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Influence of Vegetable Oil-Based Controlled Cutting Fluid Impinging Supply System on Micro Hardness in Machining of Ti-6Al-4V

Salah Gariani, Islam Shyha, Fawad Inam, Dehong Huo

Abstract**—**A controlled cutting fluid impinging supply system (CUT-LIST) was developed to deliver an accurate amount of cutting fluid into the machining zone via well-positioned coherent nozzles based on a calculation of the heat generated. The performance of the CUT-LIST was evaluated against a conventional flood cutting fluid supply system during step shoulder milling of Ti-6Al-4V using vegetable oil-based cutting fluid. In this paper, the micro-hardness of the machined surface was used as the main criterion to compare the two systems. CUT-LIST provided significant reductions in cutting fluid consumption (up to 42%). Both systems caused increased micro-hardness value at 100 µm from the machined surface, whereas a slight reduction in micro-hardness of 4.5% was measured when using CUL-LIST. It was noted that the first 50 µm is the soft sub-surface promoted by thermal softening, whereas down to 100 µm is the hard sub-surface caused by the cyclic internal work hardening and then gradually decreased until it reached the base material nominal hardness. It can be concluded that the CUT-LIST has always given lower micro-hardness values near the machined surfaces in all conditions investigated.

Keywords**—**Impinging supply system, micro-hardness, shoulder milling, Ti-6Al-4V, vegetable oil-based cutting fluid.

I. Introduction

CUTTING fluids generally serve two main key roles in machining industry specifically cooling and lubrication [1]. However, misuse of cutting fluids can affect human health and the environment adversely [2]. Hence, eliminating cutting fluid entirely in metal cutting is untenable, particularly when cutting titanium alloys, due to the generation of large quantities of heat. Without a coolant, titanium alloys are more susceptible to react with common gases and cutting tool materials at an elevated temperature causing embrittlement and reduced alloy fatigue strength along with rapid tool impairment [3], [4]. Recently, vegetable oils based fluids have been introduced as biodegradable fluids and they are significantly mitigated the ecological risks caused by conventional mineral-based fluids [5], [6]. Vegetable oils (VOs) base stocks have superior tribological properties that gave them the ability to withstand extreme contact conditions [7]. Apart from the conventional flood cooling method, several cutting fluid supply systems have been developed recently to reduce cutting fluid consumption in machining operations including cryogenic cooling, minimum quantity lubrication (MQL), compressed air/gas and water/oil mist cooling methods [8]. However, the high cost of equipment relevant to these supply systems is the main limitation [9], [10].

Additionally, to ensure a high reliability of critical aerospace machined parts, surface integrity of titanium alloys should be contented [11]. Ezugwu et al. [12] investigated surface integrity when turning Ti-6Al-4V using PCD cutting tool under traditional flood and high-pressure cooling (HPC) mode. Measured hardness values ranged between 418 and 280 HV_{100}. It has revealed that HPC tends to soften the machined surfaces with less hardening effect as well as microstructural damage, while the hardening effect was observed after cutting with traditional coolant flow owing to the intermittent cooling effect that tends to help fast quenching effect. Micro-structure and hardness have also been investigated when end milling Ti-6242S alloy under dry cutting condition [11]. The affected area was divided into three zones; soft sub-surface down to 50 µm, hard sub-surface down to 200 µm, and the third zone was down to 350 µm in which the micro-hardness progressively decreases until the base hardness material. It has concluded that sub-surface zone due to the thermal softening in the ageing process, while the hard sub-surface is due to the cyclic internal work hardening process. In addition, the micro-structure immediately below the machined surface and down to a few micrometres experiences plastic deformation. This is due to high pressure at the elevated cutting temperature. Antonialli et al. [13] evaluated surface integrity when milling Ti-6Al-4V under different cooling modes including MQL, flood, pressurised air and dry cutting conditions. Micro-hardness values were recorded at 100 till 900 µm below the machined surface and they ranged between 300 HV and 350 HV in all conditions investigated. However, MQL and pressurised air produced an undamaged surface with fewer grains alteration. A recent study [14] has examined the effect of low and high pressure cutting fluid supply system on turning of SAE EV-8 steel in terms of micro- structure and hardness using an indentation load of 0.025g. Both systems achieved a higher micro-hardness value of 650 $HV_{0.025}$ and

Salah Gariani is with the Mechanical and Construction Engineering Department, Faculty of Engineering and Environment, Northumbria University at Newcastle, Newcastle upon Tyne and Wear, NE1 8ST, UK (phone:004401912274301; e-mail: salah.gariani@northumbria.ac.uk).

Dr. Islam Shyha and Dr. Fawad Inam are academic staff in the Mechanical and Construction Engineering Department, Faculty of Engineering and Environment, Northumbria University at Newcastle, Newcastle upon Tyne and Wear, NE1 8ST, UK (e-mail: islam.shyha@northumbria.ac.uk, fawad.inam@northumbria.ac.uk).

Dr. Dehong Huo is a Senior Lecturer at School of Mechanical Engineering and Systems, Newcastle University, Newcastle upon Tyne, NE1 7RU (e-mail: dehong.huo@newcastle.ac.uk).

640 $HV_{0.025}$ respectively at 20 µm below the machined surface until it reaches the base material nominal hardness value, around 405 $HV_{0.025}$. It was revealed that low pressure cooling system produced greater deformation than the high pressure cutting fluid supply system. To date, most attention has been paid to the cryogenic, MQL, compressed air/gas and oil/water mist supply systems in trying to reduce cutting fluid consumption in machining operations. However, no study has yet been published on the impinging of an accurate amount of cutting fluid into the machining zone using well–directed and controlled coherent nozzles and based on the calculation of the heat generated. Therefore, this study aims to evaluate the performance of the CUT-LIST against the conventional flood system in terms of micro-hardness when shoulder-milling of Ti-6A-4V using vegetable oil-based cutting fluid.

II. Development of the Controlled Cutting Fluid Impinging Supply System (CUT-LIST)

In order to carry the cutting fluid, a closed loop Gusher submersible VBV type coolant pump was used. The fluid pump was mounted close to the coolant tank to minimise the pressure loss in the system feed pipes as shown in Fig. 1.

The output flow rate and pressure were controlled using a hand valve placed directly after the pump to afford the required flow rate at any given pressure. A digital oval gear-type flow meter was installed at 300 mm from the pump to ensure steady state flow condition. Additionally, the fluid pressure can be monitored by a digital OMEGA-DMPG type and two dual scale type pressure gauges mounted directly after the in-line model filter and before the cutting fluid entered the nozzles, respectively. The CUT-LIST has the ability to direct cutting fluid in feed and against feed directions simultaneously. The overhead nozzle ring was oriented on a vertical spindle head holding two coherent round nozzles. The CUT-LIST was also designed to align nozzles in tool-workpiece contact point at any given elevation angle relative to spindle and tool axis using angled mounting wedge together with movable angled nozzle clamp. Additionally, the design of the movable nozzle clamp allows the nozzle discharge tips to be relocated away from the machining zone at any given impinging distance.

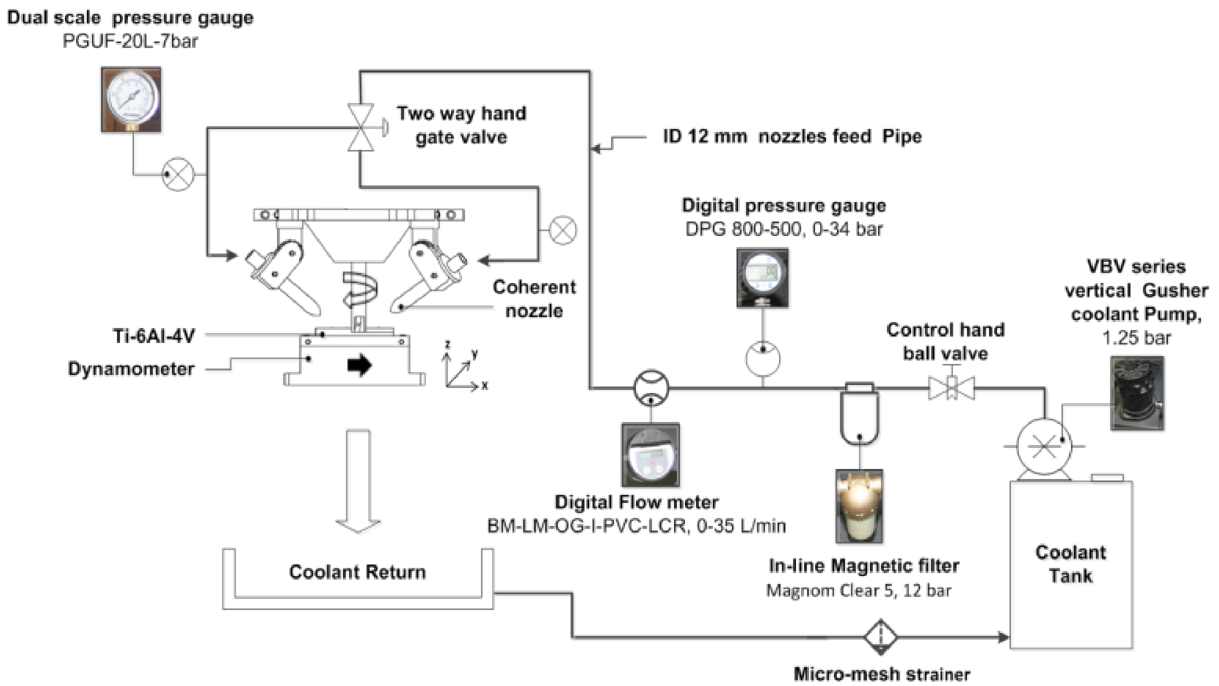

Fig. 1 Schematic of the CUT-LIST

III. Coherent Nozzle Design

The CUT-LIST nozzles were designed based on the Webster nozzle [15] to generate a high-quality coherent jet stream that forms low misting and minimum entrained air within the jet. These features will assist CUT-LIST effectively in propelling fluid further into the machining zone. The contraction ratio (inlet to exit diameter ratio) was set at more than 2:1 to attain high jet stream quality [16]. The customised coherent round nozzle used in this work had 1.75 mm aperture diameter – d (see Table II), 2.5 mm thickness (t), 12 mm feed pipe diameter (D), and 6.85:1 contraction ratio (D/d).

IV. Theoretical Work

Step shoulder-milling has been selected as a cutting strategy for assessing CUT-LIST, as shown in Fig. 2.

Cutting power as a function of metal specific cutting energy (i.e. U= 4 $W.s/mm^3$ for titanium) [17], and metal removal rate (MRR) is considered in the two system calculations. In the same vein, a great proportion of cutting power (i.e. 90-98%) is converted into heat in metal cutting [18], [19]. In this work, 90% of the total cutting power is assumed to be converted into heat. Equation (1) is utilised for the accurate flow rate computations to cool down the machining zone [20].

$$Q = \frac{60 * P_C}{4.148 * C * \rho * \eta_{nozzle} * \Delta\theta} \quad (1)$$

where Q is an accurate flow rate (L/min); P_C is the cutting power (kW); C and ρ are the cutting fluid heat capacity (0.948 cal/g·˚C) and cutting fluid mass density (0.988 g/cm^3) at 10% concertation ratio, respectively. η_{nozzle} is the coherent nozzle efficiency (0.95) [15]; Δθ is cutting fluid maximum tolerable temperature increase (i.e. 3 ˚C for wet machining) [21]. Additionally, flow rate calculations of the conventional flood supply system were based on 13 L/min per (kW) for cutting titanium as recommended by KENNAMETAL [22]. The computation outcomes show that the fluid can be supplied at a flow rate of 8 L/min per (kW) using CUT-LIST with a reduction in cutting fluid consumption by up to 42% compared to the conventional system, see Fig. 3.

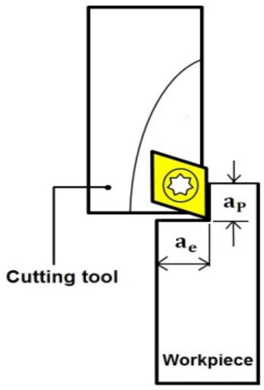

Fig. 2 Schematic of step shoulder-milling of Ti-6Al-4V

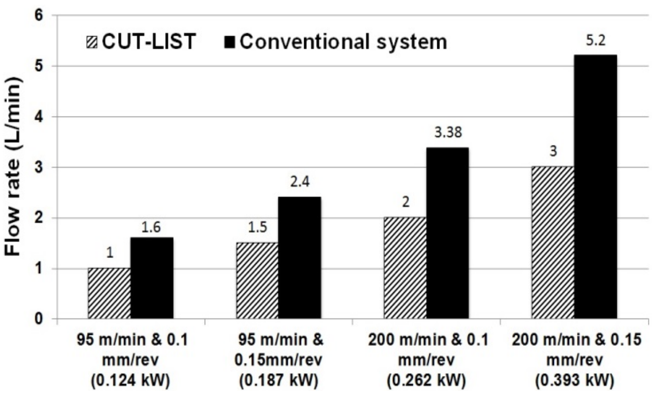

Fig. 3 Flow rate versus cutting conditions and the heat generated for the two systems

Knowing flow rate and fluid pressure, fluid velocity and the nozzle aperture diameter can be determined by applying Bernoulli's and continuity theories [15], [23], respectively. All pressures were measured by the digital pressure gauge at given flow rates resulting from (1), and results are shown in Table I.

To fulfil the flow coherency criterion, the contraction ratio (D/d) should be at least ≥ 2:1, and the actual nozzle aperture diameter (d) must be ≥ the theoretical minimal coherent nozzle aperture diameter [23]. To satisfy such criterion, the actual nozzle aperture diameter (d) was fixed at 1.75 mm for all trials, whereas the contraction ratio was set at 6.85:1.

TABLE I
RESULTS OF THE MINIMAL NOZZLE APERTURE DIAMETERS AND FLUID VELOCITIES

Cutting conditions (cutting speed x feed rate)	a*	b*	c*	d*
Cutting fluid pressure (bars)	0.34	0.55	0.78	1.16
Cutting fluid velocity (m/s)	5.86	7.46	8.88	10.83
Cutting fluid specific gravity	0.98	0.98	0.98	0.98
Nozzle aperture diameter (mm)	1.42	1.5	1.62	1.75
Flow rate (L/min)	1	1.5	2.1	3.1

a* = 95 m/min x 0.1 mm/rev, b* = 95 m/min x 0.15 mm/rev, c* = 200 m/min x 0.1 mm/rev, d* = 200 m/min x 0.15 mm/rev.

V. EXPERIMENTAL WORK

The workpiece material used was Ti-6Al-4V grade 5 samples in the form of a 103 mm x 25 mm x11 mm block. Uncoated carbide milling inserts Sandvik H13A were mounted on an ∅18.5 mm x 110 mm long single point tool holder with an overhang distance of 60 mm to eliminate chatter. Experiments were carried out on a CNC Cincinnati 750-Sabri vertical machining centre. Both systems were tested at four different machining settings (two cutting speeds and two feed rates). Machining parameters fixed throughout the trials were: the axial (a_p) and radial (a_e) depth of cuts (5 and 1.3 mm) respectively, and nozzle elevation angle (40˚). A commercial water-soluble vegetable oil-based cutting fluid (Vasco1000) containing 45% pure vegetable oil was blended at the 10% concentration ratio and was regularly checked using a hand held refractometer. Fig. 4 shows the experimental setup.

In order to conduct the micro-hardness test, workpiece samples were cut-out from the middle having a dimension of 6 mm x 10 mm using EDM wire machine as shown in Fig. 5. Cut-out Ti-6Al-4V samples were hot-mounted in Buehler Red Phenolic Bakelite and subsequently ground/polished using different SiC paper grades and ultra-fine Struers polishing machine together with hyprez diamond lapping spray fluid. The Vickers (HV) micro-hardness measurements were made on a Micromet II micro-hardness tester using an indentation load of 100g, a dwell time of 10s, with the aid of a Vickers tool indenter. Three main locations were selected for indents across the polished surface at 50 µm interval between each two consecutive measurements as shown in Fig. 6.

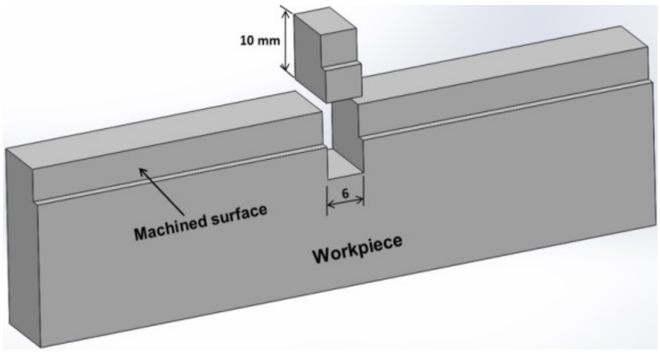

Fig. 5 Cut-out Ti-6Al-4V sample for micro-hardness test

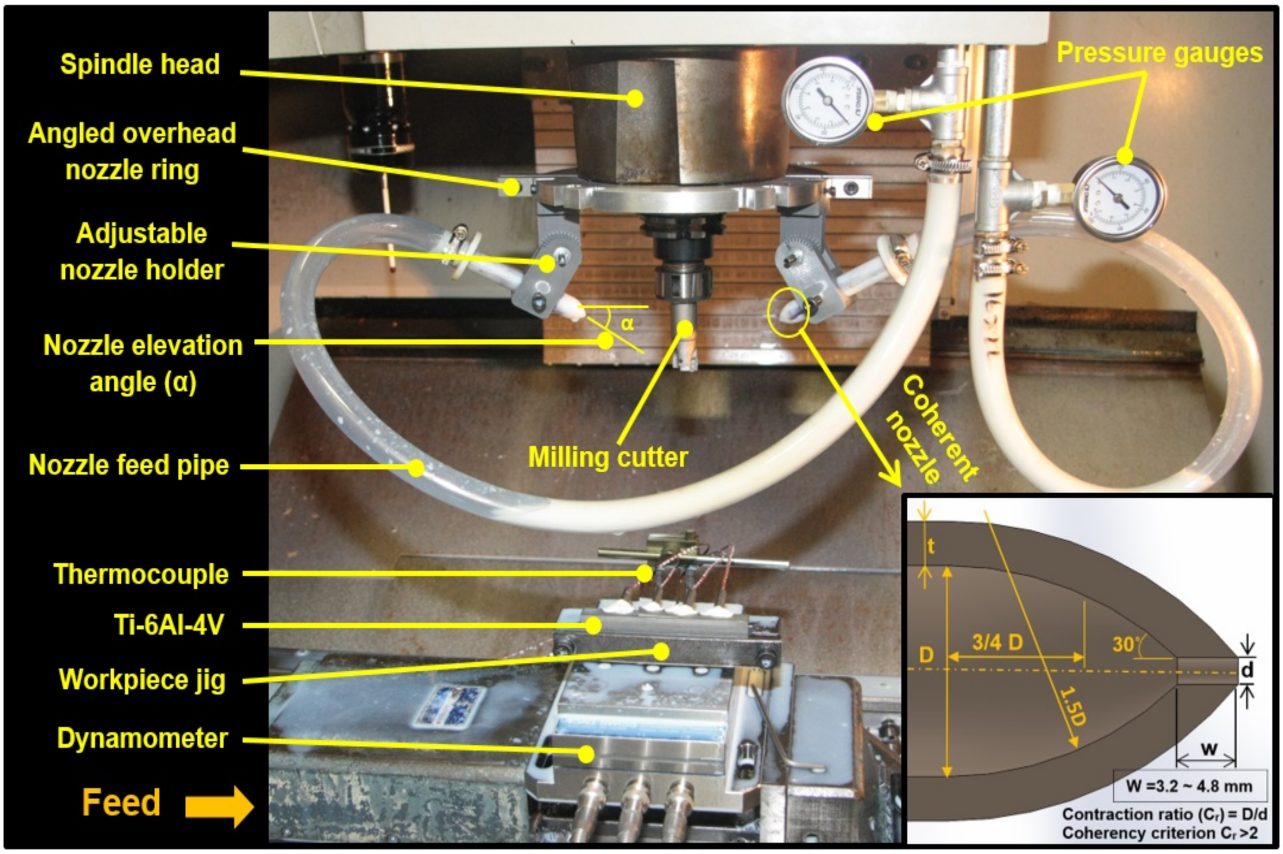

Fig. 4 Experimental setup

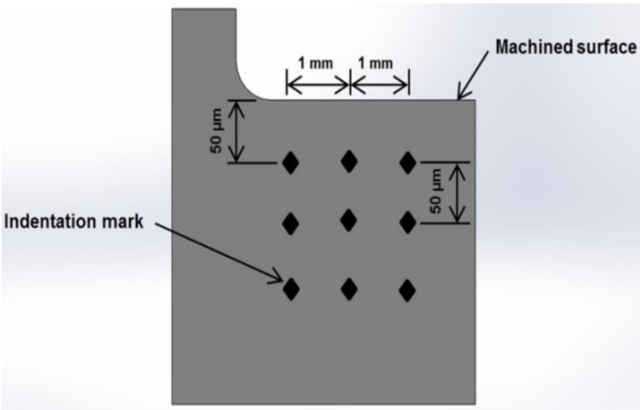

Fig. 6 Location of indentation marks used in micro-hardness test

VI. Results and Discussions

Figs. 7 and 8 show the micro-hardness results for both systems starting from 50 µm away from the machined surface at lower and higher material removal rates, respectively. Both systems showed a notable increase in micro-hardness value at 100 µm below the machined surface and gradually reduces towards the interior of the specimen until reaching the base material nominal hardness, around 349-350 HV_{100}. This could be attributed to the accumulated internal working hardening, induced by interrupted cutting during the milling operation. Additionally, generated heat from the cutting process probably acts as a thermal energy for softening the outer layer of the machined surface [11]. The thermal energy then moving down to a level of 100 µm beneath the machined surface and cumulated at this level to provide the cyclic heating/cooling for internal work hardening. Consequently, the hard sub-surface arises below the machined surface. The thermal energy beyond this region is gradually dissipated; thus, at the depth more than 100 µm beneath the machined surface, the value of micro-hardness gradually decreases to the base material nominal hardness.

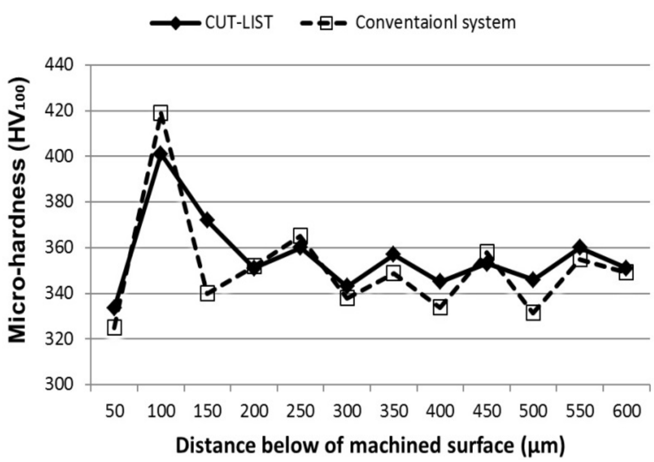

Fig. 7 Micro-hardness results below the machined surface at cutting speed of 95 m/min and feed rate of 0.1 mm/rev for the two systems

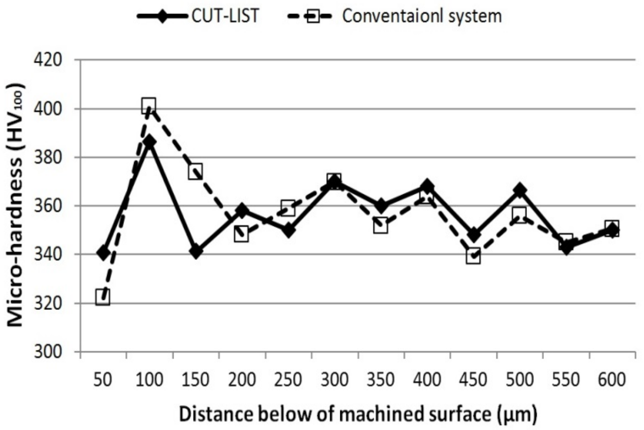

Fig. 8 Micro-hardness results beneath the machined surface at cutting speed of 200 m/min and feed rate of 0.15 mm/rev for the two systems

Fig. 9 shows maximum micro-hardness values recorded for the two systems at 100 μm below the machined surfaces under various cutting conditions. Micro-hardness generally ranged between 401 – 386.3 HV_{100} and 419 - 401 HV_{100} for the CUT-LIST and conventional systems respectively. It was noticed that achieved micro-hardness values by both systems were within the acceptable hardness range for titanium aerospace components (i.e. 419.6 HV max and 284.4 HV min) [12]. However, the CUT-LIST induced lower softening at the outer layers of the machined surfaces by reducing the micro-hardness up to 4.5% compared to conventional system. This is possibly due to the impingement effect of a high-velocity jet (i.e. up to 10.83 m/s, see Table I), which led to accelerating heat transfer from machining zone to the cutting fluid effectively. Both systems exhibited a similar drop in micro-hardness values, increasing the cutting speed and feed rate. This can be attributed to the increase in cutting fluid flow rate associated with increased cutting energy (see Fig. 3) resulting in a minimised hardening effect. It was observed that the alteration in micro-hardness is affected significantly by cutting speed rather than feed rate when shoulder-milling Ti-6Al-4V using vegetable oil-based cutting fluid.

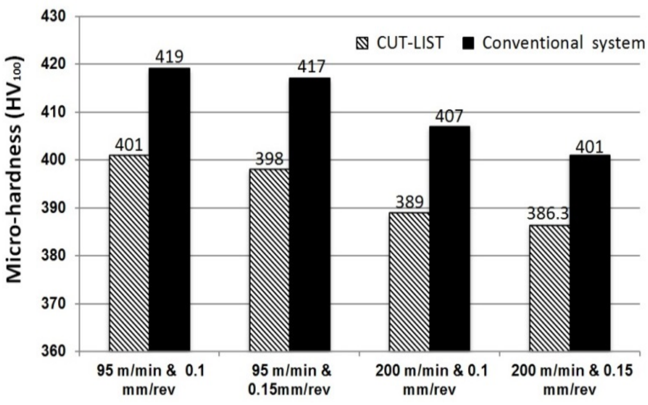

Fig. 9 Maximum micro-hardness versus cutting conditions at 100 μm beneath the machined surface for the two supply systems

VII. Conclusion

In this work, a controlled CUT-LIST was designed, manufactured, and assessed against the conventional flood system in terms of micro-hardness during shoulder-milling of Ti-6Al-4V using vegetable oil-based cutting fluid. Based on the analysis of the experimental results, the following conclusion can be drawn:

1) A total reduction of 42% in cutting fluid use was achieved when the CUT-LIST was employed.
2) Both systems achieved higher micro-hardness value at 100 μm below the machined surface with a slight reduction in micro-hardness up to 4.5 % with the use of CUT-LIST.
3) The affected zone was divided into three regions. The first region down to 50 μm is the soft sub-surface region with micro-hardness value (e.g. 2.85% and 8.5% for the CUT-LIST and the conventional system respectively at higher cutting condition) less than the nominal material hardness, around 349-350 HV_{100}. The second down to 100 μm is the hard sub-surface region with micro-hardness value (e.g. 10.85% and 14.28% for the CUT-LIST and the conventional system respectively) harder than the nominal material hardness. In the third region at depth more than 100 μm, in which the micro-hardness gradually decreases until reaching the base material nominal hardness. The soft sub-surface is due to thermal softening, whereas the hard sub-surface is due to the cyclic internal work hardening.
4) The alteration in micro-hardness is affected significantly by cutting speed rather than feed rate when shoulder-milling Ti-6Al-4V using vegetable oil-based fluid.
5) Near the machined surfaces, CUT-LIST has always given lower micro-hardness values.

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