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Complementary machining – A strategy for beneficial surface integrity modification

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Abstract. Although mechanical surface treatment adds a step to the manufacturing process chain to improve performance, it usually increases production costs and time. Hence, different hybrid processes have been developed including Complementary Machining as a novel form of machining that combines conventional cutting with a mechanical surface treatment that utilizes the same tooling to produce finished products. Typically, after conventional cutting the tool proceeds in the opposite direction with a known interference to deform the surface plastically. This investigation therefore assesses the viability of complementary machining to modify the surface integrity of Ti6Al4V by specifically establishing its effect on surface roughness, tool wear, and microhardness when utilizing three different cooling techniques i.e., dry, flood and MQL when utilizing a conventional coated carbide tool.

Keywords: complementary machining, dry machining, flood cooling, minimum quantity lubrication.

1. Introduction

One of the most widely used titanium alloys in a variety of industries, including aerospace [1], medical [2], and automotive [3], is titanium grade 5, usually referred to as Ti-6Al-4V. It's an alpha-beta alloy with two phases that is roughly 90% titanium, 6% aluminum, and 4% vanadium [4]. Its outstanding corrosion resistance, high strength-to-weight ratio, and strong biocompatibility make it ideal for a variety of uses [5]. It is perfect for applications where weight reduction and great performance are crucial because it provides an exceptional blend of high strength, low density, and superior corrosion resistance [6]. Because of its high strength and

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limited thermal conductivity, titanium Grade 5 can be difficult to machine and cause problems such tool wear, heat generation, and chip formation [6]. Machining titanium Grade 5 can lead to significant tool wear due to its high strength and abrasive nature. Tool wear mechanisms include abrasion, adhesion, and diffusion wear, which can reduce tool life and affect machining efficiency [7]. Titanium Grade 5 has low thermal conductivity, which results in poor heat dissipation during machining operations. This can lead to elevated temperatures at the cutting zone, increasing the risk of tool failure and workpiece deformation. It tends to produce long, continuous chips during machining, which can pose challenges for chip evacuation and cause issues such as chip recutting and tool jamming. Proper chip control strategies, such as the use of chip breakers and high-pressure coolant systems, are essential to mitigate these issues [8] [9].

The use of appropriate coolant and lubrication strategies, i.e., minimum quantity lubrication (MQL) has been found to have a positive influence on the surface integrity of titanium. MQL can help dissipate heat and improve chip evacuation during titanium Grade 5 machining [10]. The machining method known as Minimum Quantity Lubrication (MQL) has drawn a lot of interest lately because of its potential advantages in lowering environmental impact, extending tool life, and increasing machining efficiency [10].

One of the primary advantages of MQL is the significant reduction in fluid usage compared to traditional flood coolant methods [11]. Research [12] has shown that MQL can reduce fluid consumption by up to 95%, resulting in cost savings and environmental benefits due to reduced waste generation. MQL has been found to improve tool life by minimizing the heat generation and friction during machining processes. This can result in a decreased tool wear and extended tool life, leading to cost savings for manufacturers.

The complementary machining process involves the application of a conventional cutting tool in reverse essentially to plastically deform the surface typically immediately after a conventional machining operation [13]. The surface layer undergoes significant plastic deformation as a result of the reverse-machining direction of the process which may also result to grain refinement. Fig. 1 depicts the contact circumstances for complementary machining.

Limited literature exists as far as complementary machining is concerned. It is summarised as follows:

- Complementary machining typically increases the measured surface hardness (HV), even for perceived ductile materials [14]. It may lead to the formation of modified nanocrystalline surface layers that also exhibit a modified (usually higher) residual stress profile. These effects may significantly improve fatigue life when compared to the results after conventional machining only [14].
- An increasing interference depth causes the surface layer to deform more plastically and may finally cause temperature-driven material softening. High compressive residual stresses can be achieved via complementary machining [15].

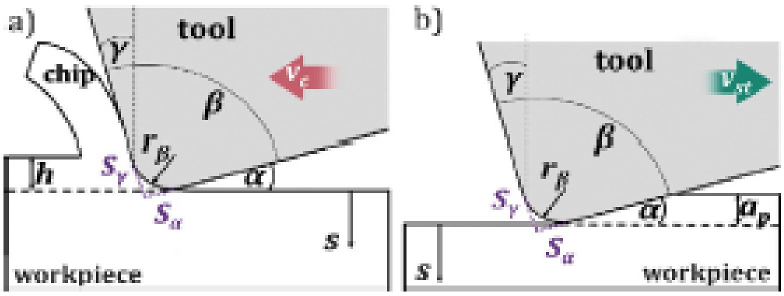

Fig. 1. Contact conditions for Complementary Machining:
a) conventional machining, and b) complementary machining [13].

- The plastic deformation associated with complementary machining may reduce the surface roughness and cause near surface grain refinement. The processing velocity has a significant effect on the resulting roughness [16].
- Complementary machining is more effective when utilizing an effective cooling and lubrication system. Hard coated tools typically outperform uncoated tools [17].

In summary, achieving and maintaining desirable surface integrity in titanium components requires careful consideration of various factors including tool wear, surface roughness, residual stresses, microstructure alterations, and surface defects. By employing appropriate machining techniques, tooling, process parameters, and surface treatments, manufacturers can ensure the optimal performance, reliability, and longevity of titanium components in critical applications. Ongoing research and advancements in machining technology and surface engineering continue to enhance our understanding and control of surface integrity in titanium alloys.

2. Experimental details

The scope of the experiment is to assess the viability of complementary machining to modify the surface integrity of titanium Ti6Al4V by specifically establishing its effect on surface roughness, tool wear, and microhardness when subjected to three machining environments i.e., dry, flood and MQL machining using a coated carbide tool. During the experimental work, MQL paraments, machining parameters and complementary machining parameters were kept constant and regards as independent, whilst tool wear (Tw), surface roughness (Ra), and microhardness (HV) are dependent variables. Table 1 shows the Input parameters and the machining environment.

The experimental matrix that was adopted for the main experiment is shown in Table 2. This matrix is based on the number of output parameters involved. The validation of the results was done through repeated measurements. Three measurements were taken for each output parameter, meaning three workpiece bars were used. Surface roughness (Ra), tool wear (Tw), and microhardness (HV) are the dependent variables.

Table 1. Input parameters and the machining environment

Machining Parameters	Machining Environment
V_c = 100 m/min, f_c = 0.16 mm/rev, ∂_{pc} = 100 µm	Minimum quantity lubrication, dry cutting, flood cooling
Complementary Machining Parameters	MQL Parameters
V_{st} = 10 m/min, f_{st} = 0.045 mm/rev, ∂_{pst} = 10-30 µm	M_{FR} = 70 ml/hr, N_D=30 mm, N_p = 4 bar, A_{FR} = 31 l/hr
Type of Tool	
ISCAR cutting inset, CNMG120408 (coated)	

Table 2. Experimental matrix for the main experiment.

Expt. No	Tool Wear (mm)	Surface Roughness (µm)	Microhardness (HV)
	T_w	R_a	HV
1	T--1	T--2	T--4
2	T--8	T--9	T--11
3	T--15	T--16	T--18
4	T--22	T--23	T--24

2.1. Material

For the investigations was Ti6Al4V was used. The chemical composition according to the supplier can be found in Table 3.

Table 3. Supplied chemical composition for titanium Ti6Al4V.

CP-Ti	Chemical Composition							
	Ti	Al	V	Fe	O	H	C	N
Ti6Al4V	Bal	6.1	3.95	0.16	0.15	0.003	0.02	0.01

2.2. Experimental setup

A Yunnan CY-L1660G high-speed gap bed lathe (Figure 2) was used for both the machining and complementary machining processes. The MQL system used during the experimental work, can also be seen in Fig. 2, which is fitted with three supply lines. However, only one supply line was utilised during the experimental work.

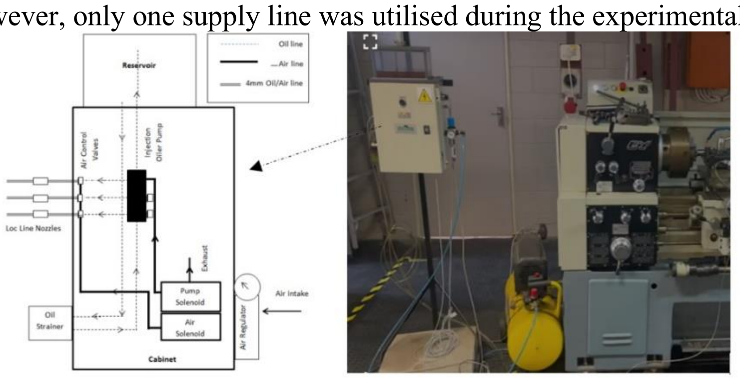

Fig. 2. Experimental setup

2.3. Output measurement

Based on the experimental design outline in section 3.2, various output parameters were evaluated during the experimental work. This section provides a description of each of these output parameters, the aim of measuring these output parameters, and the tools and devices used for the measurements.

2.3.1 Tool wear

For assessments of flank wear, the Tescan Vega 3 SEM (see Figure 3-10) was utilized. With a 20 kV resolution of up to 3.9 nm and the ability to be upgraded to 30 kV, the Tescan Vega 3 is a basic and adaptable analytical tungsten filament scanning electron microscope that enables the observation of sub-microscale sample microstructure.

Fig. 3. Tescan Vega 3 SEM.

2.3.2 Surface roughness

Two methods (i.e., manually using a handheld machine (see Fig. 5) and automatically machine (see Fig. 6) based measures) were used to measure surface roughness. After machining and complementary machining in each instance, three measurements were made at various points along the specimen's length. The surface roughness level tiers diagram in Fig. 4 serves as an illustration of this.

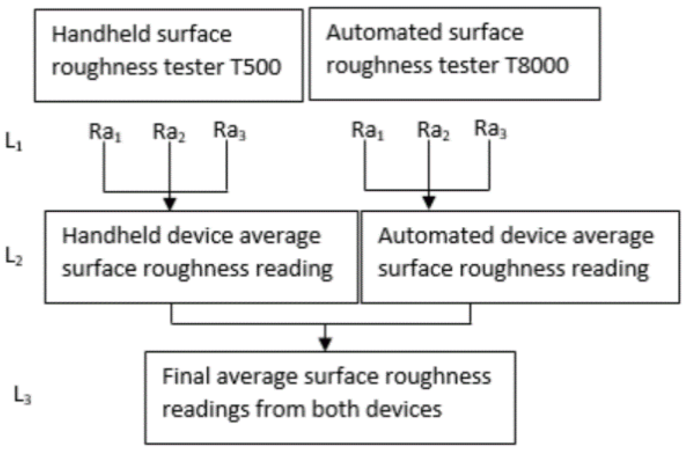

Fig. 4. Surface roughness measurement stages.

Fig. 5. Hand-held surface roughness test – Hommel T500.

Fig. 6. Automated surface roughness tester – Jenoptic Hommel Etamic T8000

2.3.3 Microhardness

A Vickers microhardness tester used to assess the specimens' microhardness is seen in Fig. 7. Depending on the indenter mounted on the indenter head, this machine can measure both Vickers and Knoop hardness. Eye observation is used to measure the indentation length.

Fig. 7. TIME HM-6 digital microhardness tester.

3. Results

3.1. Effect of conventional machining on surface roughness

The arithmetical mean roughness value (Ra) for the various machining environments is shown in Fig. 8. Dry cutting generally has the worst (highest) roughness. Flood cooling demonstrated improved surface roughness results, while MQL machining exhibited the best (lowest) surface roughness. All things considered, MQL assisted machining showed improvements of 29% over flood cooling and 35% over dry cutting. The findings imply that decreased adhesion and less built-up edge creation at the tool/workpiece interface are caused by the enhanced lubrication and cooling, which is linked to better surface roughness associated with MQL and flood cooling. The outcomes and the literature have good correlations. For example, Dhar et al. [18] found a direct correlation between increased flank wear and surface roughness.

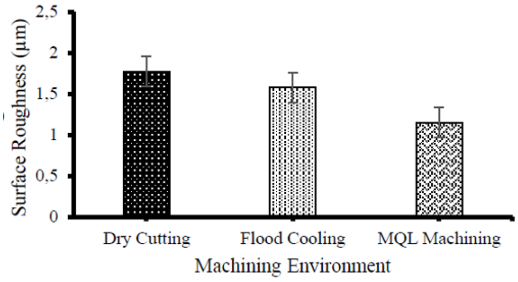

Fig. 8. Effects of cooling/lubrication technique on the surface roughness for a coated carbide tool.

3.2. Effect of complementary machining on surface roughness

The surface roughness results obtained after complementary machining are presented in Fig. 9. Overall, data indicate that in all cases the surface finish improved due to the complementary machining as compared to the conventionally machined surface. Increasing the interference depth to 20 and 30 µm caused an increase in surface roughness and largely negated the initial improvement demonstrated at 10 µm trending towards the surface roughness of the originally conventional machined surface roughness. The findings demonstrated a direct correlation between surface roughness and interference depth. Surface roughness often increases with increasing interference depth.

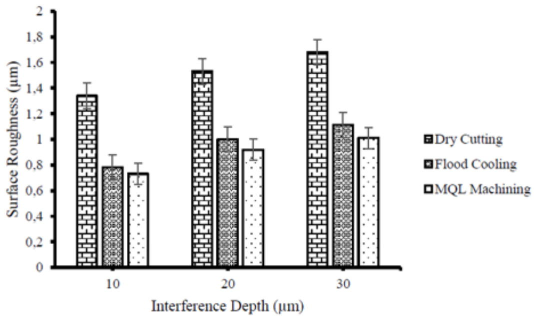

Fig. 9. Effect of interference depth on surface roughness for a coated carbide tool.

Fig. 10 present an evaluation of how significantly the originally machined surface finish is affected by the subsequent complementary machining. In essence it indicates how the originally machined surface finish changed when subjected to the complementary machining step. Data indicate that in all cases the surface finish improved due to complementary machining when compared to the original machined surface.

The best improvement was demonstrated when utilising MQL with a nearly 50% improvement demonstrated for 10 µm interference depth (see Figure 10). Complementary machining under dry cutting conditions displayed the lowest improvement of 24% with flood cooling in between at 35%. Increasing the interference depth of the complementary machining, the initial improvement is significantly reduced with the surface roughness trending towards the originally machined surface roughness.

Improvement in the surface finish of the originally machined specimen due to the subsequent complementary machining is due to the localised plastic deformation that the complementary machining imparts on the original machined surface finish. The peaks and valleys of the original machined surface finish are flattened extensively, improving surface finish. This effect is reduced with an increased interference depth due to the increased tool load that leads to higher friction and subsequently to wear.

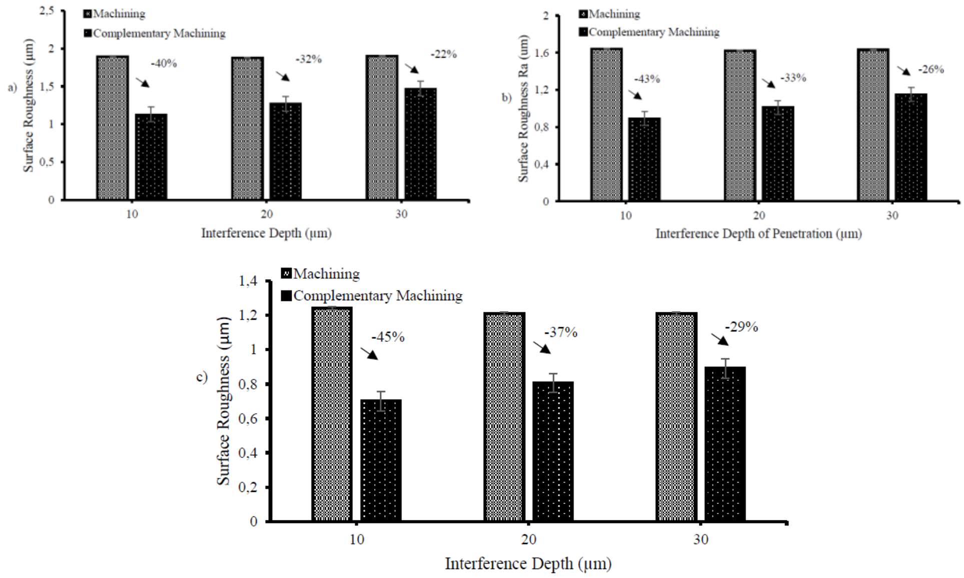

Fig. 10. Surface roughness that results from machining and complementary machining when employing a coated carbide tool under the following circumstances: a) dry cutting; b) flood cooling; and c) MQL machining.

3.3. Effect of conventional machining on tool wear

The variation of tool flank wear for the three cooling/lubrication techniques employed during conventional machining are presented in Fig 11. The results clearly indicate that, as expected, conventional machining produced significant flank wear on the cutting edge. Once again, the least wear was produced when machining with MQL and the most during dry cutting. Due to the fact that MQL machining reduced cutting temperatures, abrasion wear was lessened while maintaining tool hardness and the temperature-sensitive adhesion and diffusion forms of wear.

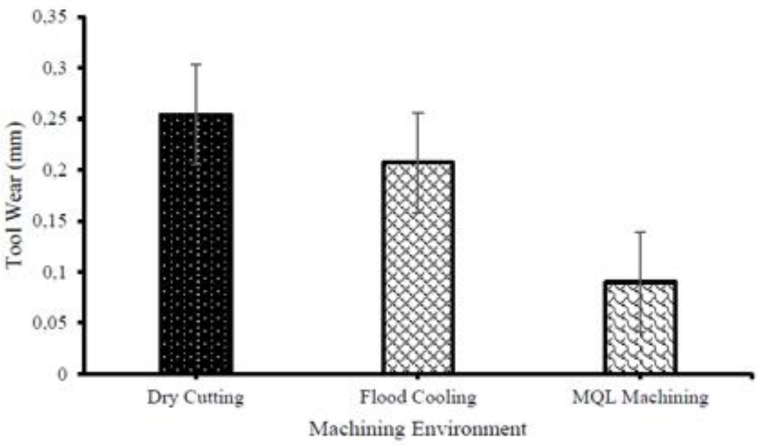

Fig. 11. Effects of cooling/lubrication technique on the flank wear for a coated carbide tool

Fig. 12 displays representative views of the flank surface of the cutting tools for each of the three cooling strategies. Upon closer inspection, the tool's flank face had significant abrasions caused by the chip's back surface. On the insert, there are also a few indications of adhesive wear. There was some micro chipping and plastic deformation during the dry and flood cooling processes. Some of the cutting tools displayed severe wear on the flank face in the form of notches and grooves from machining under dry and flood cooling conditions.

The primary reasons of the notch wear on the main cutting edge are chemical wear and oxidation when the thermo-mechanical stress gradient is also high. An abrasive wear mechanism is involved because the interaction between the auxiliary cutting edge, and the uncut ridges of the work surface is the main cause of the notch wear. MQL's efficient temperature control nearly stopped the main cutting edge's notch and groove wear from growing. It has also made it possible to lessen the wear on the auxiliary notch. Additionally, machining under MQL machining circumstances revealed a decreased crater, average auxiliary flank wear, and average flank wear. Da Silva et al. [19] and Pretorius et al. [20] reported similar outcomes.

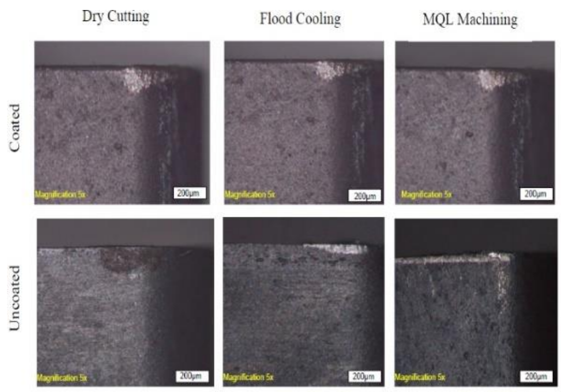

Fig. 11. Comparison of tool wear on the flank side of the cutting inserts.

3.4. Effect of complementary machining on tool wear

The variation of tool wear for the three cooling/lubrication techniques employed during complementary machining are presented in Fig. 14. In general, the tool wear experienced during complementary machining is significantly less than experienced during conventional machining except for the dry complementary machining which was more. The flank wear demonstrated during flood and MQL complementary machining was low when compared with conventional machining. It also did not significantly increase due to an increased interference depth. Dry complementary machining however displayed significant tool wear in excess of the wear experienced during conventional machining and did increase significantly with interference depth. Similar results were found by Wang et al. [21] and Abbas et al. [22].

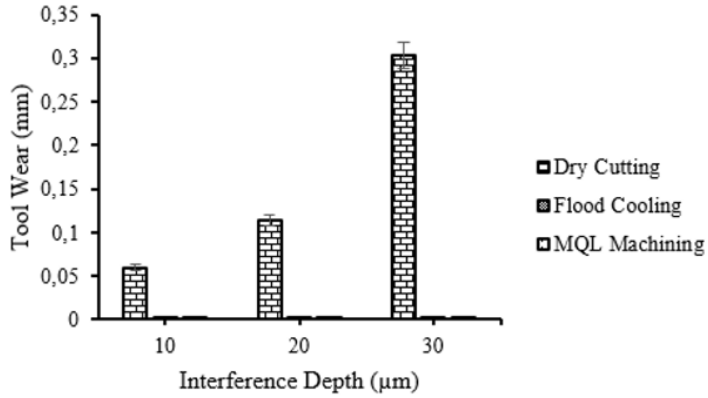

Fig. 14. Effects of complementary machining on the flank wear for a) coated carbide tool and b) uncoated carbide tool.

Since Ti6Al4V is a hard-to-cut material with high elasticity and low thermal conductivity, the initial VB values severely increase the thermal mechanical loading on the wear lands. This, in turn, accelerates the diffusion of titanium and the tool-chip interface, that caused the formation of build-up edges (BUEs), as seen in Fig 15. The flank face and nose radius showed the most wear on the cutting instruments.

In dry cutting conditions, a sizable abrasive wear land is seen along the cutting edge for an interference depth of 30 µm. Small edge chipping or plastic deformation from increased friction brought on by wear producing thermal stress at the edge signal the beginning of tool failure as wear progresses. The cutting edge and flank land exhibit BUEs as a result of adhesion between the materials both the tool and workpiece. This could potentially accelerate abrasion and friction between the tool and the workpiece, increasing wear. When using MQL machining and flood cooling, very little wear was seen. The lack of coolant or lubrication during the tool's continuous contact with the workpiece may be the cause of the flank wear that was noticed following dry cutting. Dhar et al. [416] showed similar progressive wear on the flank land for the coated tool in titanium cutting.

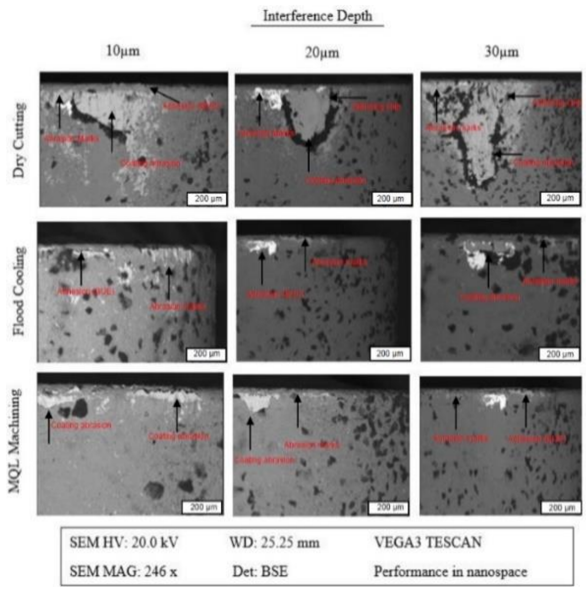

Fig. 15. Wear land and mechanism of coated carbide tool after complementary machining.

3.5. Effect of conventional machining on microhardness

A region closer to the centre of the specimen was used to measure the bulk material's hardness, and the results showed that it was 354 HV. The hardness depth profile achieved for each of the three cooling/lubrication techniques is displayed in Fig. 16.

The curves show a cascade shape with greater values of hardness on the workpiece's surface, as would be predicted. The hardness then decreases to eventually attain the bulk material hardness. This is because the material underwent significant plastic deformation during the machining process. This strain hardening is highest at the surface, subsequently decreasing in a similar way as obtained by Khan [23]. Dry cutting displayed the largest hardness increase relative to the bulk material of approximately 4.5%. This was followed by MQL-assisted cutting at approximately 3% and lastly flood cooling at 2%. In all cases the hardening extended to approximately 150 μm.

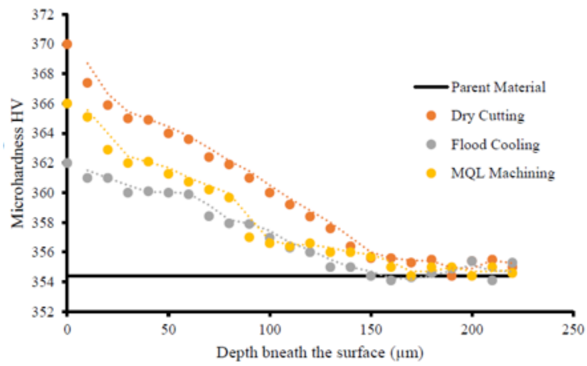

Fig. 16. Effect of machining conditions on microhardness using a) coated carbide tool

3.6. Effect of complementary machining on surface and near surface hardness

Fig. 17 present the effect that the interference depth (10, 20, and 30 µm) on the evolution of microhardness relative to bulk material hardness. Complementary machining typically follows a conventional machining pass that produces a near surface hardness profile as described in the previous paragraph. The effect of the conventional machining is subsequently superimposed onto this profile. The results indicate that in all cases the resultant increase in near surface hardness due to the conventional machining is further increased by the complementary machining.

An increase in interference depth during complementary machining inevitably produced a resultant increase in the surface hardness, demonstrated for all three cooling/lubrication environments. The highest microhardness values were obtained at an interference depth of 30 µm and the lowest at 10 µm. This is due to the increased localised plastic deformation that a higher interference depth produces during the complementary machining process.

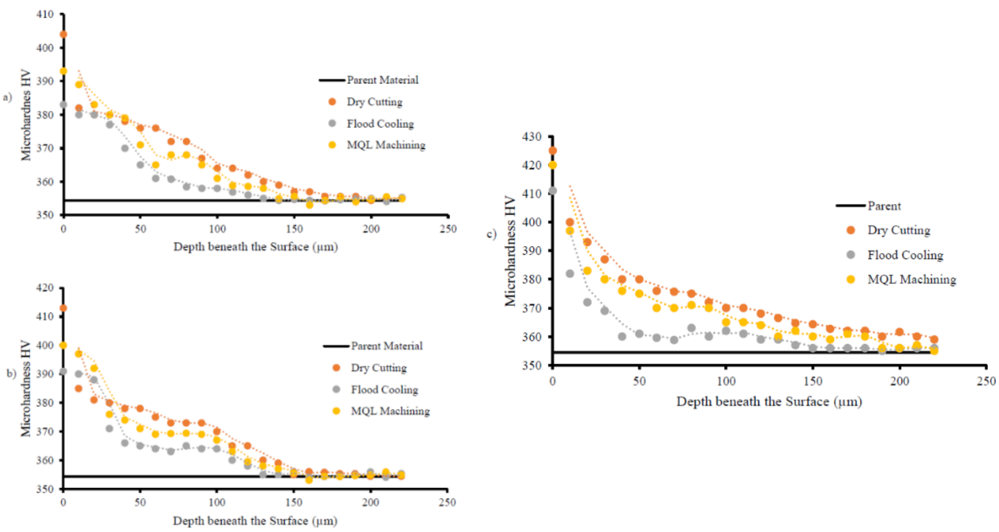

Fig. 17. Microhardness depth profiles after complementary machining using a coated carbide tool, at, interference depths of a) 10 µm, b) 20 µm and c) 30 µm

Fig. 18 present the resulting microhardness after conventional machining and after complementary machining. It is worth noting that there was a significant improvement in the surface hardness after complementary machining as compared to the resultant surface after conventional machining only, for all three cooling/lubricating techniques.

During complementary machining, it can be noted that the highest microhardness values were obtained with an interference depth of 30 µm for all three machining environments and tool types (coated and uncoated). Based on the results shown in Figure 17, it is worth noting that complementary machining increases the surface hardness significantly relative to the parent material and the surface hardness values obtained after conventional machining. An interference depth of 30 µm yielded the highest microhardness values.

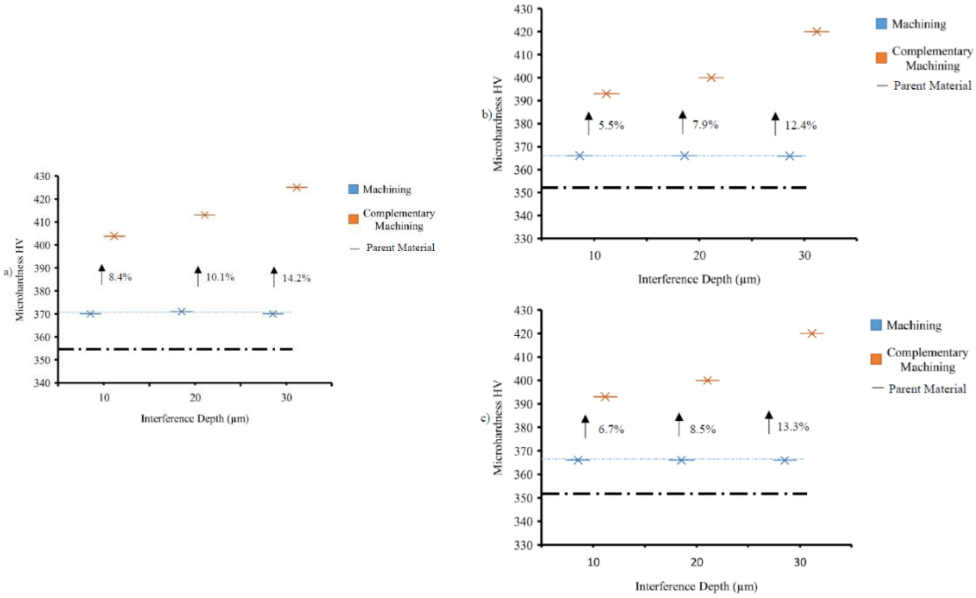

Fig. 18. Resulting surface microhardness after conventional machining and subsequent complementary: a) dry cutting, b) flood cooling and c) MQL when using a coated carbide tool.

4. Conclusion

This research work was proposed to identify and evaluate a potential sustainable mechanical surface modification technique to improve the mechanical performance of selected titanium alloy parts.

The viability of complementary machining to modify the surface integrity of Ti6Al4V has been investigated. It has been clearly demonstrated that complementary machining may be employed to modify and/or improve selected mechanical properties of the workpiece. The surface finish may be improved along with an increase in hardness (surface) by utilizing conventional cutting tools without subjecting them to significant increased wear rates.

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