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ORIGINAL ARTICLE

Surface integrity and tool life when turning of Ti-6Al-4V with coolant applied by different methods

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Abstract The main focus of this study is to investigate the behaviour of cemented carbide tools and the surface integrity obtained when turning Ti-6Al-4V alloy. Machining trials were carried out with emulsion cutting fluid applied under conventional and high-pressure supplies and also in an argon-enriched environment. Tool life, cutting force, surface roughness, micrograph and microhardness beneath machined surface were evaluated for better understanding the relationship between the fluid environment and the surface integrity of the machined workpiece. Machining with high-pressure coolant supply generated the best tool life results, while enriched argon showed lower tool life because of the lower conductivity and poor lubrication characteristics of argon gas that lead to heat to be more concentrated at the cutting area, thus weakening the strength of the cutting tool and accelerating tool wear. No plastic deformation was observed on the machined surfaces under the conditions investigated. However, there was evidence of surface hardening after machining with conventional and in an argon-enriched environment due to the poor cooling function of argon. Surface hardening was minimal after machining with high-pressure coolant supplies.

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Keywords Surface integrity · Ti-6Al-4V · High-pressure coolant · Argon-enriched environment

1 Introduction

Surface integrity analyses are employed to identify the surface characteristics of machined components. They consider aspects of the surface like form, waviness, lay, roughness and also subsurface characteristics like residual stress, granular plastic flow orientation and defects (porosity, microcracks, tears, laps, etc.).

The seizure effect during machining is a cyclic process and can be divided into four steps [1]: elastic and plastic deformation, rupture and finally the movement of the removed material onto the tool rake face. Machined surfaces produced by conventional processes (turning, milling, drilling, reaming, etc.) have a tendency to develop compressive residual stress at depth above 50 μm from surface. At the first analysis, it can be positive, because the compressive status tends to hinder propagation of the possible microcracks generated by the machining process or pre-existing in the bulk material. Unfortunately, tensile stress occurs not less frequently as reported by Arunachalam et al. [2, 3] the existence of compressive or tensile when machining nickel-based materials (Inconel 718). According to them, this surface status was hardly dependent on the cutting parameters, tool geometry, tool material and cutting fluid conditions. For example, in dry cutting, the residual stresses were always tensile from all depths beneath the machined surface. On the contrary, when turning using cutting fluids at the same conditions, compressive stress were recorded up to 15 μm beneath the machined surface, and below this value, the residual stress becomes tensile.

Frequently when machining hardened steels, a thin hardened layer called white layer is produced. It is attributed to high tensile stress level, generated at high cutting speeds in addition to the use of water-based cutting fluids, like emulsion, semi-synthetic and synthetic [4–8]. These cutting fluids have high cooling ability, and therefore, cooling occurs faster which may lead to microcrack generation. This can drastically reduce the fatigue life of the machined component. On the other hand, fatigue life is highly influenced by surface parameters, such as form, waviness and roughness. It is well known that an increase in the surface roughness parameters decreases the fatigue life of the machined components. Therefore, control of the surface integrity of the machined components is necessary to maintain the fatigue life of the machined components [9, 10].

Titanium alloys are largely used for aerospace applications, due to their superior properties such as lightweight, superior mechanical properties at high temperatures and excellent corrosion resistance. Generally, components made from this difficult-to-cut alloy usually require strict adherence to surface integrity control in order to ensure the reliability of the component. Surface integrity analyses when dry turning Ti-6Al-4V and Ti-6Al-2Sn-4Zn-6Mo with uncoated cemented carbide tools encountered a thin layer of disturbed or plastically deformed layer immediately underneath the machined surface [6, 7, 11]. These studies showed that machining with nearly worn or worn tool led to the generation of irregular surface, consisting of tearing and plastically deformed surface due to the high chip-tool interface temperature when turning titanium alloys without coolant.

Titanium alloys are normally machined with cutting fluids, with high cooling ability such as water-based emulsions, which offer better heat exchange performance, hence minimizing the temperature at the cutting zone. Other cutting fluids employed for machining titanium alloys include semi-synthetic and synthetic fluids applied under conventional or at high-pressure coolant supply. In an attempt to improve tool life, gaseous environments such as enriched argon and minimum quantity lubrication (MQL) have been evaluated. Brinksmeier et al. [12] reported that the MQL provided considerably improvement in the machinability of aerospace alloys compared to conventional coolant flow. Dry air, oxygen, nitrogen, CO_2 and organic compounds such as tetrachloromethane (CCl4) and ethanol vapour (C_2H_5OH) are also expected to improve the machinability of titanium alloys by improving the characteristics of the tribological processes present at the tool-workpiece interface and at the same time eliminate environmental damages as well as minimizing some serious problems regarding the health and safety of operators [13–15].

Specially designed tribosystems were developed to investigate the cooling and lubrication capabilities of cutting fluids, CO_2, Ar, He, Ne, N_2, and polymers, among others, under extreme contact conditions [16, 17]. Machining tests were also carried out in order to establish relationships between the results. In most cases, it was clear that neither the liquid nor the gas nitrogen was able to decrease friction coefficient of Ti6Al4V against cemented carbide cutting tools. Applying liquid nitrogen (−195.8 °C) decreases the amount of heat transmitted to the pin, and this can reduce the high temperature at the interface and consequently tend to decrease the adhesion phenomenon [16, 18–20]. Boswell and Islam [21] in their recent work in machining of Ti6Al4V alloy with cemented carbide tools evaluated the performance of various cooling environments (cold air, MQL and cryogenic cooling method) in the surface finishing and cutting forces. They employed cutting speeds varying from 120 to 180 m/min and feed rate in range of 0.11–0.22 mm/rev and observed that the combination of cold air, medium cutting speed and the lowest feed rate provided the best surface finish. The lowest cutting forces were recorded after machining with cryogenic cooling at speed of 150 m/min and $f = 0.11$ mm/rev.

Therefore, this study has the main objective to evaluate the performance of the uncoated cemented carbide tools when turning the Ti-6Al-4V alloy with different cutting fluids and application methods as follows: emulsion applied at conventional and high-pressure coolant supply (11 and 20.1 MPa) and gaseous, with enriched argon. Tool life, cutting force, surface roughness, micrograph and microhardness beneath the machined surface were evaluated for better understanding the relationship between the fluid environment and the surface integrity of the machined workpiece.

2 Experimental procedures

The workpiece was Ti-6Al-4V bar with a length of 300 mm and a diameter of 300 mm. Table 1 shows the nominal chemical composition, and Table 2 shows some physical and mechanical properties of the alloy.

The machining trials were carried out on a CNC lathe, with an 11-kW motor drive, which generate a maximum torque of 1411 Nm. The spindle rotational speed ranges from 18 to 1800 rpm.

The tool material was cemented carbide with ISO designation SNMG 120412-M1.

The cutting fluid was a high lubricity emulsion diluted with water to 6% concentration that was applied by flooding

Table 1 Nominal chemical composition of Ti-6Al-4V alloy (wt%)

	Chemical composition (wt%)								
	Al	V	Fe	O	C	H	N	Y	Ti
Min.	5.50	3.50	0.30	0.14	0.08	0.01	0.03	50 ppm	Balance
Max.	6.75	4.50		0.23					

Table 2 Physical properties of Ti-6Al-4V alloy

Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)	Density (g cm^{-3})	Melting point (°C)	Measured hardness (99% CI)[a] HV_{100}	Thermal conductivity at 20 °C (W m^{-1} K^{-1})
900 to 1160	830	8	4.50	1650	Min. = 292 Max. = 346	6.6

[a] Confidence interval (CI) of 99%, represented by the minimum (Min.) and maximum (Max.) values

(conventional cooling method) the cutting interface at a pressure of 0.3 MPa and average flow rate of 2.7 L min^{-1}. The high-pressure pumping coolant system was a Chipblaster, model CV26-3000 with a power of 30 HP and flow rate of 93.6 l/min, that delivers a maximum pressure of 21 MPa. Argon was directed at the chip-tool interface through a hose connected to a valve and supplied at a constant flow rate of 12 L min^{-1} and at pressure of 0.25 MPa. Thermal conductivity of argon at a temperature of 300 K (27 °C) is 0.0177 Wm^{-1} K^{-1}. High coolant pressures of 11 and 20.3 MPa were employed for the machining trials, which resulted in flow rate values of 18.5 and 24 L min^{-1}, respectively. These pressure values were selected based on the maximum available pressure in the pumping system (21 MPa). Eleven megapascals is practically the middle point between 0.3 MPa (for conventional coolant supply) and 20.3 MPa. The distance from the nozzle to the cutting zone was kept at 100 mm for both conventional cooling method and argon gas.

Figure 1 schematically shows the possible directions for cutting fluid application. In this work, the overhead (conventional) and the chip-tool positions were selected for the conventional method and high coolant pressure supplies, respectively. The argon gas was also delivered in the overhead (conventional) position.

The cutting conditions employed for the turning trials are cutting speeds (v_c) = 100, 110, 120 and 130 m/min; feed rate (f) = 0.15 mm/rev; and depth of cut (a_p) = 0.5 mm. Values of these parameters were selected for finish turning of Ti-6Al-4V alloy based on those usually employed in the aerospace

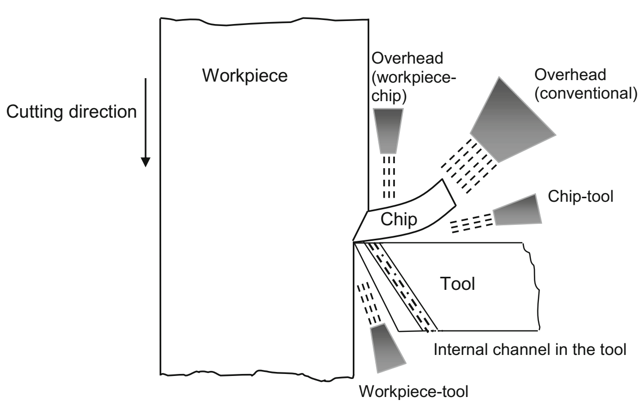


Fig. 1 A schematic illustration of main directions of application of cutting fluids [8]

industry. Fifteen-minute tool life was chosen as the benchmark for establishing acceptable cutting conditions during the turning trials. The trials with uncoated cemented carbide tools were aimed at establishing high-speed conditions that consistently achieved 15-min tool life under conventional coolant supply, based on the stipulated tool wear rejection criterion: average flank wear, $VB_B \geq 0.3$ mm. The highest speed conditions achieved were used as the baseline conditions for machining with various grades of advanced tools such as polycrystalline diamond (PCD) and CBN/PCBN tool materials also tested in finish turning of Ti-6Al-4V alloy, which the results were published elsewhere [8]. Four levels of cutting speed values were selected based on the fact that at least three data points are needed to establish a tendency line and also to better assess the performance of high-pressure coolant supplies.

The tool rejection criteria for finishing operations were employed in this work. These values were considered in relation to ISO Standard 3685 [22] for tool life testing. Machining trials were stopped when one/more of the following tool rejection criteria were exceeded: average flank wear, $VB_B = 0.3$ mm; maximum flank wear, $VB_{max} = 0.4$ mm; nose wear, $V_C = 0.4$ mm or notch wear, $V_N = 0.6$ mm; or surface roughness value (R_a) ≥1.6 μm (centre line average).

The output parameters were tool life, cutting force, surface roughness, micrograph and microhardness beneath machined surface.

Tool wear measurements were carried out at various machining intervals using a travelling microscope connected to a digital read out device at a magnification of ×25 fitted with digital micrometre XY table with resolution of 0.001 mm. The insert is removed from the tool holder and mounted on a small vice placed on the microscope prior to measurement.

The component forces were measured at the early stages of machining up to 1 min, when the inserts have not suffered significant wear, with a piezoelectric Kistler dynamometer (model 9441B), connected to a charge amplifier. The system was managed by the LabVIEW software with a sampling rate of 50 Hz, and then the arithmetic mean of the values was calculated.

Surface roughness measurements were taken after each complete pass with the aid of a portable stylus-type instrument (Surtronic 10) with a cutoff length set at 0.8 mm. The average of three readings at different locations on the workpiece bar represents the surface roughness value of the machined surface.

With regard to micrograph and microhardness, samples of the workpiece material were cut from the machined surface at the end of tool life test with a hacksaw. The sample was then mounted in bakelite, grounded and polished ready for microhardness analyses. The hardness alterations on the machined surfaces were monitored with a microhardness testing machine, Mitutoyo (MVK-VL), at ×55 magnification and with an applied load of 0.98 N. Recorded values were treated statistically and a confidence interval (CI) of 99%, represented by the minimum (LW_limit) and maximum (UP_limit) values, was used as a reference. The samples were etched to reveal the microstructure, which is captured using an optical microscope and at higher magnification using a scanning electron microscope (SEM). The microstructure of machined surfaces was examined and photographed with metallurgical optical microscope with an attached camera.

3 Results and discussions

Table 3 shows tool life and tool wear recorded after machining under the four cutting environments evaluated.

Figure 2 shows plots of flank wear rate against cutting speed in various environments. It can be seen that flank wear rate increased with prolong machining in all the cutting environments tested. Results shows that increasing the cutting speed gave substantial increase in the flank wear rate. Figure 2 also shows that lower flank wear rate values were recorded when machining with high-pressure coolant supplies. At the initial stages of cutting, flank wear was generally uniform when machining with high coolant pressures. Machining in an argon-enriched environment gave higher wear rates, while in conventional coolant supply, the wear rate was intermediate. Also, when machining under conventional coolant supply, the flank wear rate gradually increases with cutting speed up to 120 m/min, and from this point, it rapidly increases at a cutting speed of 130 m/min (0.05 mm/min), unlike uniform and gradual flank wear rate recorded when machining with higher pressure coolant supplies, especially at 11 MPa (0.025 mm/min) in the same range of speeds tested.

Cutting speed is associated with plastic flow rate of the work material and consequently heat generation at the chip-tool and tool-workpiece interfaces. Thus, higher cutting speeds result to higher temperatures, hence accelerating thermally dependent wear mechanisms like plastic deformation at the cutting edge, shearing on the rake face, diffusion and oxidation processes [1, 23–25]. Ezugwu et al. [26] reported that higher nose wear rate and, consequently, lower tool life achieved in an argon-enriched environment compared to conventional coolant supply are due to the poor thermal conductivity of argon gas as well as its poor lubrication characteristics. These tend to concentrate more heat at the cutting area, thus weakening the strength of the cutting tools and accelerating the tool wear. The poor lubricant characteristics of argon were also responsible for an increase in friction at the cutting interfaces during machining and an increase in cutting forces required for efficient shearing of the workpiece [26].

When turning at cutting speeds between 100 and 130 m/min, the conventional overhead coolant acts mainly as a coolant. The lubrication effect is compromised due to the direction of the application, and its access to the chip-tool and tool-workpiece interfaces tends to be compromised. In addition, the boiling temperatures of conventional delivered cutting fluids are about 350 °C [27], thus, rendering the cutting fluids ineffective as lubricants at higher speed conditions.

Table 3 Tool life and tool wear obtained after machining at the cutting conditions evaluated

Stage	Cutting speed (m/min)	Cutting time (min)	Maximum flank wear, VB_{max} (mm)
Conventional coolant supply	100	27.4	0.352
	110	18.2	0.411
	120	13.0	0.349
	130	8.2	0.428
High pressure (11 MPa)	110	29.7	0.305
	120	23.2	0.303
	130	18.9	0.296
High pressure (20.3 MPa)	110	53.7	0.351
	120	24.2	0.336
	130	15.1	0.389
Argon-enriched	100	13.7	0.319
	110	9.4	0.453
	120	6.3	0.450
	130	4.9	0.444

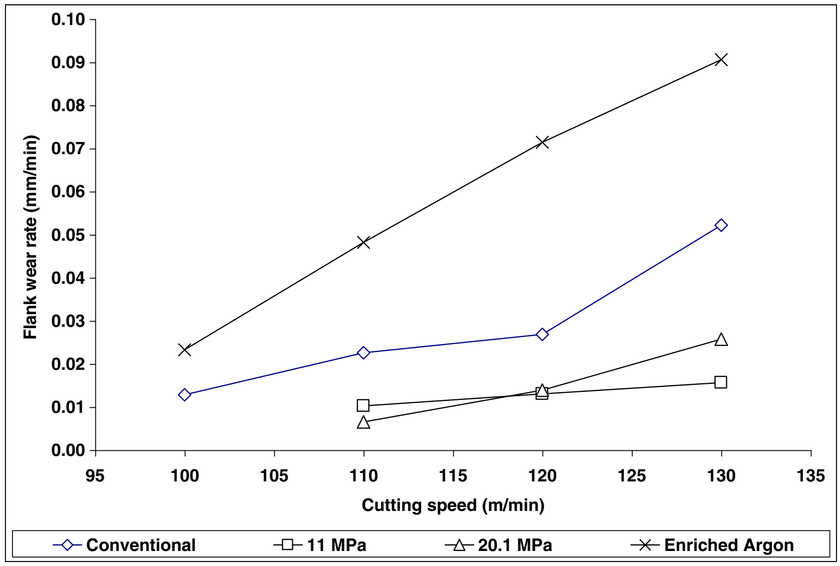


Fig. 2 Flank wear rate at various cutting speed and environments

Mazurkiewicz et al. [28] reported that coolant jet at high pressure exerts sufficient force, which ensures easy access of the fluid to cutting interfaces, resulting in a better chip flow. Trent [23, 24] demonstrated the existence of two distinct zones at the chip-tool interface when machining: seizure and sticking zones. According to him, in the seizure zone, there is complete contact with no access for the fluid. On the contrary, in the sticking zone, there are intermittent contacts due to some asperities; thus, the cutting fluid can access this area. It is therefore evident that the cutting fluid at high pressure can access efficiently the sticking zone resulting in friction reduction and consequently reduced chip-tool interface temperature.

Machado and Wallbank [29], when turning Ti-6Al-4V with cemented carbide tools with various coolant delivery techniques, reported improvement in tool life by over 300% when machining under high-pressure coolant supply technique compared to conventional coolant supply technique. Ezugwu et al. [30] and Da Silva et al. [31] also reported over 20-fold improvement in tool life when machining Ti-6Al-4V with PCD tools at the highest pressure coolant supply of 20.1 MPa relative to the conventional coolant technique. In addition, chip breakability was significantly improved.

Figures 3 and 4 respectively show variation of cutting force and surface roughness (R_a) with cutting speed in various cutting environments evaluated. Determination of cutting forces is indispensable to design the machine tools since they can prevent deformation of machine components as well as maintain the desired dimensional and geometric tolerances of machined components [32].

Figure 3 shows that lower cutting forces were encountered when machining with high-pressure coolant supply at

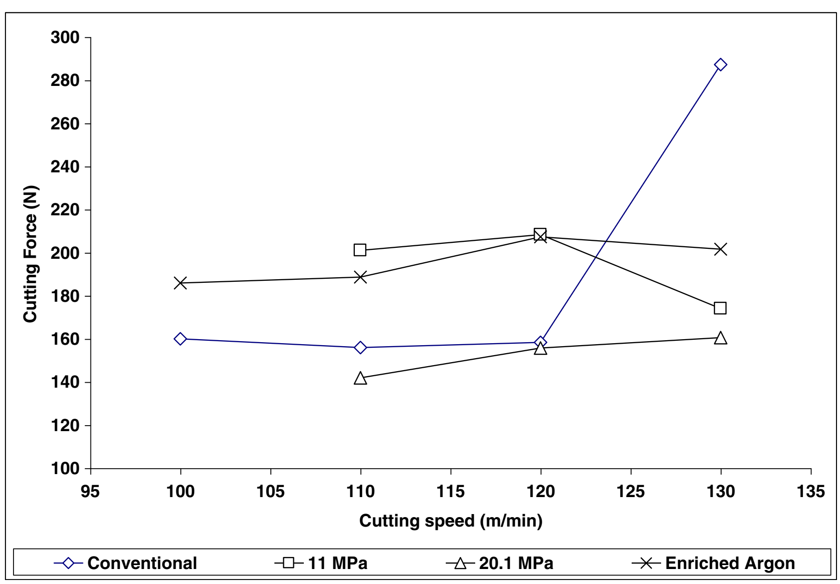
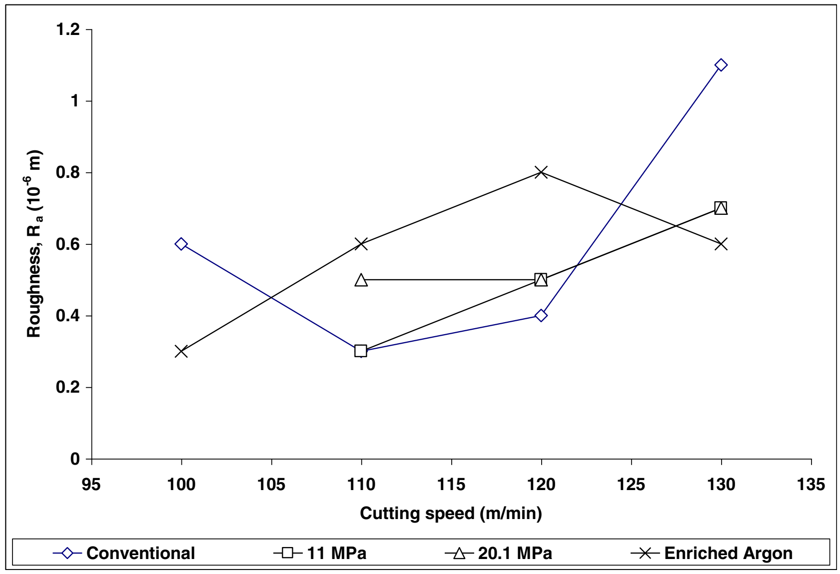


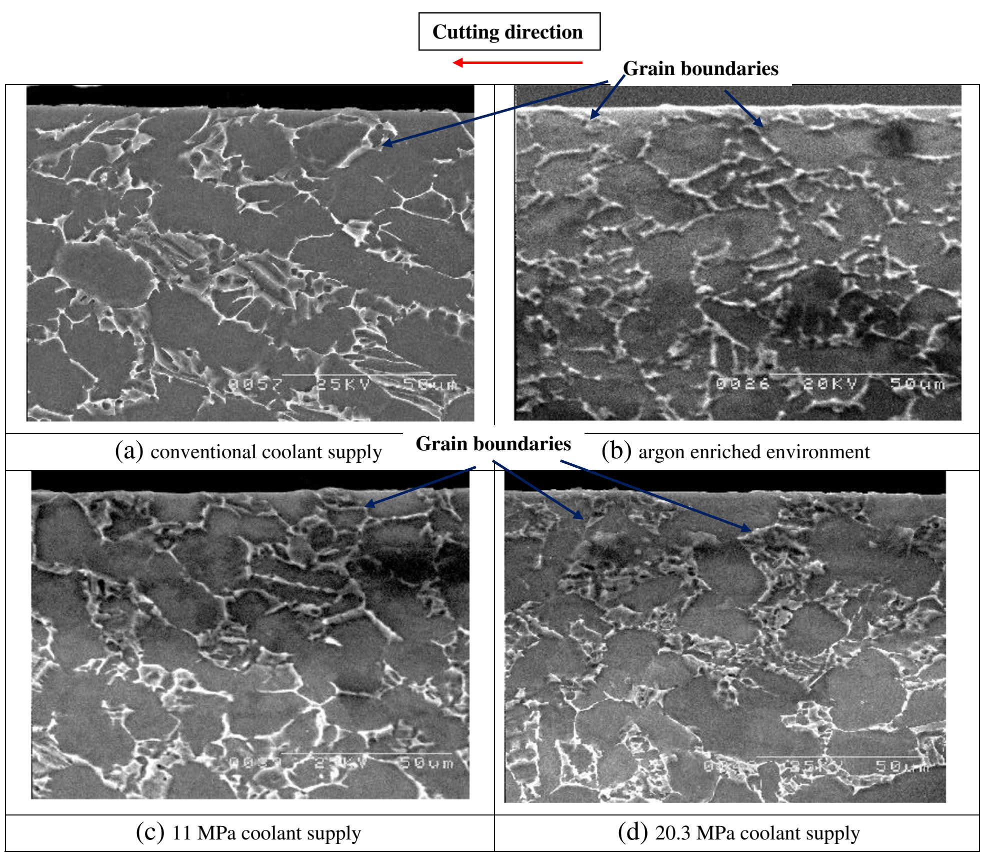
Fig. 3 Cutting force measured at various cutting speeds and environments

Fig. 4 Surface roughness values after machining at various cutting speeds and cutting environments



20.1 MPa. At a cutting speed of 100 m/min, machining with conventional coolant supply gave lower cutting force than with argon-enriched environment. This can be attributed to better lubrication ability of the oil-based fluid relative to argon. At cutting speeds of 110 and 120 m/min, the high-pressure condition of 11 MPa provided higher cutting forces, but at 130 m/min, the high-speed jet was efficient in reducing friction and consequently the cutting forces. The least cutting forces were recorded when machining with 20.1 MPa coolant supply pressure. This may be attributed to improved coolant access to the cutting interfaces as well as improved chip breakability. Ezugwu et al. [33] reported that, besides the effective cooling at higher speeds, the coolant under high pressure also acts as a chip-breaker. This also may explain the

Fig. 5 Microstructures beneath machined surface of the Ti6Al4V alloy after machining with uncoated carbide tools at v_c = 120 m/min, f = 0.15 mm/rev, doc = 0.5 mm and under various cooling environments: **a** conventional coolant supply, **b** argon-enriched environment, **c** 11 MPa coolant supply and **d** 20.3 MPa coolant supply



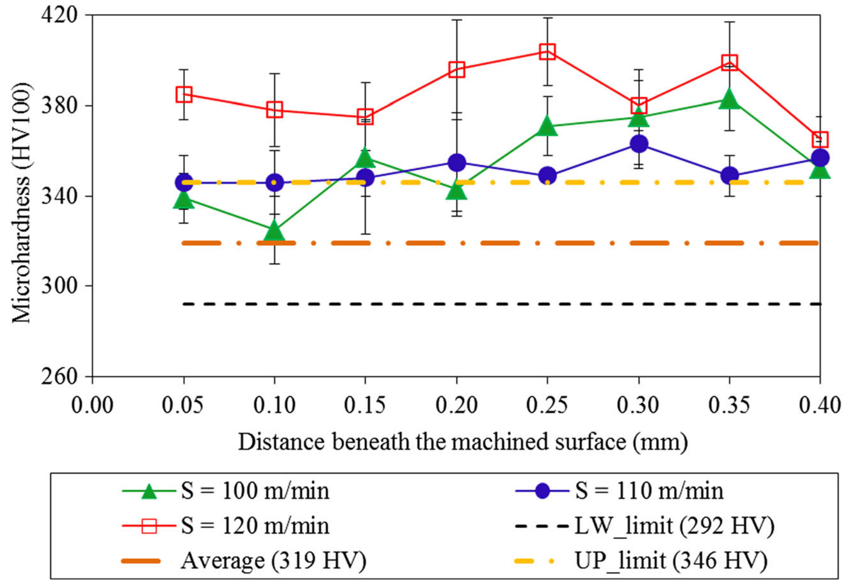


Fig. 6 Microhardness measured beneath the machined surface with conventional coolant supply

reason of the highest cutting force recorded after machining with conventional coolant supply at cutting speed in excess of 120 m/min (Fig. 3).

Figure 4 shows the surface roughness data from machined surfaces when the tools reached their useful life. As illustrated in Table 3, different maximum flank wear values may be difficult to adequately analyse. Generally, the plots show that higher R_a values were recorded with increasing cutting speed. Figure 4 also shows that surface roughness values recorded at all the cutting conditions evaluated in this study were all below the stipulated rejection criterion of 1.6 μm. In general, the values increased with cutting speed and the highest surface roughness values were recorded during machining with the argon-enriched environment. Similar results were also obtained by Da Silva [8] after machining Ti-6Al-4V with uncoated and coated carbide tools in the presence of argon and under conventional coolant supply. This author reported that the poor thermal conductivity of argon can only prevent combustion taking place during machining and most of the heat generated tends to concentrate at the cutting interface. This tends to further accelerate tool wear during machining and, consequently, causes deterioration of the surface finish.

Subpanels a–d of Fig. 5 are micrographs of the microstructure of the machined surfaces after machining with conventional coolant supply, argon-enriched environment, 11 MPa and 20.3 coolant supplies, respectively. The well-defined

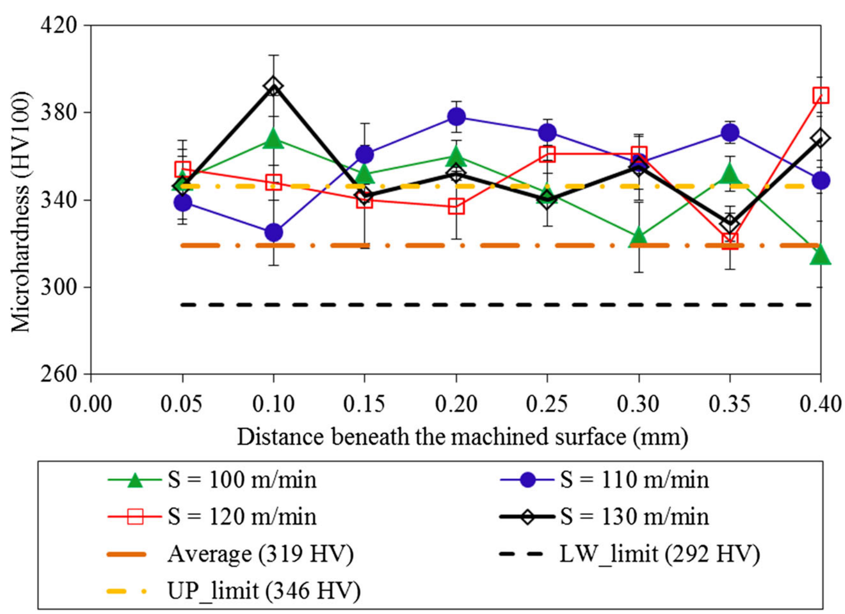
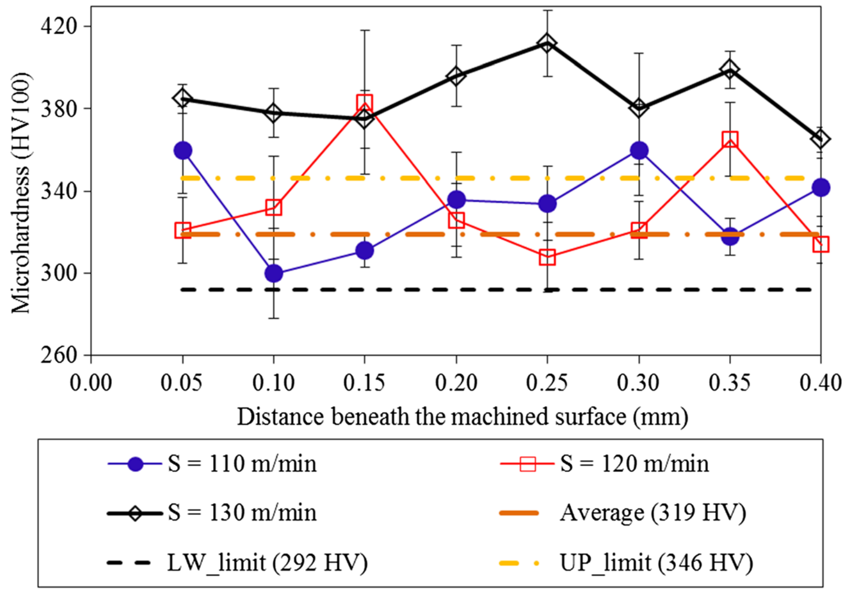


Fig. 7 Microhardness measured beneath the machined surface with enriched argon environment

Fig. 8 Microhardness measured beneath the machined surface with high pressure of 11 MPa



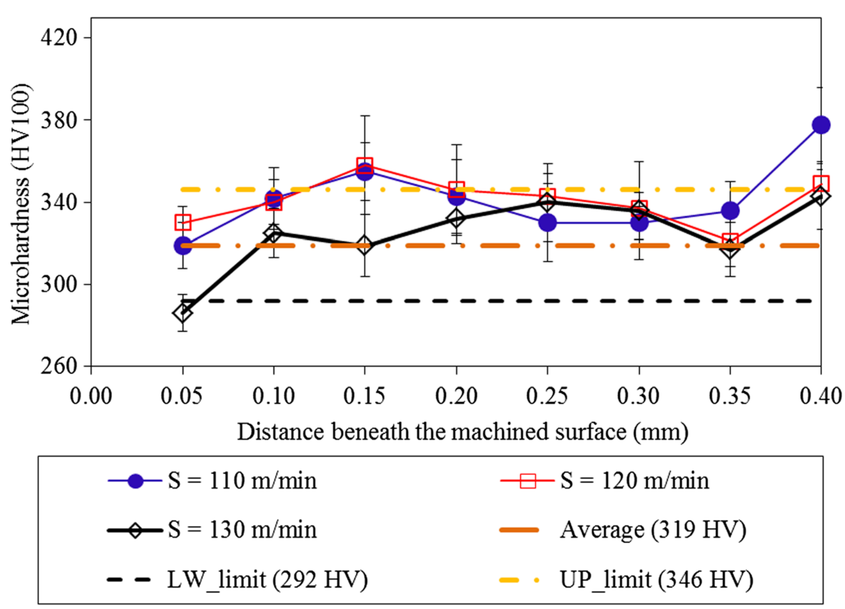
grain boundaries are clear evidence that there was no plastic deformation in the subsurface of machined surfaces under the conditions investigated.

Figures 6, 7, 8 and 9 show plots of microhardness beneath the machined surface in different cooling environment measured up to a depth of cut of 0.4 mm below the machined surface. Machining with conventional coolant supply promotes hardening of machined surface (Fig. 6) under all speed conditions investigated. Similarly, machining in argon-enriched environment (Fig. 7) exhibited lower surface hardening effect when machining with conventional coolant supply. LW_limit and UP_limit stand respectively for lower limit and upper limit of microhardness of workpiece material measured prior to machining.

Figures 8 and 9 show the recorded microhardness measurements for high-pressure coolant supply at 11 and 20.3 MPa. From both graphs, it can be observed that the measured microhardness fluctuates around the average hardness value. However, it is apparent that at 20.3 MPa, there was less dispersion around the average value when compared to 11 MPa.

Analysis of Figs. 6, 7, 8 and 9 shows that the hardening effect was most accentuated in the following decreasing order: conventional overhead flow, argon-enriched and 11 and 20.3 MPa coolant pressures, respectively. However, the results for conventional overhead flow may be attributed to severe plastic deformation generated during machining with this environment when compressive and shear stresses at the cutting interface become higher than the

Fig. 9 Microhardness measured beneath the machined surface with a high pressure of 20.3 MPa



yield point of the work material due to high wear land and cutting temperature [25, 29].

Recorded results show a clear trend that increasing coolant pressure reduces the hardening effect. Hardening effect is due to high plastic flow rate combining with the heat generation at the primary shear zone. Efficient coolant supply conditions enhance access of the coolant to the chip-tool interface and contribute to reducing friction coefficient and resistance at the primary shear zone during machining [1, 28–30]. Therefore, lowering heat generation reduces cutting temperatures and plastic flow during machining. This results to less hardening effect.

4 Conclusions

1. Higher tool wear rates were observed when machining in an argon-enriched environment due to argon being a poor heat conductor.
2. Machining with 20.3 MPa high-pressure coolant supply generated the least wear rates; hence, longer tool life was achieved.
3. Machining Ti-6Al-4V alloy with uncoated carbide tools produced acceptable surface finish under the cutting and different cooling environment investigated.
4. No evidence of plastic deformation of the machined surface was observed under all coolant conditions investigated.
5. Hardening of machined surface was observed after machining with conventional and in an argon-enriched environment.
6. When machining with high-pressure coolant, the hardness values of Ti-6Al-4V alloy were not significantly altered due to efficient cooling achieved at the cutting interface by the high-pressure coolant jet.

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