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Effect of Cooling Coherent Nozzle Orientation on the Machinability of Ti-6Al-4V in Step Shoulder Milling

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Abstract**—**In this work, a cooling coherent round nozzle was developed and the impact of nozzle placement (i.e. nozzle angle and stand-off/impinging distance) on the machinability of Ti-6Al-4V was evaluated. Key process measures were cutting force, workpiece temperature, tool wear, burr formation and average surface roughness (Ra). Experimental results showed that nozzle position at a 15° angle in the feed direction and 45°/60° against feed direction assisted in minimising workpiece temperature. A stand-off distance of 55 and 75 mm is also necessary to control burr formation, workpiece temperature and Ra, but coherent nozzle orientation has no statistically significant impact on the mean values of cutting force and tool wear. It can be concluded that stand-off distance is more substantially significant than nozzle angles when step shoulder milling Ti-6Al- 4V using vegetable oil-based cutting fluid.

Keywords**—**Coherent round nozzle, step shoulder milling, Ti-6Al-4V, vegetable oil-based cutting fluid.

I. INTRODUCTION

MACHINING is the most prevalent metal shaping process in the manufacturing industry. Turning, milling, boring, drilling, grinding and shaping are common metal cutting processes employed on machine shop floors nowadays [1].

Most machining processes cannot be implemented efficiently without cutting fluids, particularly when cutting refractory materials such as nickel, iron, cobalt and titanium-based alloys where excessive generated heat is the main problem [2], [3]. Cutting fluids also prevent corrosion and contribute to reducing the friction between the cutting tool and workpiece material due to their lubrication action at lower cutting speeds and dissipate heat from the machining zone by cooling at higher cutting speeds, resulting in extended tool life and improved machining quality [4]. Cutting fluids are categorised in three main groups of neat cutting oils and water-soluble and gas-based fluids [5], [6]. Mineral oil (MO)-based cutting fluids are widely used in the machining industry. However, they pose various environmental and health issues throughout their lifecycle [7], [8].

Recently, vegetable oil (VO)-based fluids have been suggested as favourable alternatives to conventional fluids owing to their superior tribological properties and high biodegradability [9]-[12]. Cutting fluid can be delivered into the machining zone using different cutting fluid supply systems, such as conventional flooding, high pressure cooling (HPC), minimum quality lubricant (MQL), oil mist and cryogenic cooling [13]-[16]. However, the cutting fluid supply is not only influenced by the fluid type and the amount of fluid supplied but also by nozzle type and design, which significantly affect the cutting fluid's speed and positioning as well as power consumption [17], [18]. The conventional sloped nozzle is the predominant nozzle type, particularly in standard machining such as turning, milling, and drilling. However, other nozzle types such as coherent, tapered, slot, spot jet, and shoe-type nozzles are often utilised during various grinding operations such as cylindrical and surface grinding [19], [20]. This is probably because the grinding process can generate a huge amount of heat compared to other machining operations owing to the large contact area between the grinding wheel and the workpiece surface [21]. It is concluded from a review of the relevant literature that the pace of development of cutting fluid nozzle design, particularly for milling and turning operations, is still slower than for grinding. In practice, the majority of existing commercial computer numerical control (CNC) lathes and milling machines are fitted with two or more conventional slopped nozzles which are commercially known as the Loc-line nozzle [22]. These are used particularly in flood cooling supply systems where an ample amount of cutting fluids is required. These nozzles are often made of plastic with spherical or conical connectors that can be directed manually at any required position randomly during the cutting operation [17]. The knowledge gap addressed in this work relates to the development of a new efficient and inexpensive round coherent nozzle instead of the conventional sloped nozzle, which will assist in propelling cutting fluid further into the machining zone during the step shoulder milling of Ti-6Al-4V. Furthermore, the use of a coherent nozzle in standard machining milling operations may encourage machine tool manufacturers to accommodate the next generation of commercial CNC milling and lathe machines with coherent nozzles to increase the efficiency of cooling supply systems.

II. DEVELOPMENT OF THE NEW COHERENT ROUND NOZZLE

The coherent nozzle developed here was built based on Webster's model [23]. According to Irani et al. [24], a nozzle with a rounded shape has a unique inner shape with convex walls which is able to produce a better jet stream, guaranteeing flow coherency with less dispersion of fluid during its. The

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unique characteristics of nozzle geometry have the ability to increase kinetic energy (dynamic pressure) by up to four times in the form of a homogenous jet, assisting the cutting fluid to penetrate further into the cutting region [25]. To comply with the criteria of fluid dynamics and flow coherence, the contraction ratio (D/d) was set at 6.85:1. Fig. 1 shows a 3D sectional view of the bespoke coherent round nozzle used throughout the work, while Table I details the dimensions and contraction ratio of the nozzle. The nozzles were made from PETG (Polyethylene Terephthalate Glycol) filaments using a MakerBot 3D printing machine. Additionally, the coherent nozzles were designed to supply cutting fluid both in and against the feed direction simultaneously. Moreover, the nozzles can be aligned 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. The design of the adjustable nozzle holder allows the nozzle discharge tips to be placed away from the tool-workpiece contact zone at different stand-off distances of 35, 55 and 75 mm. The existing coolant pump of the CNC Cincinnati 750-Sabri was used to carry the cutting fluid. The pump was placed directly over the cutting fluid tank so as to minimise the pressure drop in the system's feed pipes. The output flow rate was controlled using an oval gear digital type flow meter/ regulator located 300 mm away from the coolant pump in order to ensure steady-state flow. Fluid pressure was monitored employing an OMEGA DPG digital type and dual scale pressure gauges which were mounted directly after an in-line type filter and before the cutting fluid entered the nozzles.

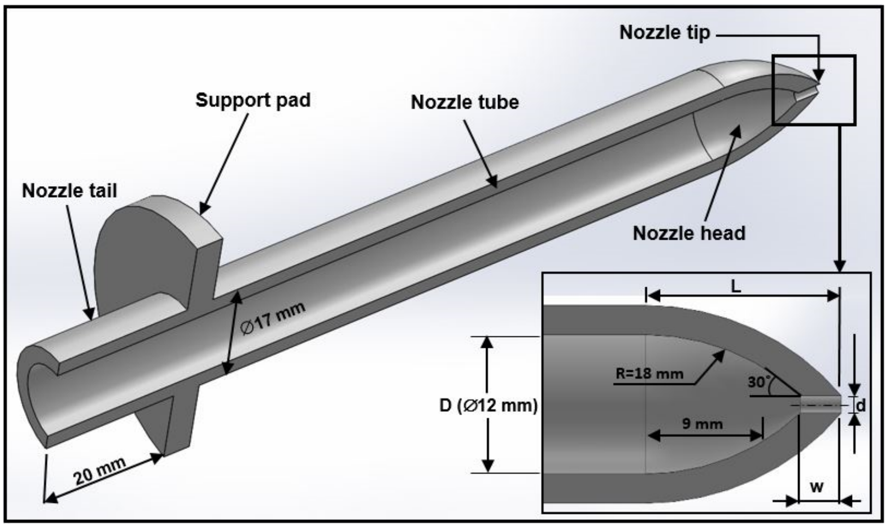

Fig. 1 3D sectional view of bespoke coherent round nozzle

TABLE I
Internal Geometry of Bespoke Coherent Round Nozzle

Dimension	Value
Nozzle internal diameter (D)	12 mm
Nozzle aperture diameter (d)	1.75 mm
Contraction ratio (D/d)	6.85:1
Nozzle head length (L)	16 mm
Nozzle mid-section radius (1.5D)	18 mm
Nozzle mid-section axial length (0.75D)	9 mm
Nozzle aperture cross-sectional width (w)	3.4

The developed nozzles were fixed and mounted on a CNC Cincinnati 750-Sabri vertical machining centre using an angled overhead nozzle ring placed on a vertical spindle head holding two nozzles for the delivery of fluid at three different angles of 15˚, 45˚ and 60˚ in the feed direction and similar angles against the feed direction as shown in Fig. 2.

III. Design of Experiment

A full factorial experimental design (2x2x3x3x3) was used in this study, which gives a total of 108 tests. Table II shows the control factors and corresponding levels. Mean effect analysis and analysis of variance (ANOVA) were performed to determine the influence of nozzle orientation in the milling of Ti-6Al-4V using VO-based cutting fluid.

IV. Experimental Work

Rectangular plates 25 mm in height, 11 mm thick and 103 mm long were used as workpiece materials [26]. These plates were made of Ti-6Al-4V with a hardness of 36 HRC. All milling trials were conducted on a 3-axis CNC Cincinnati Milacron 750-Sabre VMC, as shown in Fig. 3. Each test involved a machining length of 102 mm, and a fresh indexable milling insert was employed to avoid the accumulation of wear from different trials. Axial (ap) and radial (ae) depths of cut of 5 mm and 1.3 mm respectively and a nozzle elevation angle (α) of 40˚ were maintained in all trials.

Sandvik H13A uncoated milling carbide inserts with a positive rake angle were utilised. In order to avoid the effect of tool run-out on the examination of tool flank wear, the inserts were mounted on a single tooth milling tool holder having a total length of 110 mm and diameter of 18 mm. The lead angle (κ) and overhang span of the tool holder were 90° and 60 mm respectively. Fig. 4 shows the shape and geometry of the

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milling insert (R390-11 T3 08M-KM) used in all machining tests. A commercial water-soluble VO-based lubricant (BLASER VASCO 1000) was used. This lubricant is based on non-edible VOs (45%) which are biodegradable and more efficient lubricants than conventional petroleum-based fluids. Fresh lubricant was mixed with water at a 10% concentration (1:10 oil-to-water ratio) and was monitored regularly using a portable refractometer. The heat capacity, mass density and dynamic viscosity of the mixed lubricant were; 3.98 J/g/°C, 987.92 kg/m^3 and 1.84 cP at 30 °C respectively [27].

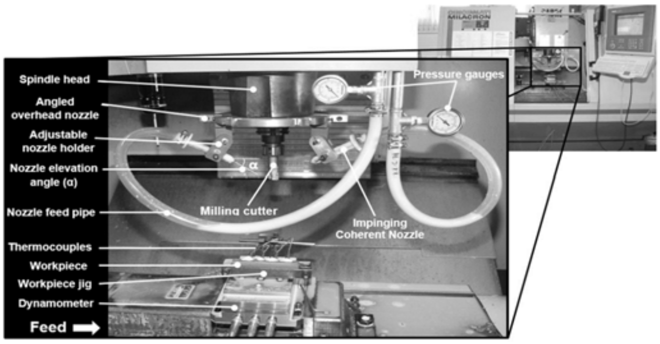


Fig. 2 Image of experimental set-up using bespoke coherent round nozzles

TABLE II
CONTROL FACTORS AND CORRESPONDING LEVELS

Factor	Level 1	Level 2	Level 3
Nozzle angle positions in the feed direction	15˚	45˚	60˚
Nozzle angle positions against the feed direction	15˚	45˚	60˚
Nozzle stand-off (mm)	35	55	75
Cutting speed (m/min)	95	200	
Feed rate (mm/rev)	0.1	0.15	

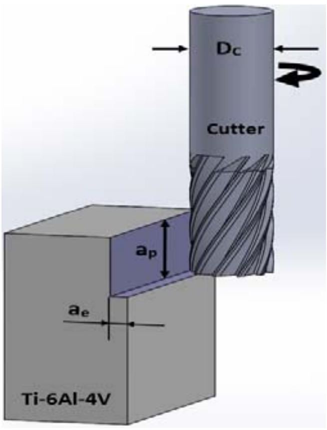
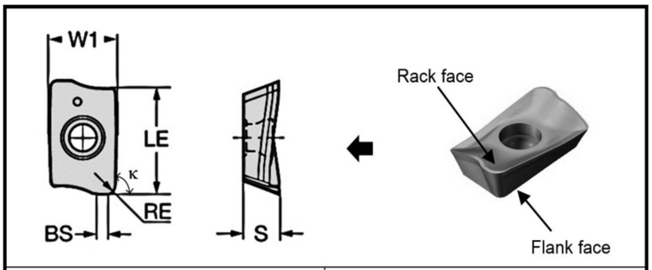


Fig. 3 Schematic of step shoulder milling of Ti-6Al-4V

A Taylor Hobson surface tester (Surtroni III) was used to quantify the average surface roughness (Ra) of the machined parts. The average tool flank wear (VB) was also measured after each cutting trial using an optical 3D microscope (Alicona Infinite Focus G4). Each trial involved a cutting length of 103 mm, the worn insert was removed after each test, and a fresh insert tip was used to maintain reference (zero) tool wear conditions. All measurements of Ra and tool flank wear were carried out in accordance with ISO 4287/4288 and 8688/2 respectively. A three-component dynamometer (Kistler 9257) was employed for force measurements and a three-channel amplifier was used to amplify signals for the measurement of cutting forces. A digital micro-depth gauge was used to measure burr formation on the machined samples. Four thin mineral insulated thermocouple sensors (Type T) were employed to measure the temperature underneath the workpiece surface. Each sensing probe is 10 mm long with a diameter of 1.0 mm. The sensing probes were inserted into each sample to measure the temperature at 0.5 mm beneath the milled surface. An Onset HOBO 4-channel data logger and HOBOware were used for data collection and analysis.



Insert width (W1) = 6.8 mm	Insert thickness (S) = 3.6 mm
Corner/nose radius (RE) = 0.8 mm	Cutting edge length (LE) = 10 mm
Wiper edge length (BS)= 1.2 mm	Major cutting edge angle (κ) = 90°

Fig. 4 Geometry of R390-11 T3 08M-KM milling insert [28]

V. RESULTS AND DISCUSSION

A. Cutting Force

Fig. 5 shows the effect of nozzle orientation on cutting force at the optimal cutting conditions of 95 m/min and 0.1 mm/rev. The best nozzle position to minimise cutting forces when shoulder milling Ti-6Al-4V was found to be 15˚ in the feed direction and 45˚ against the feed direction with a stand-off distance of 75 mm. On the other hand, the ANOVA analysis (Table III) suggested that nozzle orientation had no statistically significant effect with only a limited impact on cutting force, whereas feed rate made a major contribution (47.64%) in minimising cutting force. This is due to the high correlation between cutting force and cutting area (which includes uncut chip thickness) and thus with feed rate. It was also noted that cutting force increased with higher cutting speed. This agrees with the assumption that more energy and hence higher cutting force is required to remove a higher volume of material [29], [30].

B. Average Workpiece Temperature

Average workpiece temperature was found to be influenced by nozzle orientation (nozzle angle and stand-off distance), in particular in the feed direction at the optimal cutting conditions of 200 m/min and 0.15 mm/rev, as can be seen in Fig. 6. Positioning the nozzle at 15˚ in the feed direction apparently helped to create the efficient trapping of fluid between the tool and workpiece surfaces which, in turn, led to the improved access of cutting fluid to the machining zone so as to perform both cooling and lubrication functions adequately. A similar phenomenon has been observed in another study [31] 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˚ to the tool/workpiece contact point contributed in minimising the particle dispersion in the fluid caused by tool rotation, which allowed the particles to adhere to the tool and workpiece surfaces more effectively and to persist in working as a lubricant in the machining zone. Conversely, at nozzle positions of 45˚ or 60˚ in the feed direction, more cutting fluid particles were driven away from the tool surface while the cutting tool rotated in a cyclical loop process [32]. In addition, nozzle placement at an angle of 45˚ or 60˚ against feed direction tends to offer sufficient space to assist in chip evacuation. This helped to minimise interference between the impinging jet and the removed chip, leading to better lubrication and cooling ability and consequently improved machined surface quality. Apart from other control factors such as feed rate and cutting speed, the ANOVA analysis (Table IV) showed that nozzle orientation has a considerable effect on average workpiece temperature, while stand-off distance was the most influential factor (5.20%) affecting workpiece temperature compared to nozzles angles in and against the feed direction (3.29% and 1.19% respectively).

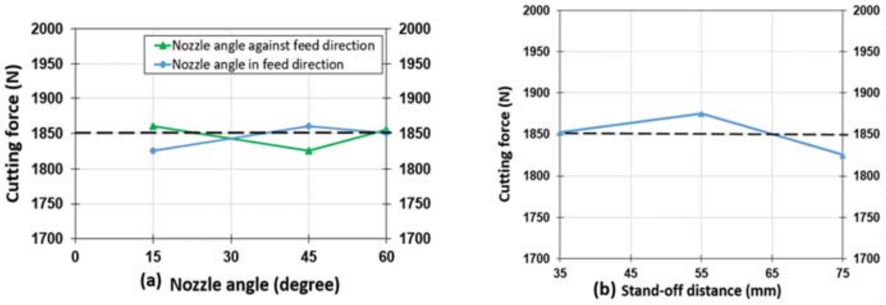


Fig. 5 Mean effect analysis of nozzle orientations for cutting force at optimal cutting conditions: (a) nozzle angle; (b) stand-off distance

TABLE III
ANOVA RESULTS FOR CUTTING FORCE

Source	DF	SS	MSS	F	P	PCR
Nozzle angle in the feed direction (degrees)	2	16525	8263	0.66	0.520	0.41%
Nozzle angle against the feed direction (degrees)	2	28991	14495	1.15	0.320	0.72%
Stand-off distance (mm)	2	37345	18672	1.49	0.231	0.93%
Cutting speed (m/min)	1	764510	764510	60.86	0.0*	19.14%
Feed rate (mm/rev)	1	1903072	1903072	151.49	0.0*	47.64%
Error	99	1243674	12562			31.13%
Total	107	3994117				

S = 112.082; R-Sq = 68.86%; R-Sq (adj) = 66.35%

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

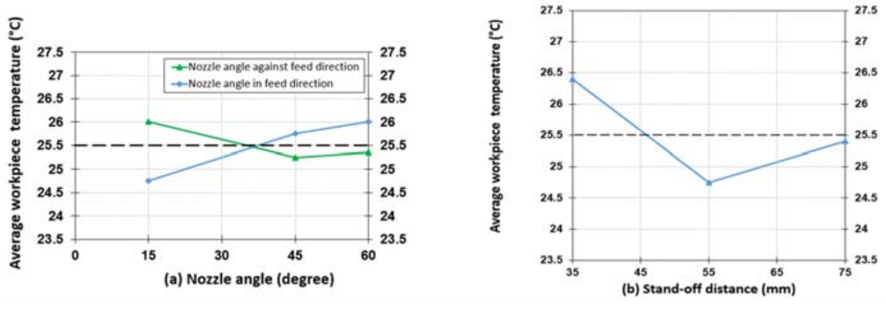


Fig. 6 Mean effect analysis of nozzle orientations for average workpiece temperature at optimal cutting conditions: (a) nozzle angle; (b) stand-off distance

C. Tool Wear (VB)

Fig. 7 presents the effects of control factors on the mean values of tool flank wear (VB). Generally, tool wear mean values ranged between 38 µm and 128 µm. Nozzle locations at 15˚ in the feed direction and 45˚ against the feed direction and a stand-off distance of 75 mm can be selected as the best nozzle position for the control of tool wear at the optimal cutting conditions of 95 m/min and 0.15 mm/rev. Furthermore, the ANOVA results (Table V) indicate that cutting speed has a statistically significant impact in minimising VB, with a percentage contribution ratio (PCR) of 59.23%, while tool wear values seem to be independent of nozzle orientation in terms of angles and stand-off distance as well as feed rate.

TABLE IV
ANOVA RESULTS FOR AVERAGE WORKPIECE TEMPERATURE

Source	DF	SS	MSS	F	P	PCR
Nozzle angle in the feed direction (degrees)	2	30.805	15.403	7.74	0.001*	3.29 %
Nozzle angle against the feed direction (degrees)	2	11.172	5.586	2.811	0.05*	1.19%
Stand-off distance (mm)	2	48.751	24.376	12.25	0.0*	5.20%
Cutting speed (m/min)	1	435.206 46.50	435.206	218.70	0.0*	46.22%
Feed rate (mm/rev)	1	212.801 22.74	212.801	106.94	0.0*	22.74%
Error	99	197.008	1.990			21.05%
Total	107	935.744				

S = 1.410; R-Sq = 78.95%; R-Sq (adj) = 77.25%

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

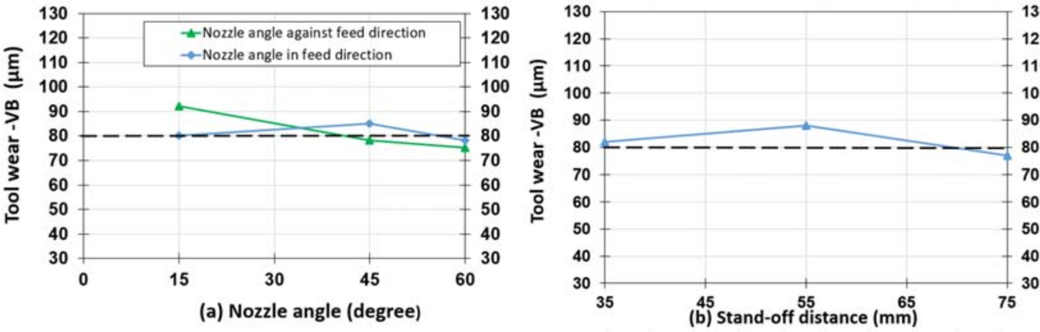


Fig. 7 Mean effect analysis of nozzle orientation for tool flank wear at optimal cutting conditions: (a) nozzle angle; (b) stand-off distance

TABLE V
ANOVA RESULTS FOR TOOL FLANK WEAR

Source	DF	SS	MSS	F	P	PCR
Nozzle angle in the feed direction (degrees)	2	807	403	0.29	0.748	0.22%
Nozzle angle against the feed direction (degrees)	2	5236	2618	1.89	0.157	1.46%
Stand-off distance (mm)	2	2339	1170	0.84	0.434	0.65%
Cutting speed (m/min)	1	212351	212351	152.98	0.0*	59.23%
Feed rate (mm/rev)	1	358	358	0.26	0.613	0.099%
Error	99	137423	1388			38.33%
Total	107	358514				

S = 37.25; R-Sq = 61.67%; R-Sq (adj) = 58.57%

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

D. Burr Formation

Fig. 8 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 best nozzle orientation which gave the smallest burr height at optimal cutting conditions of 200 m/min cutting speed and 0.15 mm/rev feed rate was 45° both in and against the feed direction along with a stand-off distance of 55 mm. It was observed that burr height tends to decrease rapidly with increased cutting speed and feed rate. At lower temperature, the yield stress of the workpiece material increases and smaller burrs are formed [33]. Besides this, it was found that burr formation is relatively more sensitive to impinging and stand-off distance rather than nozzle angle. This can be attributed to the effect of stand-off distance in affecting fluid velocity [34], which leads to the cutting edge being maintained in a sharper condition with less metal tearing. Furthermore, the ANOVA results shown in Table VI indicate that feed rate is the major contributor in minimising burr formation with a PCR of 38.69%, while cutting speed and nozzle orientation have no significant impact on burr height. These trends are in accordance with the findings by Chen et al. [35] that feed rate and tool nose geometry have a substantial effect on burr formation while cutting speed has little influence on top burr height when up-milling Ti-6Al-4V. Fig. 9 shows burrs formed on the milled top surfaces of Ti-6Al-4V at various cutting conditions.

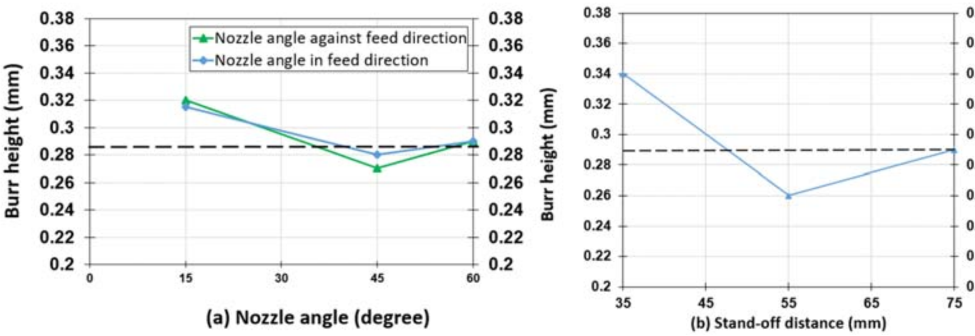


Fig. 8 Mean effect analysis of nozzle orientation on burr formation at optimal cutting conditions: (a) nozzle angle; (b) stand-off distance

TABLE VI
ANOVA RESULTS FOR BURR FORMATION

Source	DF	SS	MSS	F	P	PCR
Nozzle angle in the feed direction (degrees)	2	0.01502	0.00751	0.81	0.446	0.85%
Nozzle angle against the feed direction (degrees)	2	0.03602	0.01801	1.95	0.147	2.04%
Stand-off distance (mm)	2	0.11307	0.05654	6.13	0.003*	6.42%
Cutting speed (m/min)	1	0.01161	0.01161	1.26	0.264	0.62%
Feed rate (mm/rev)	1	0.68163	0.68163	73.95	0.0*	38.69%
Error	99	0.91250	0.00922			51.81%
Total	107	1.76987				
S = 0.096; R-Sq = 48.44%; R-Sq (adj) = 44.28%						

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

E. Average Surface Roughness (Ra)

Fig. 10 shows the effect of nozzle orientation on Ra at the optimal cutting conditions of 200 m/min and 0.1 mm/rev. The best nozzle positions for the minimisation of Ra when shoulder milling Ti-6Al-4V were found to be 45° and 60° in and against the feed direction respectively with a stand-off distance of 75 mm. Ra values were found to decrease with rises in cutting speed and reductions in feed rates. This can also be attributed to the increase in cutting fluid flow rate associated with higher cutting speed. A comparable finding was also reported by Cai et al. [34] in an investigation of 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 Ra seems much higher than that of cutting speed. This is likely to be due to the fact that Ra is theoretically directly proportional to the square of the feed rate per revolution. In the same vein, a lower feed rate possibly gave the cutting fluid sufficient time to carry heat away from the machining zone, leading to a low rate of material removal and the accumulation of chips in the tool-workpiece zone and thereby resulting in an improved surface finish. The ANOVA results (Table VII) show that the most effective factor in reducing Ra is the feed rate (PCR 39.10%) followed by cutting speed and impinging distance, while nozzle angles had little effect on Ra values. It can be noted from Tables IV, VI and VII that stand-off distance has a statistically more significant effect than nozzle angle, and it had a noticeable impact particularly on average workpiece temperature, burr formation, and Ra. According to Bernoulli's Equation (1) [32], the hydraulic head (h) (where, in this case, impinging/stand-off distance is equal to the hydraulic head) has an effect on jet velocity (V_j) and this consequently affects the efficiency of cutting fluid penetration. The cutting fluid jet velocity (V_j) increases as stand-off distance decreases. However, too short a stand-off distance has a negative effect on the cutting fluid droplets owing to the high levels at which they rebound from the workpiece and cutter. Therefore, stand-off distance should be controlled at an optimal level, since shorter stand-off distances would conspicuously affect workpiece temperature, burr formation, and average surface roughness. Since the optimal stand-off distances obtained to control the aforementioned responses were 55 or 75 mm, these tend to exert a combined action by improving fluid penetration ability with less fluid dispersion and spring-back effects, which in turn assists the cutting fluid droplets in adhering firmly to the workpiece and cutter surfaces. Fig. 11 shows the stand-off distance and impingement zones during the shoulder milling of Ti-6Al-4V alloy.

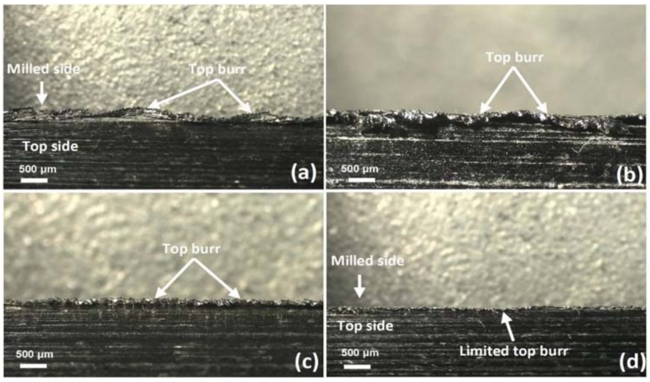


Fig. 9 Images of burrs formed on milled top surfaces at different cutting conditions: (a) 95 m/min x 0.1 m/rev; (b) 95 m/min x 0.15 mm/rev; (c) 200 m/min x 0.1 mm/rev; (d) 200 m/min x 0.15 mm/rev

$$\frac{1}{2}\rho V_j^2 + \rho g h + p = constant. \tag{1}$$

VI. CONCLUSION

In this work, a cooling coherent round nozzle was developed and the impact of the nozzle's orientation (nozzle angles and stand-off distances) on cutting force, workpiece temperature, tool wear, burr formation, and surface roughness have been experimentally examined during the step shoulder milling of Ti-6Al- 4V. The following conclusions are drawn from this work:

1) Nozzle angles both in and against feed direction and stand-off distances were shown to have a noticeable impact on mean values of average workpiece temperature, while the stand-off distance had a more substantial statistically significance effect than nozzle angles, at 5.20% PCR compared to 3.29% respectively.

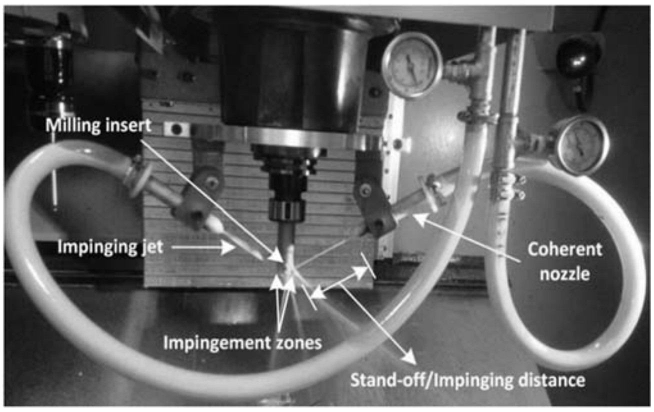


Fig. 11 Stand-off/impinging distance locations during the step shoulder milling of Ti-6Al-4V

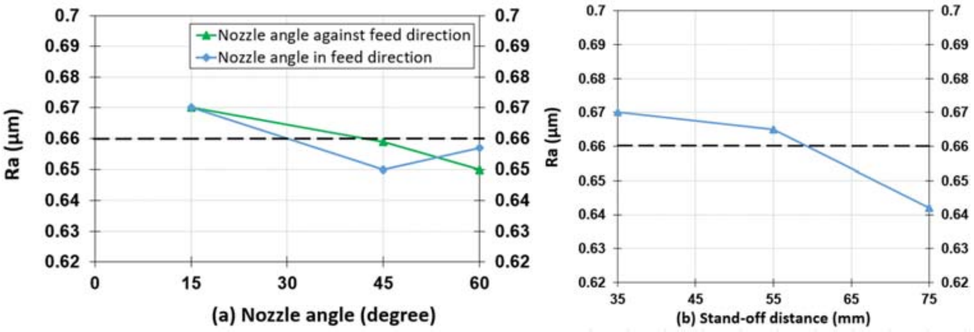


Fig. 10 Mean effect analysis of nozzle orientation on Ra at optimal cutting conditions: (a) nozzle angle; (b) stand-off distance

TABLE VII
ANOVA RESULTS FOR SURFACE ROUGHNESS

Source	DF	SS	MSS	F	P	PCR
Nozzle angle in the feed direction (degrees)	2	0.005702	0.002851	1.67	0.1944	1.32%
Nozzle angle against the feed direction (degrees)	2	0.007891	0.003945	2.31	0.105	1.86%
Stand-off distance (mm)	2	0.015919	0.007959	4.65	0.012*	3.98%
Cutting speed (m/min)	1	0.030334	0.03033	17.73	0.00*	7.97%
Feed rate (mm/rev)	1	0.147408	0.14743	86.18	0.00*	39.10%
Error	99	0.169334	0.0017			44.95%
Total	107	0.376588				
S = 0.01849; R-Sq = 55.03%; R-Sq (adj) = 51.40%						

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

2) Burr formation and surface roughness are more sensitive to stand-off/impinging distances than to nozzle angles.
3) The orientation of the cooling coherent round nozzle was found to have no influence on cutting force and tool wear when milling Ti-6Al- 4V using vegetable-oil based cutting fluid.
4) With regards to the influence of cutting conditions of cutting speed and feed rate on process output, the ANOVA results revealed that feed rate was the dominant factor affecting cutting force, burr formation and surface roughness, while cutting speed has the greatest impact on average workpiece temperature and tool flank wear.

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