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Experimental analysis of system parameters for minimum cutting fluid consumption when machining Ti-6Al-4V using a novel supply system

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Abstract This paper presents the development of a new controlled cutting fluid impinging supply system (Cut-list) to deliver an accurate quantity of cutting fluid into machining zones through precisely oriented coherent round nozzles. The performance of the new system was evaluated against a conventional system during the step shoulder milling of Ti-6Al-4V using a water-miscible vegetable oil-based cutting fluid, which was phase 1 in this comprehensive study. The use of Cut-list resulted in a significant reduction up to 42% in cutting fluid consumption as well as reductions in cutting force, tool flank wear, average surface roughness (R_a) and burr height (Gariani et al. in Appl Sci 7(6):560, 2017). This paper details phase 2 of the study which was aimed to investigate the effects of working conditions, nozzle positions/angles and impinging distances on key process measures including cutting forces, workpiece temperature, tool wear, burr formation and average surface roughness of the machined surface. Feed rate showed a significant effect on mean

values of cutting force, burr formation and surface roughness, whereas average workpiece temperature and flank wear values are very sensitive to cutting speed. Nozzle position at a 15° angle in the feed direction and 45°/60° against feed direction assisted in minimising workpiece temperature. An impinging distance of 55/75 mm is also necessary to control burr formation, workpiece temperature and average surface roughness. It can be concluded that Cut-list gave promising results compared to conventional flood cooling systems in terms of the evaluated machining outputs. Therefore, the new system can be considered as a feasible, efficient and ecologically beneficial solution, giving less fluid consumption in machining processes.

Keywords Fluid consumption · Coherent nozzle, vegetable oil-based · Cutting fluid · Shoulder milling · Ti-6Al-4V

1 Introduction

Historically, manufacturing by machining has prospered from the use of cutting fluids. Cutting fluids are supplied to the machining zone in order to improve machining performance. Cooling and lubrication are the key functions of cutting fluids. Additionally, they transport chips away from the machining zone, minimise the built-up edge (BUE) and protect machined components and machine tool parts from corrosion [1, 2]. It is reported that the costs related to cutting fluids are approximately 16.9% of the total manufacturing costs, compared to tooling costs which represent about 7.5% [3]. This cost can be increased to up to 30% for machining refractory materials such as titanium and nickel-based alloys [4]. It is also estimated that the annual consumption of cutting fluids is about 100 million gallons in the USA [5]. A more effective cutting fluid supply method will significantly contribute to reducing fluid consumption and improving cutting performance. Currently,

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conventional flood cooling is the most common method used on machine shop floors, in which a large quantity of cutting fluid (e.g. up to 225 l/min for multiple teeth tool cutters) is continuously supplied into the machining zone [6]. However, high fluid consumption and low penetration ability, particularly at high cutting speeds, are the main disadvantages of this technique [7, 8]. High fluid consumption results in increasing disposal and maintenance costs, particularly when mineral/petroleum oil-based fluids are used. These types of fluids are claimed to cause human and environmental hazards due to their high content of toxic elements such as chemical agents, hydrocarbons and extreme pressure (EP) additives [9, 10]. Between 13 and 32% of cutting fluids used in the EU and USA are disposed of without treatment [11]. Thus, additional processing for fluid waste (e.g. oil/water separation, ultrafiltration, conditioning and incineration) prior to disposal is always required [5, 10]. In order to address these issues, minimum quantity lubrication (MQL) and minimum quantity cooling lubrication (MQCL) have been introduced to minimise fluid consumption in the machining operations. Fluid is atomised by mixing with compressed air and is supplied as an aerosol. The cutting fluid in MQL and MQCL reaches the tool-workpiece interface through capillarity forms a film at the interface. This helps in lubrication and reducing contact pressure. Good penetrability of MQL and MQCL was also assisted to minimise cutting temperature in machining zone (particularly MQCL owing to its variant properties such as cooling compared to MQL), resulting in a reduction of tool wear and built-up edge formation. Improved surface integrity and desirable chip shape were also obtained when MQL and MQCL are used compared to dry and conventional flood cooling conditions [12–15]. Although MQL and MQCL are often used with biodegradable lubricants, resulting fumes by these systems particularly at higher cutting speeds is the main limitation [16]. High-pressure cooling (HPC), cryogenic cooling, oil/water mist and compressed air/gas/vapour supply systems have also been employed as alternative methods instead of conventional flood cooling supply systems to reduce fluid consumption and mitigate the hazards of using mineral oil-based fluids [17, 18]. However, the high cost of the consumables involved (e.g. liquid nitrogen and gases), pumping and micro-particle filtration equipment are substantial limitations [19–23]. Additionally, the inaccurate estimation of cutting fluid flow rates during machining operations is also a clear disadvantage.

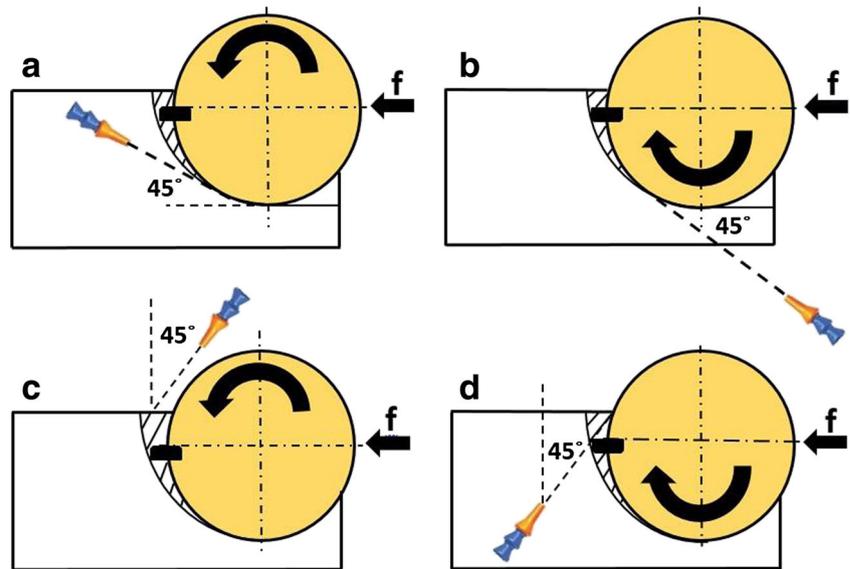
In the same vein, vegetable oil (VO)-based cutting fluids have been introduced as potential alternatives to conventional fluid counterparts due to their high biodegradability (i.e. 100% within 28 days) [24] and superior physical and chemical properties [25, 26]. The homogeneity and super-density of vegetable oil molecules can also help to form a thick, durable and strong film layer that affords VOs the ability to withstand high contact pressure [27, 28]. Vegetable oil-based stocks have a

high kinematic viscosity (e.g. 40.05 cSt at 40 °C for sunflower oil) and high heat conductivity of up to 0.17 W/m.K compared to 20.06 cSt at 40 °C and 0.12 W/m.K for mineral oil-based fluids [29, 30]. Thus, it is estimated that the global demand for biodegradable fluids is expected to increase by around 58% or 0.3 million tonnes in 2018 compared to 2011 [17].

Nozzle placement plays a crucial role, particularly in supply methods using less fluid consumption (e.g. MQL and oil/water mist). The impact of nozzle position on the turning of the AISI 1045 at an angle of 20° and 50° has been investigated [31] using MQL with palm oils and water/mist. Tests were performed at a cutting speed of 125 m/min, feed rate of 0.2 mm/rev and 0.2 mm depth of cut and 1000 mm cutting length. The results showed that nozzle placement at 20° produced lower tool flank wear of 63 and 71 µm for MQL and water/mist cooling, respectively, compared with 71 and 85 µm when a 50° angle was employed. In another study [32], nozzles positioned at 45° with respect to feed direction resulted in the best lubrication for the upmilling and downmilling of Inconel 182 using MQL (Fig. 1). The influence of nozzle position has also been evaluated when grinding 100Cr6 hardened steel using an MQL application [33]. It was found that MQL oil mist effectively penetrated into the boundary layer flow around the grinding wheel when the nozzle was positioned toward the wheel at an angle of 10°/20° to the workpiece surface.

Additionally, titanium alloys are very attractive materials, particularly for aerospace and automotive applications, due to their superior inherent physical and mechanical properties (e.g. ~50% density of steel, high strength, high operational temperatures and exceptional corrosion resistance). Ti-6Al-4V is the most widely used titanium alloy which is currently used in a wide range of engineering sectors including aerospace, automotive, medical, military aviation and sports equipment. It features relatively higher mechanical properties (i.e. high strength, low weight ratio and excellent corrosion resistance). However, Ti-6Al-4V has low machinability index compared to other metallic alloys such as steels owing to its low thermal conductivity (7.2 W/m.K for annealed Ti-6Al-4V) and high dynamic shear strength. This generates a large quantity of heat close to the machining zone, which leads to the use of relatively lower cutting speeds (i.e. 30–90 m/min) to remain economical [34, 35] as well as has a knock on effect on cutting tool life. Additionally, the low E modulus of titanium alloys (~110 GPa for annealed Ti-6Al-4V) promotes tool rubbing, chatter and product geometry issues and contributes to higher tool wear rates [36, 37]. On the other hand, increasing machining speed when cutting Ti-6Al-4V alloy with less manufacturing cost (e.g. using minimum amount of cutting fluid) is deemed necessary for process improvement. These reasons encouraged the authors to use Ti-6Al-4V as the workpiece material to examine the novel cutting fluid supply system. In the same vein, vibration is more prone to occur in

Fig. 1 MQL traditional nozzle positions. **a** Against feed direction in downmilling. **b** With feed direction in upmilling. **c** With feed direction in downmilling. **d** Against feed direction in upmilling [32]



milling titanium due to self-excited vibrations (i.e. chatter) between the workpiece and cutting tool (owing to its low E modulus) [38]. Localised shearing, which is correlated to the generation of cyclic force, is responsible for self-excited vibration. This vibration induces waviness of the surface in the first cut. In the following cut, the tool cuts into the wavy surface and generates a further variation of chip geometry/thickness and force that excites the structure, providing greater vibration between the workpiece and cutter, resulting in wave regeneration phenomenon [35, 39]. Thus, rigid clamping is essential for avoiding effect of low E modulus of titanium alloys particularly for chatter-free surfaces [40]. Additionally, cutting tool path (i.e. contouring and ramping) and the inclined surfaces (e.g. concave and convex) can also affect cutting force, tool and workpiece deflection when milling titanium. It was revealed that the cutting force and tool deflection in contouring tool path style were found to be lower than that of ramping tool path mode. This was explained by the outcome that the contouring tool path style offers movements parallel to the inclined surface from the axis and ideal to move the chips away. In addition, the cutting forces obtained in the machining of convex inclined surfaces are found smaller in comparison to that obtained in the machining of concave inclined surfaces. This is because the chip was comfortably removed from the machining zone in the convex inclined surface. Furthermore, the cutting tool works on the inner surface and comes in contact with the workpiece with a longer cutting edge, resulting in increases in the cutting force and tool deflection values [41]. In a similar vein, it was indicated that cutting forces are strongly affected by the surface inclination angle (α) in milling operations. Influence of surface inclination angle on cutting forces was lower in

the case of $\alpha \geq 15$, whilst the highest impact of inclination angle on cutting forces was found with the $\alpha = 0^\circ$ [42].

Additionally, increasing the machining speed of titanium components is necessary for process improvement. Currently, a parallel machining strategy has been presented in order to extend metal cutting capacity and to minimise chatter. Also, parallel machining involves less bending force applied to the work part, affording additional improvements in product accuracy [43]. In the absence of coolant, titanium alloys are more disposed to react with atmospheric gases and cutting tool material at elevated temperatures, resulting in the degradation of machined surface quality as well as rapid tool wear [36]. Traditionally, using copious amounts of cutting fluid helps when machining titanium and is a dominant ‘machining culture’ on machine shop floors [44, 45]. Thus, more attention is deemed necessary to reduce fluid consumption during machining titanium alloys, with a particular emphasis on the use of environmentally friendly cutting fluids.

In this work, a novel controlled cutting fluid impinging supply system (Cut-list) is developed and applied to the shoulder milling of Ti-6Al-4V to reduce cutting fluid consumption. Key process measures include cutting force, workpiece temperature, tool flank wear, burr formation and surface roughness. The effects of working conditions (cutting speed and feed rate), nozzle position and impinging distances are also assessed employing the new supply system. The originality of the developed supply system depends on synchronisation between the calculated generated heat in the machining zone with an accurate cutting fluid quantity required to minimise its consumption and simultaneously enhance the cutting performance of titanium alloys. Furthermore, the developed system is beneficial to the machine tool industry, making it very viable in terms of the minimum fluid consumption for machining applications without substantial additional costs.

2 Experimental work

Cut-list (Fig. 2) was designed to supply cutting fluid in feed and against feed directions simultaneously. The angled overhead nozzle ring was placed on a vertical spindle head holding two round coherent nozzles for delivering fluid at three different impinging angles of 15°, 45° and 60° in the feed direction and similar angles against the feed direction as shown in Fig. 3. Cut-list was also developed to align nozzles in the tool-workpiece contact area at any given elevation angle relative to tool axis using an angled mounting wedge together with an adjustable nozzle holder. Additionally, the design of the adjustable nozzle holder allows the nozzle discharge tips to be placed away from the tool-workpiece contact zone at different impinging distances of 35, 55 and 75 mm. A closed loop Gusher vertical type coolant pump (Gusher Pumps Ltd., Wolverhampton, UK) was used to carry the cutting fluid. The pump was placed directly over the cutting fluid tank to minimise pressure drop in the system feed pipes. The output flow rate was controlled using an oval gear digital type flow meter/regulator (Badger Meter Europa, Neuffen, Germany) located at 300 mm away from the coolant pump to ensure steady state flow conditions. The fluid pressure was monitored employing an OMEGA DPG digital-type and dual-scale pressure gauges (OMEGA Engineering Ltd., Manchester, UK), which were mounted directly after an in-line type filter (Magnum Corporation Ltd., Warwick, UK) and before the cutting fluid enters the nozzles.

The new system nozzles were designed based on Webster nozzle geometry [46, 47] to generate a high-quality coherent jet stream that affords low misting and minimum entrained air within the jet. These features help Cut-list to penetrate cutting fluid into the machining zone effectively. The internal

dimensions of the manufactured coherent nozzle are aperture diameter ($d = 1.75$ mm), thickness ($t = 2.5$ mm) and an internal diameter of the feed pipe ($D = 12$ mm) (see Fig. 3). Step shoulder milling was selected as a cutting strategy in evaluating the new supply system, as shown in Fig. 4. During metal cutting, a greater proportion of the energy consumed (i.e. 90–98%) is converted into heat, whereas the remaining energy is retained as elastic energy in the chip [48–53]. In the present work, 90% of the total cutting power is considered to be converted into heat (i.e. the total heat generated in the primary, secondary and tertiary deformation zones). Equations 1 and 2 were used to calculate the metal removal rate (MRR) and cutting power, respectively. The accurate flow rate of the cutting fluid required to cool the machining zone is then computed according to Eq. 3 [54].

$$\text{MRR} = f \cdot Z \cdot N \cdot K_1 \cdot a_p \cdot a_e \quad (1)$$

$$P_c = \frac{U \cdot \text{MRR}}{60} \quad (2)$$

$$Q = \frac{U \cdot \text{MRR}}{4.148 \cdot C \cdot \rho \cdot \eta_{\text{nozzle}} \cdot \Delta\theta} \quad (3)$$

where MRR is the metal removal rate (mm^3/min); a_p and a_e are the axial and radial depth of cut, respectively (mm); f is the feed rate (mm/rev); Z is the number of teeth; N is the spindle speed (rpm); K_1 is a compensation factor for minimising chip thinning ($K_1 = 1.96$) [55]; P_c is the cutting power (W); U is the specific cutting energy ($U = 4 \text{ W s/mm}^3$ for titanium) [56]; Q is the accurate flow rate (L/min); η_{nozzle} is the coherent nozzle efficiency (0.95) [57]; $\Delta\theta$ is the cutting fluid maximum tolerable temperature increase ($\Delta\theta = 3$ °C for wet machining)

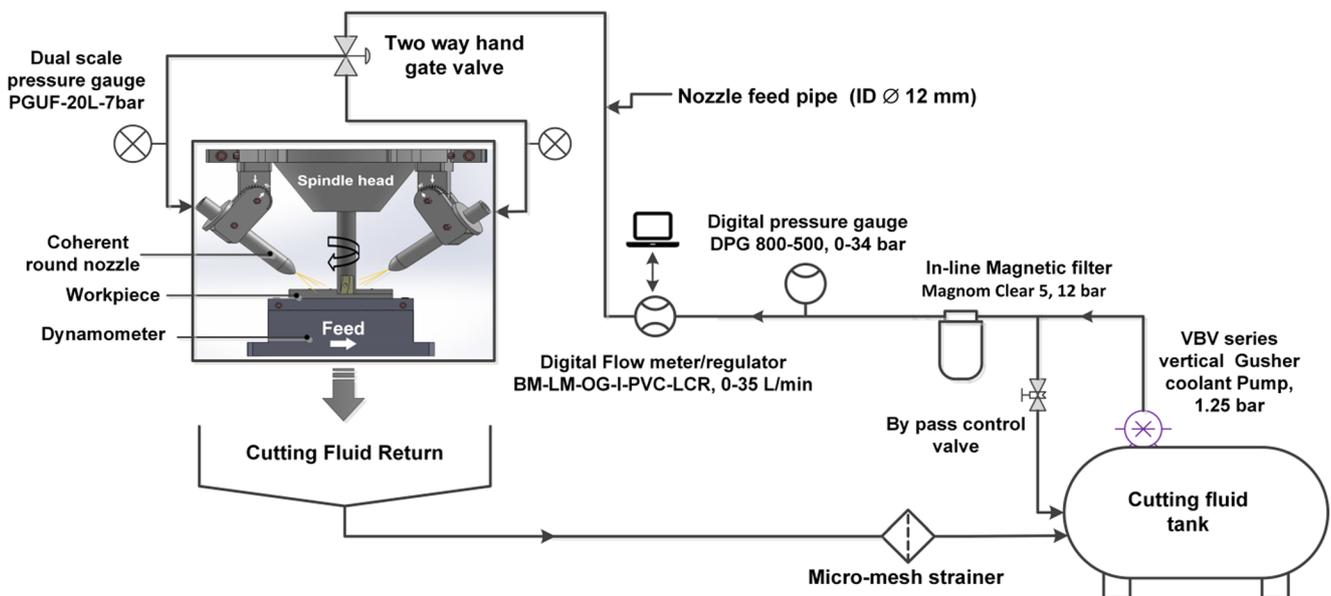
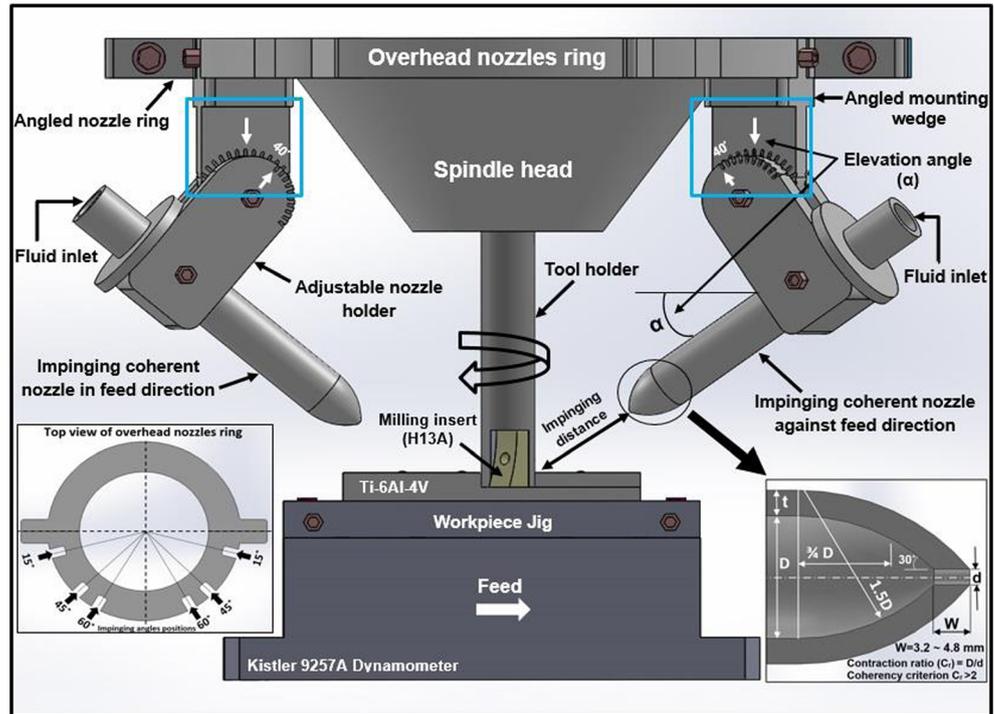


Fig. 2 Schematic view for the new controlled cutting fluid impinging supply system (Cut-list)

Fig. 3 Detailed view of the new supply system (Cut-list)



[58]; and ρ and C are the cutting fluid mass density and fluid heat capacity at 10% concentration ($\rho = 0.988 \text{ g/m}^3$ and $C = 0.948 \text{ cal/g } ^\circ\text{C}$), respectively. Table 1 shows the cutting conditions used for accurate flow rate calculations.

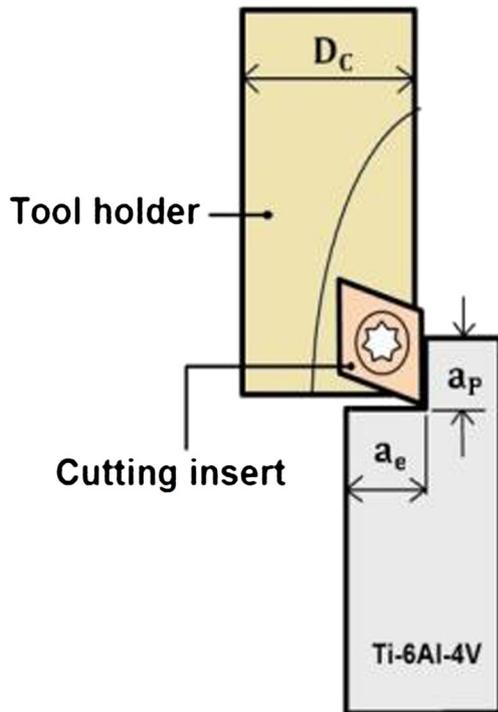


Fig. 4 Schematic illustration of step shoulder milling of Ti-6Al-4V

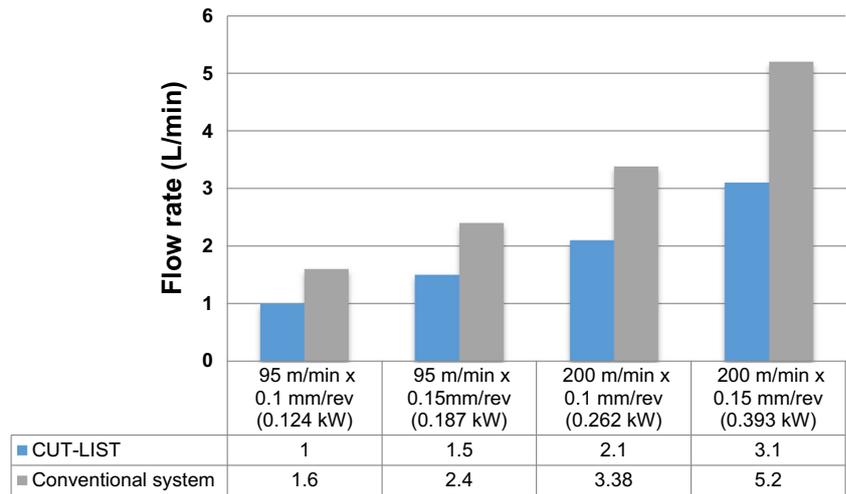
Additionally, the conventional flood estimations were based on 13 L/min per (kW) for cutting titanium as recommended by the Kennametal tool manufacturer [44]. The results showed that the fluid can be supplied at a flow rate of 8 L/min per (kW) using Cut-list with a reduction in cutting fluid consumption by up to 42% compared to the conventional system (see Fig. 5). Cutting fluid velocity and the minimal exit diameter of the round coherent nozzle were determined using Bernoulli's [46] and fluid continuity theories [57], respectively. Table 2 shows the experimental results for all cutting tests.

To fulfil the flow coherency criterion, the contraction ratio (D/d) should be at least $\geq 2:1$ and the actual nozzle exit diameter (d) must be greater than or equal to the theoretical minimal coherent nozzle exit diameter [57]. To obtain the highest jet stream quality, the actual nozzle exit diameter (d) was fixed at 1.75 mm for all trials, whereas the contraction ratio was set at $\sim 7:1$ based on the calculated actual nozzle aperture diameter (i.e. 1.75 mm) and nozzle internal feed pipe diameter (i.e. 12 mm) which satisfy the above criterion.

Table 1 Cutting conditions and levels used for accurate flow rate computation

Cutting conditions	Corresponding levels
Cutting speed (m/min)	95, 200
Feed rate (mm/rev)	0.1, 0.15
Axial and radial depth of cut (mm)	5, 1.3

Fig. 5 Flow rate versus cutting conditions and generated heat for the two systems



3 Experimental plan

The experimental plan was divided into two main parts. Part I evaluated the effect of the settings of the new system on machining output, whereas part II focused mainly on a comparison between the proposed and conventional supply systems. Because the new system has the capability for more settings (i.e. nozzle angles and impinging distance) compared to the existing conventional flood supply system, Cut-list was initially evaluated at three impinging angles in the feed direction, three impinging angles against feed direction and three impinging distances, giving 27 tests at each setting of cutting speed and feed rate (i.e. two levels each). This gives a total of 108 experiments conducted using the new system. Table 3 shows the evaluated factors with their corresponding levels. All trials were carried out using a CNC Cincinnati 750-Sabri vertical milling machine (Cincinnati Machine UK Ltd., Birmingham, UK) with a maximum spindle power of 11 kW. Step shoulder downmilling was performed on annealed Ti-6Al-4V ASTM B 265 grade 5 rectangular blocks, each having a width of 11 mm, height of 25 mm and length of 103 mm. Each trial involved cutting a length of 103 mm, and a new cutting insert was used to avoid the accumulation of wear from different tests. The axial (a_p) and radial (a_e) depths of cut and nozzle elevation angle (α) of 5 mm, 1.3 mm and 40° , respectively, were maintained for all tests.

Table 2 Results of minimal nozzle exit diameters and fluid velocities for Cut-list

Cutting conditions	95 m/min and 0.1 mm/rev	95 m/min and 0.15 mm/rev	200 m/min and 0.1 mm/rev	200 m/min and 0.15 mm/rev
Fluid pressure (bars)	0.34	0.55	0.78	1.16
Fluid velocity (m/s)	5.86	7.46	8.88	10.83
Fluid specific gravity	0.988	0.988	0.988	0.988
Minimal nozzle exit diameter (mm)	1.42	1.50	1.62	1.75
Accurate flow rate (L/min)	1	1.5	2.1	3.1

Sandvik H13A coarse grain uncoated tungsten carbide inserts with a positive rake angle and a nose radius of 0.8 mm were used. These inserts were mounted on a $\varnothing 18.5$ (i.e. D_c) \times 110-mm-long square shoulder milling tool holder (Sandvik Coromant, Halesowen, UK), implying a major cutting edge angle $\kappa = 90^\circ$ with an overhang distance of 60 mm (i.e. to eliminate chatter). Figure 6 shows the experimental setup using the new Cut-list system.

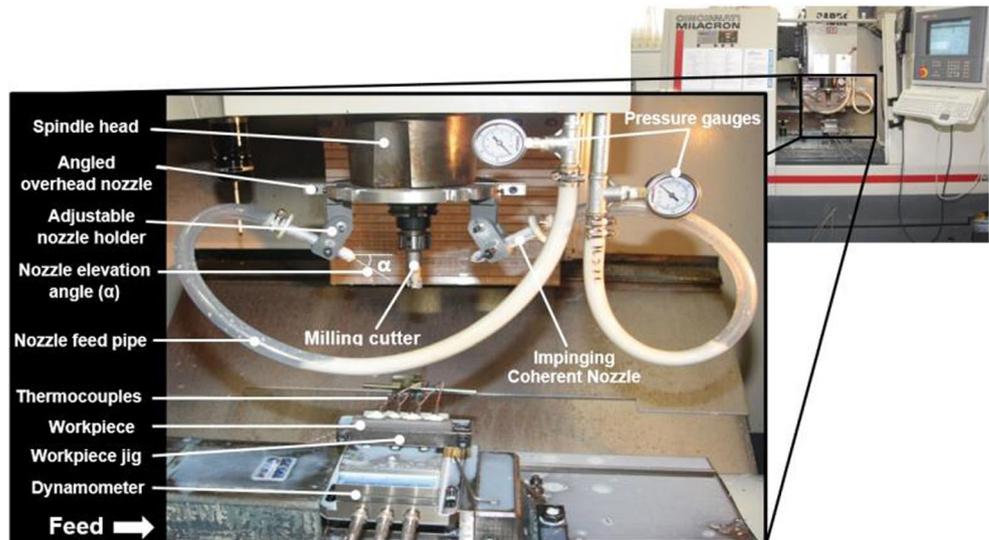
The single tooth cutter (i.e. $Z = 1$) was used to facilitate tool wear measurements. A commercial (Vasco1000) water-soluble vegetable oil-based cutting fluid (Jemtech Ltd., East Sussex, UK) containing 45% pure vegetable oil was used. The fluid was blended at 10% concentration and regularly checked using a portable refractometer (Cromwell Tools, Luton, UK). Table 4 details the chemical composition and thermo-physical properties of the cutting fluid used throughout the experimentation.

An Alicona Infinite Focus G4 optical microscope (Alicona UK Ltd., Kent, UK) was utilised to capture the average tool flank wear (VB). Average tool flank wear (VB) was measured following each trial in accordance with the ISO 8688-2 (1989) standard. The average surface roughness (R_a) of machined samples was measured using a Taylor Hobson Surtroni 3+ (Taylor Hobson, Leicester, UK). Three R_a readings (at the beginning, middle and end of the cut) were recorded, and an average was then computed (see Fig. 7, view A). All R_a

Table 3 Process variables and their corresponding levels

Factor	Level 1	Level 2	Level 3
Nozzle angle in feed direction	15°	45°	60°
Nozzle angle against feed direction	15°	45°	60°
Nozzle impinging distance (mm)	35	55	75
Cutting speed (m/min)	95	200	
Feed rate (mm/rev)	0.1	0.15	

measurements were conducted in accordance with ISO 4287 and ISO 4288 using a 0.8-mm cutoff and an evaluation length of 4 mm. Top burr height measurements were taken using a digital micro-depth gauge, whilst the burrs images were captured utilising optical microscope (Leica L2). Cutting force signals were collected using a Kistler 9257A dynamometer (Kistler, Winterthur, Switzerland) via a multichannel laboratory charge amplifier. A sample frequency of 2000 Hz and high-pass filter type with (n^{64}) filter order were used to record the cutting force signals. All signals were then analysed utilising Kistler Dynaware software. Workpiece temperature was measured using mineral insulated thermocouple sensors (TEMPCON, West Sussex, UK). A digital four-channel data logger (Onset-HOBO UX120-014M) having sampling rate of 2000 samples/s was utilised for temperature logging. Four T-type thin sensing probes with \varnothing 1.0 mm diameter \times 10 mm probe length \times 2 m extension cable length were inserted into \varnothing 1.0-mm drilled holes in each sample at 0.5 mm from the machined surface and 20 mm apart. A distance of 20 mm was also allocated before passing over the first thermocouple for ensuring stable steady state thermal conditions (see Fig. 7). Prior to each test, each workpiece material was left for a few seconds to reach ambient temperature (~ 19 °C). It is worth mentioning that the lowest values of process outputs (i.e. tool wear, R_a and burr height) are crucial for the quality

Fig. 6 Image of experimental setup using (Cut-list)**Table 4** Chemical composition/thermo-physical properties of the water-soluble cutting fluid (Vasco1000)

Composition/property	Corresponding value
Mineral oil content	0%
Oleoyl sarcosine (additives)	1.0–2.4%
Methylenebismorpholine (additives)	1.0–4.9%
Zinc alkyl dithiophosphate (additives)	1.0–4.9%
pH value	8.5–9.2
Mass density (kg/m^3)	988
Dynamic viscosity at 25 °C (cP)	1.8
Average heat capacity at 25 °C ($\text{J/g}^\circ\text{C}$)	3.97

improvement of the machined parts and reducing manufacturing costs. For this reason, ‘the-lower-the-better’ criterion was adopted in this study. For workpiece temperature, surface roughness, burr height and tool wear, three measurements were taken for each test and average was calculated.

4 Results and discussion

4.1 Process analysis and effect of the new system (part I)

Cutting force Figure 8 shows the effect of process variables on the cutting force. The best settings to minimise cutting forces when shoulder milling Ti-6Al-4V were found to be 95-m/min cutting speed, 0.1-mm/rev feed rate and nozzle position at 15° in the feed direction, 45° against feed direction and 75-mm impinging distance. Feed rate was found to have a considerable influence on the cutting force over the evaluated range; i.e. cutting forces increased with the increase of feed rate. This is due to the high correlation between cutting force and cutting area (where uncut chip thickness is part of it) and

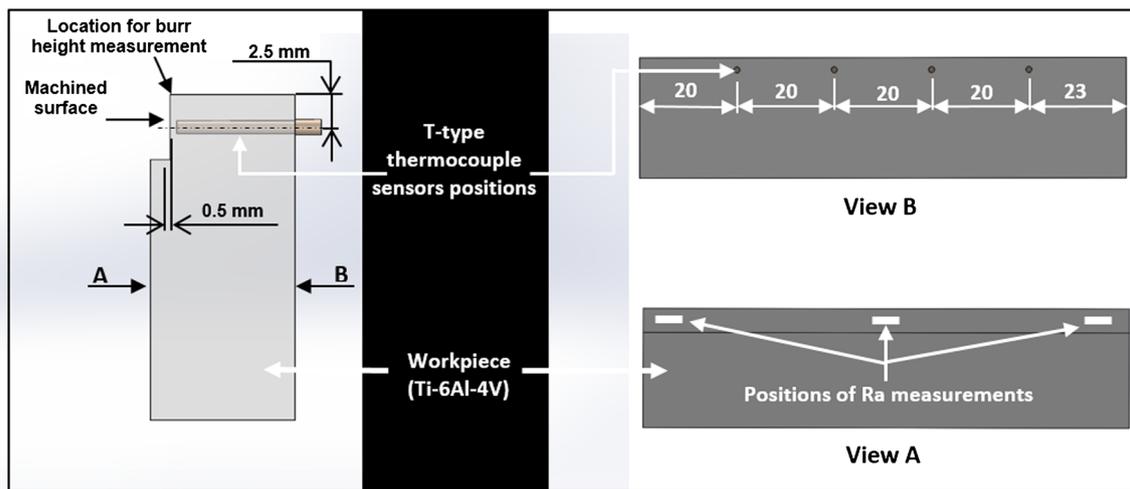


Fig. 7 Positions of R_a measurement (view A) and thermocouple arrangement (view B) for workpiece temperature measurement (dimension in mm)

thus to feed rate. It was also noticed that cutting force increased with higher cutting speed. This agrees with the assumption that more energy is required to remove a higher volume of material and hence higher cutting force [59, 60], although this is in disagreement with the finding that higher cutting speeds may cause material softening, and hence lower cutting forces when machining steel alloys as described by Veiga et al. [36]. Additionally, variations in nozzle positions/angles and impinging distance had only a limited impact on cutting force.

Workpiece temperature Figure 9 presents the variation of average workpiece temperatures functions of all process variables evaluated in this research. Average workpiece temperature values ranged between 23.5 and 27.5 °C. This is probably because only a small proportion (~20%) of the heat

generated when cutting titanium is conducted into the workpiece and chip whilst 80% of the heat are expected to be transferred to the cutting tool [61]. In addition, the impinging fluid jet on targeted heat-affected zones helped to dissipate more than 30% of the heat generated during the cutting process [35].

Additionally, the decrease in workpiece temperature with higher cutting speeds can be attributed to the increase in cutting fluid flow rate associated with increasing cutting energy (in accordance with increasing working conditions). Increasing the flow rate resulted in improving the cooling capacity of the cutting fluids which assisted to transfer more heat from the workpiece to the cutting fluid, hence a reduction in workpiece temperature. Unexpectedly, the optimal (low) workpiece temperature was recorded at the higher cutting condition and nozzle position at an angle of 15° in the feed

Fig. 8 Main effects analysis for cutting force

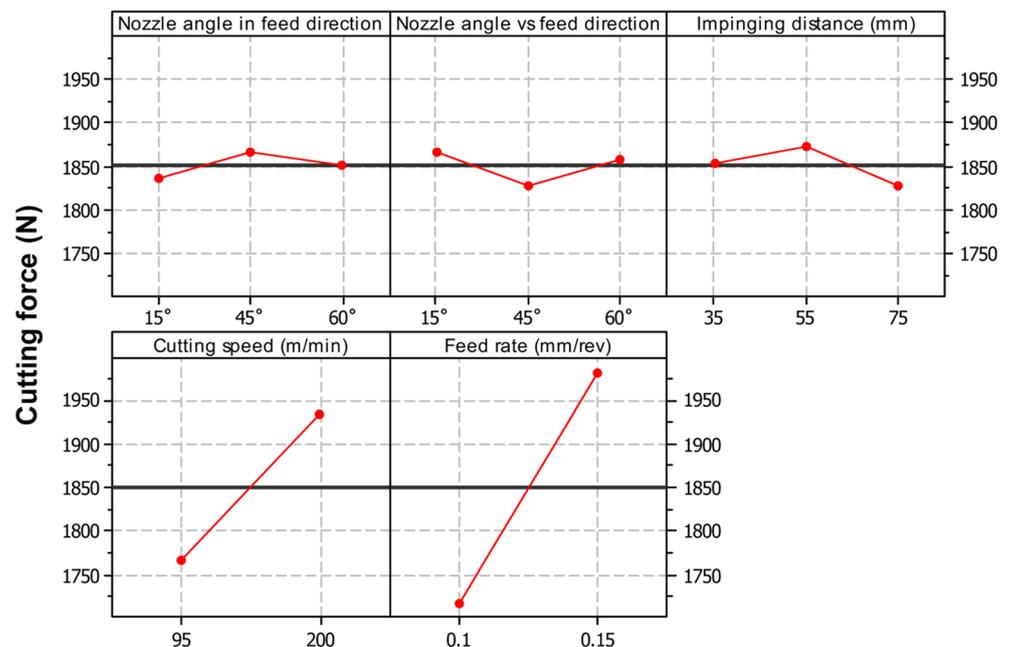
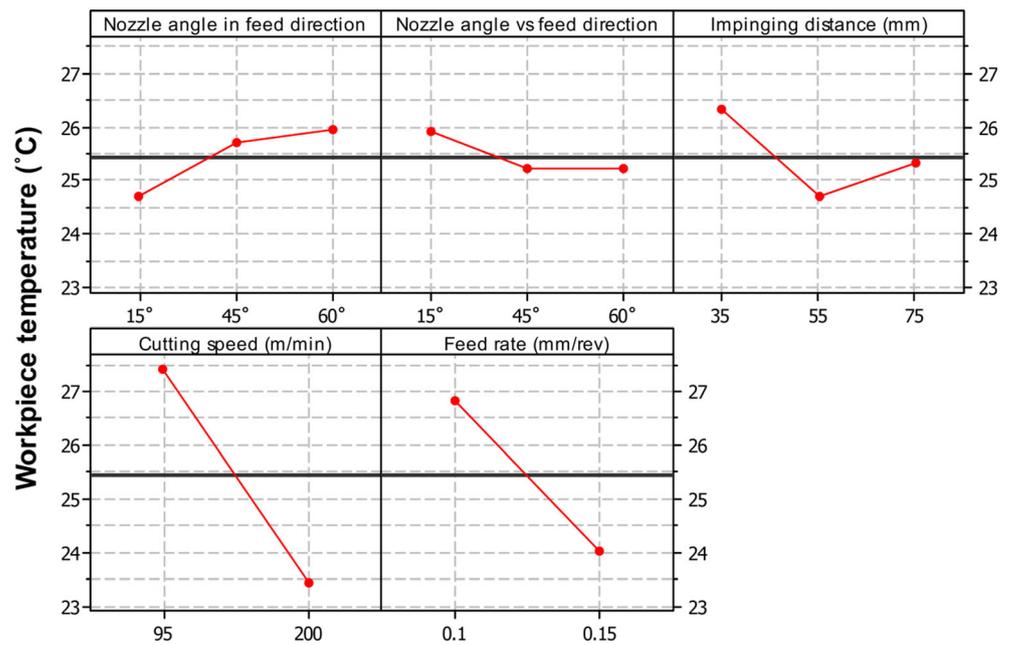


Fig. 9 Main effects analysis for workpiece temperature

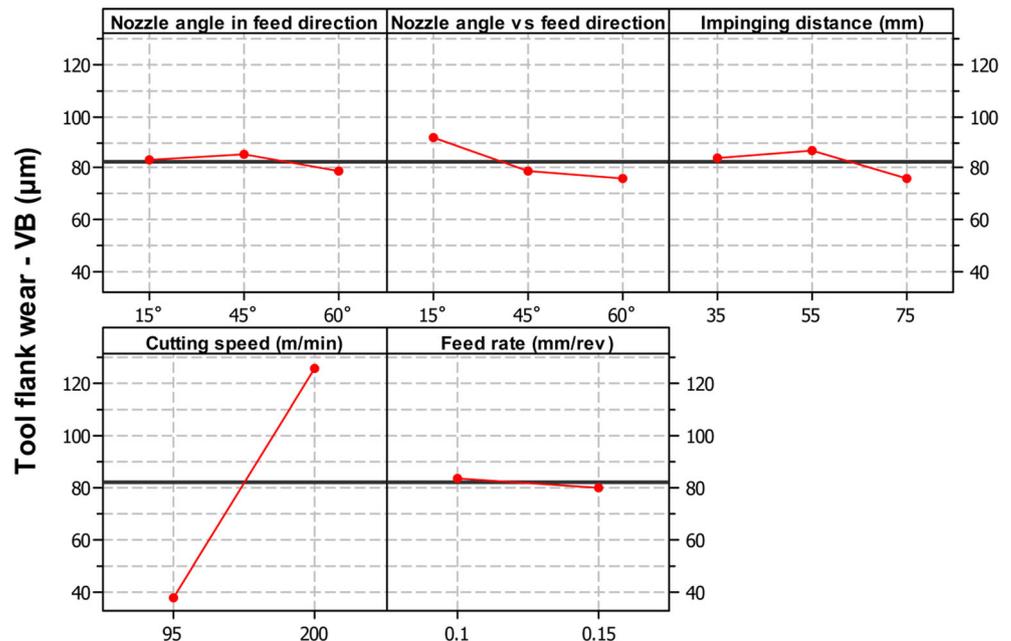


direction and 45°/60° against feed direction, and an impinging distance of 55 mm. This is due to the increase in the fluid flow rate associated with increasing cutting energy (see Fig. 5), which improved the fluid’s ability to transfer more heat from the workpiece to the cutting fluid. Feed rate, impinging distance and nozzle positions, particularly in the feed direction, showed a considerable response to average workpiece temperature.

Tool flank wear Figure 10 demonstrates the effects of control factors on mean values of tool flank wear (VB). A cutting

speed of 95 m/min, feed rate of 0.15 mm/rev and nozzle location at 15° in the feed direction and 45° against feed direction and an impinging distance of 75 mm can be selected as the optimal cutting conditions for controlling tool wear. However, the use of the controlled cutting fluid through the developed Cut-list system meant that tool wear increased rapidly with increased cutting speed owing to the rise in heat generated. The heat generated at the tool edge would have softened the insert edge, causing tool flank wear to sequentially increase [62]. Tool flank wear values seem to be independent of feed rate, nozzle position and impinging distance. It can also be

Fig. 10 Main effects analysis of tool flank wear



concluded that the traditional understanding that cutting speed is the dominant variable affecting tool wear is still applicable to the Cut-list cutting fluid supply system.

Figure 11 shows an SEM analysis of the used uncoated WC cutting tool edges at various cutting conditions. Wear occurred mainly on the flank face of the cutting tool where uniform abrasive wear was observed at low cutting speed, whereas adhesion has already taken place at higher cutting speed. The adhered substances were examined using EDX, and the presence of titanium element in the adhered materials on the rake face of the tool substrate was found, as shown in Fig. 12. In addition, a few elements such as tungsten (W) and cobalt (Co) from the tool substrate were found in the adhered workpiece material at higher cutting speed, which proves that diffusion took place. The increase in heat generated with increased cutting energy may offer a good atmosphere for the diffusion of tool material atoms across the tool-workpiece interface, and thus, by impairing bonding strength in the tool materials, diffusion wear has occurred [63].

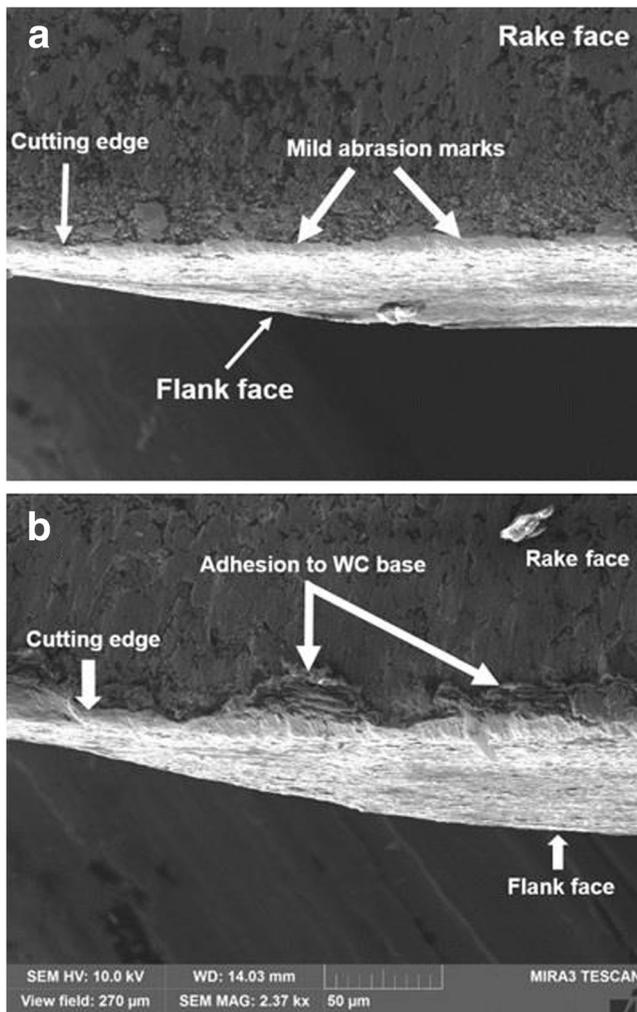


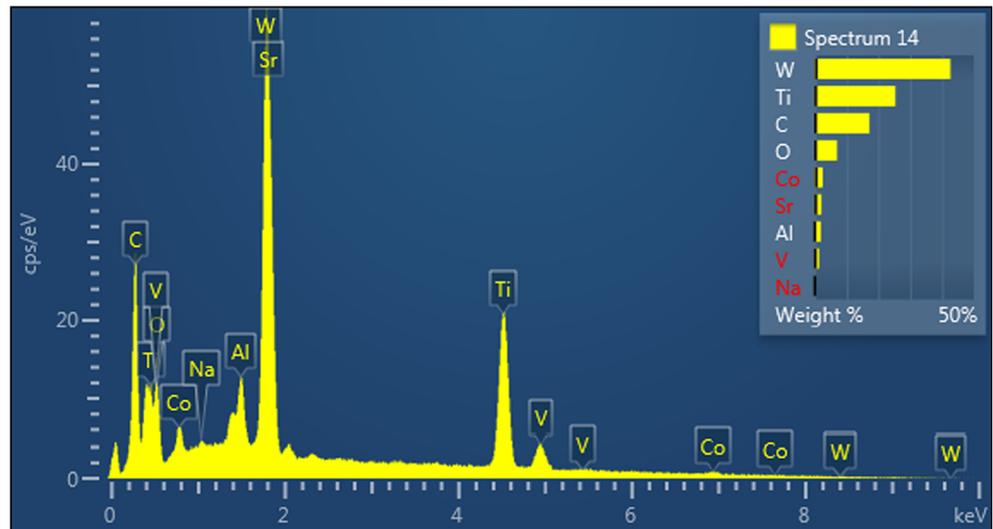
Fig. 11 SEM micrographs of worn tools used to machine Ti-6Al-4V at a 95 m/min, 0.1 mm/rev, and **b** 200 m/min, 0.1 mm/rev

Burr formation Figure 13 presents the variation in average burr height measured at the edge of the machined surface as a function of various process variables assessed in this work. The smallest burr height can be achieved at 200-m/min cutting speed, 0.15-mm/rev feed rate, nozzle location at 45° in the feed direction and 45° against feed rate direction and an impinging distance of 55 mm. It was observed that burr height tends to decrease rapidly with increased cutting speed and feed rate, and it is relatively sensitive to impinging distance rather than nozzle positions/angles. This is deemed to be due to the impinging distance affecting the fluid velocity [64], which led to maintaining the cutting edge in a sharper condition with less metal seizing. In addition, cutting speed and nozzle angle do not show a significant impact on burr height. Figure 14 shows burrs formed on the milled top surfaces of Ti-6Al-4V at various cutting conditions.

Surface integrity Average surface roughness (R_a) results at various process and system levels are shown in Fig. 15. Minimum surface roughness was achieved at a cutting speed of 200 m/min, feed rate of 0.1 mm/rev, nozzle positions of 45° and 60° in feed and against feed direction, respectively, and 75-mm impinging distance. Surface roughness values were found to decrease with rises in cutting speed and decreased feed rates. This can also be attributed to the increase in cutting fluid flow rate associated with increased cutting speed (see Fig. 5). A comparable finding was also reported recently [64] when Xiao et al. investigated the end-milling of Ti-6Al-4V under MQL at four different fluid supply rates (2, 6, 10 and 14 ml/h). However, the effect of feed rate on mean values of R_a seems much higher than that of cutting speed. This is likely to be due to the theoretical surface roughness being directly proportional to the square of the feed per revolution. In the same vein, decreased feed rate possibly gave the cutting fluid enough time to carry away the heat from the machining zone, and led to a low material removal rate and the accumulation of chip in the tool-workpiece zones, which resulted in an improved surface finish. It was noted that the major effective parameter to reduce R_a is the feed rate, whilst cutting speed and impinging distance showed less noticeable effects on R_a values. Additionally, SEM images for titanium samples before and after the machining trials confirmed that no major changes in the micro-structure as well as no signs for surface or sub-surface damage are seen in Fig. 16.

Nozzle position effect Workpiece temperature was found to be influenced by nozzle position/angle, in particular in the feed direction, as can be seen in Fig. 9. Seemingly, locating nozzle at 15° in the feed direction helped to create efficient fluid trapping between the tool and workpiece surfaces which, in turn, led to improving the accessibility of cutting fluid into the machining zone to perform both cooling and lubrication functions adequately. A similar phenomenon was observed in

Fig. 12 EDX analysis performed on the rake face of the insert at cutting speed of 200 m/min and feed rate of 0.1 mm/rev



another study [65], where it was found that shifting the nozzle from a 45° angle to an acute angle of 12.5° in the feed direction when end-milling H13 steel under MQL assisted in increasing the amount of cutting fluid reaching the machining zone. Additionally, the proximity of the nozzle positioned at an angle of 15° from the tool-workpiece contact point contributed in minimising the fluid particle dispersion caused by tool rotation, which allowed them to adhere to the tool and workpiece surfaces effectively and to persist in working as a lubricant in the machining zone. Conversely, at the nozzle positions of 45° or 60°, more cutting fluid particles are driven away from the tool surface whilst the cutting tool rotates in a cyclic loop process [66]. In addition, nozzle placement at an angle of 45° or 60° against feed direction tends to offer enough space to assist in chip evacuation and this helped to minimise

the interference between the impinging jet and the removed chip, which led to better lubricating and cooling ability and consequently improved machined surfaces.

Impinging distance effect According to Figs. 9, 13 and 15, impinging distance had a noticeable impact on workpiece temperature, burr formation and average surface roughness. According to Bernoulli’s equation (Eq. 4) [66], the hydraulic head (h) (where in this case, the impinging distance is equal to the hydraulic head) has an effect on jet velocity, and this consequently affected fluid penetration efficiency. The cutting fluid jet velocity (V_j) increases as the impinging distance decreases. However, too short impinging distance has a negative effect on the cutting fluid droplets owing to their high levels of rebounding from the workpiece and cutter surfaces [66].

Fig. 13 Main effects analysis for average burr height

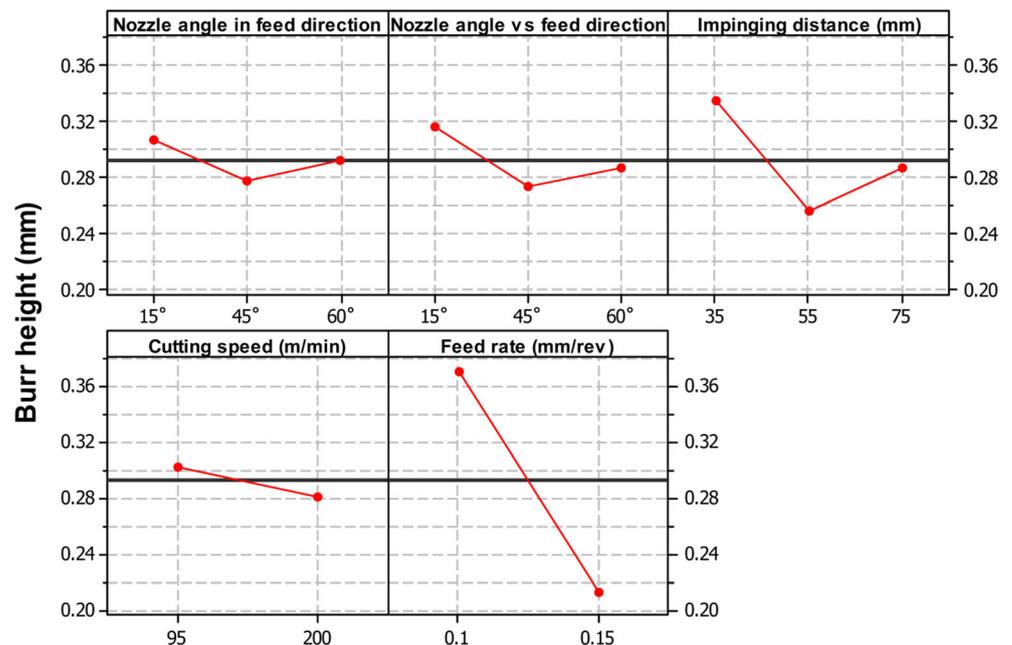
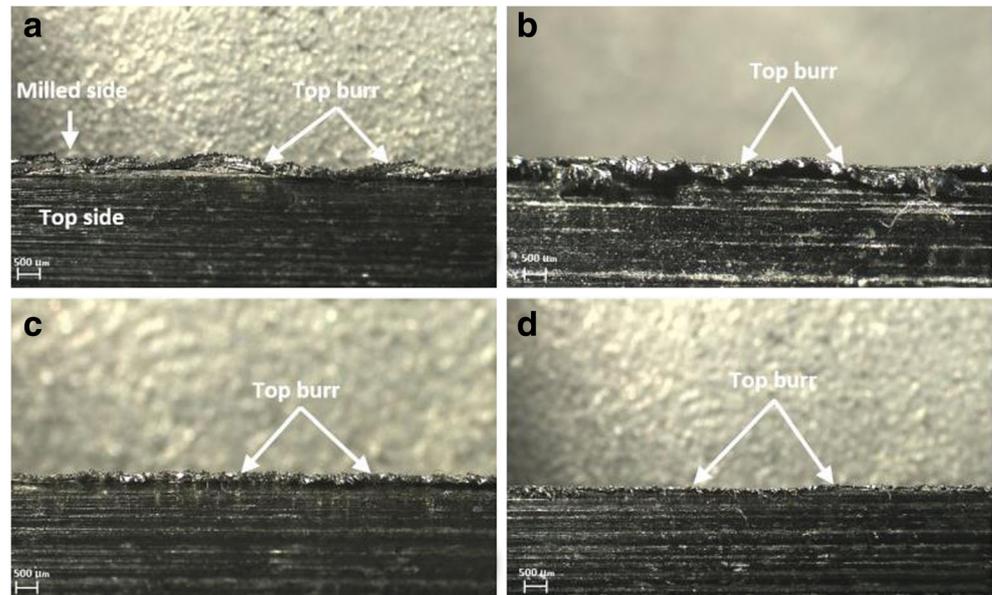


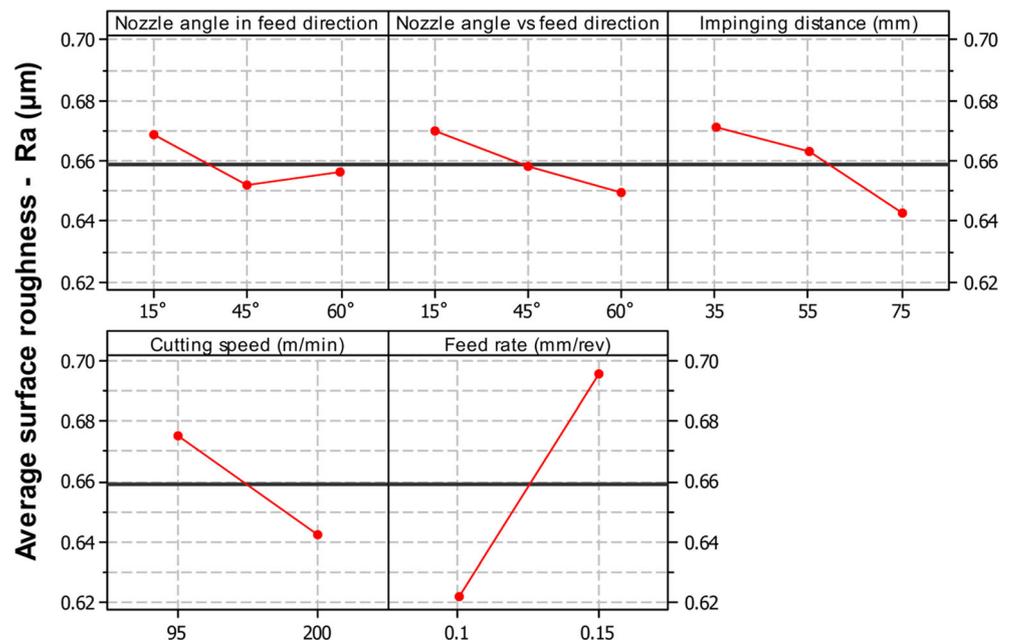
Fig. 14 Images for the burrs formed on milled top surfaces at different cutting conditions. **a** 95 m/min \times 0.1 m/rev. **b** 95 m/min \times 0.15 mm/rev. **c** 200 m/min \times 0.1 mm/rev. **d** 200 m/min \times 0.15 mm/rev



Therefore, impinging distance should be controlled at an optimal level, as the impact of shorter impinging distance would be to conspicuously affect the workpiece temperature, burr formation and average surface roughness. Since the optimal impinging distances obtained for controlling the aforementioned responses were 55/75 mm, they tend to have a combined action by improving the fluid penetration ability with less fluid dispersion and spring-back effect, which in turn assisted the cutting fluid droplets to adhere firmly to the workpiece and cutter surfaces.

$$\frac{1}{2} \rho V_j^2 + \rho g h + p = \text{constant} \quad (4)$$

Fig. 15 Main effects analysis for surface roughness



4.2 Performance comparison with a conventional flood system (part II)

Data collected using the new system was compared with a conventional (uncontrolled) flood supply system. The best results were considered (i.e. amongst every 27 tests conducted at the same cutting speed and feed rate). In general, the new system (Cut-list) showed better performance compared to the conventional system although the 42% reduction in cutting fluid consumption achieved by the Cut-list. Cutting force ranged between 1600–1903 N and 1340–1879 N for the conventional and new system, respectively. This provided a

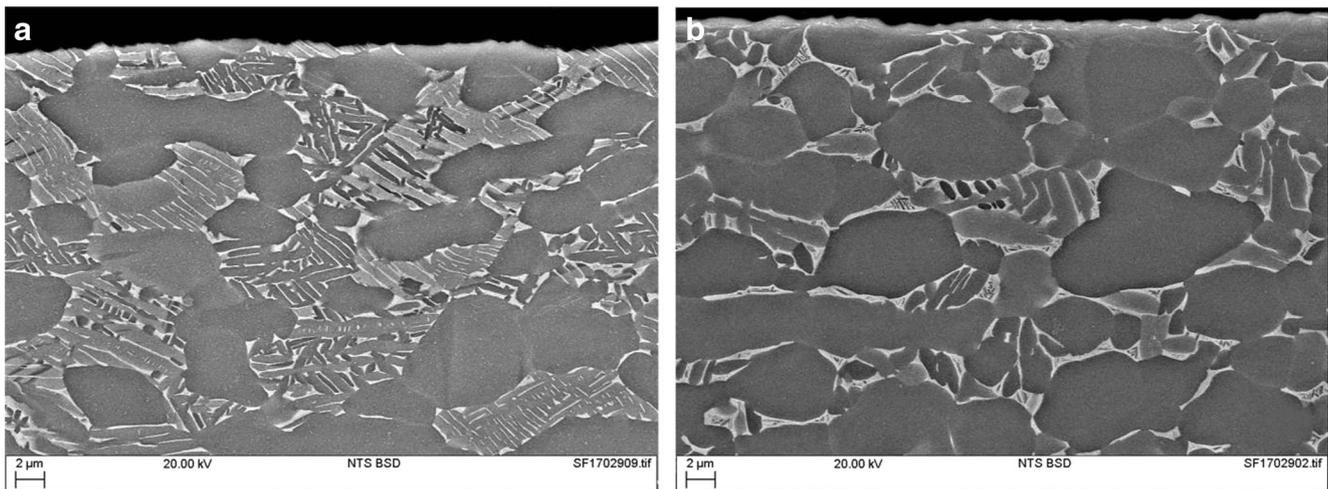


Fig. 16 SEM images for the micro-structure of **a** as received annealed Ti-6Al-4V and **b** machined surface using the new Cut-list at 200-m/min cutting speed and 0.15-mm/rev feed rate

reduction of 16% in cutting force, particularly at a low feed rate (0.1 mm/rev) owing to the good penetrability of the new system, which led to forming the boundary of the oil film between the workpiece and cutting tool surfaces, resulting in reducing contact pressure. Additionally, a significant reduction in tool wear up to 46.77% was achieved at the higher cutting condition (i.e. 200 m/min and 0.15 mm/rev) utilising the Cut-list. Impinging the cutting fluid in both directions (with and against feed) helped to penetrate the fluid effectively into machining zone and cool the tool insert at the end of the cyclic process. In terms of burr formation, burr height ranged between 0.11–0.41 mm and 0.1–0.17 mm for the conventional and new system, respectively. This afforded a significant reduction up to 31.70% in burr height, particularly at higher cutting speed (i.e. 200 m/min) owing to the high velocity of the jet (i.e. 10 m/s). In addition, no substantial differences were found between systems in workpiece temperature results (maximum of 1.5 °C), whilst average surface roughness (R_a) values were relatively smaller with the use of the new system.

5 Conclusions

This paper presents a comprehensive experimental evaluation of a new cutting fluid supply system (Cut-list) when machining Ti-6Al-4V using vegetable oil-based cutting fluid. In general, the new system (Cut-list) was found to perform favourably as compared to the conventional system. It significantly reduced cutting fluid consumption up to 42%, cutting force by 16.41%, tool flank wear by 46.77% and burr formation by 31.70%. However, no notable discrepancy in workpiece temperature values was found between the two systems [67]. Feed rate was the dominant factor affecting mean cutting force, burr formation and surface roughness, whilst cutting

speed has the greatest impact on workpiece temperature and tool flank wear. The cooling performance of the new system is relatively sensitive to nozzle positions and impinging distance with respect to workpiece temperature, burr formation and surface roughness (R_a). Lastly, it can be concluded that coherent round nozzle can be used effectively to replace conventional sloped nozzle in milling operations.

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