPTSC modifications were applied. Thus, the outcomes show that the focused HPTSC did not improve upon flood cooling. Similar observations, however, were made for the flood cooling and to a lesser extent for HPTSC original (MI) too.

When there is an increase in tool life under the same cutting conditions, there is a reduction in costs. In conclusion, using the cutting parameters previously stated, dry cutting with an ambient external compressed air stream is most advantageous rendering the best tool life. The observation that flood cooling performs better than the focused HPTSC modifications, at 150m/min, provides evidence of its potential for heat removal. This leaves room for investigation into roughing or more severe cutting conditions/parameters.

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