Chapter 6

Application of eco-friendly emulsions with different flow rates during MQL assisted micromilling of Ti6Al4V

This chapter introduces minimum quantity lubrication (MQL) using vegetable oil-water emulsion and paraffin oil-water emulsion to minimize the surface roughness, cutting forces, and top burr produced during the micromilling of Ti6Al4V alloy. Emulsion provides cooling and lubrication to tool-chip and tool-workpiece interfaces through atomized aerosol droplets during micromilling. Effects of different MQL flow rates (60, 125, and 250 ml/h) with two different spindle speeds (10000 and 35000 RPM) have been investigated on machining performance characteristics such as cutting forces, surface roughness, surface topography, and burr formation.

6.1. Experimental procedure

6.1.1. Work material and MQL assisted micromilling

The Ti-6Al-4V alloy used in this experiment had sample dimensions of 55 x 50 x 5 mm, and micromilling experiments were performed on a three-axis precision micromachining center (Mikrotools DT110) with detailed specifications described in Chapter 3. Fig. 6.1 shows an enlarged view of the experimental setup with an MQL attachment. Two flutes of fine grain uncoated WC with a diameter of 200 μm made up the micro end-mills that were taken into experimentation. A tool overhang of 15 mm is employed throughout all tests to prevent the tool run-out and chatter phenomena during micro-milling operations. In Table 6.1, the specifications of the machining and MQL parameter values are listed. In this investigation, an emulsifier called TWEEN-20 (Polyoxyethylene (20) sorbitan monolaurate) is used to form an emulsion of soybean oil and deionized water. It is also used to make an emulsion of paraffin oil and deionized water. The surfactant was dissolved in soybean oil/paraffin oil before being combined with deionized water in soybean oil-water emulsion (SO+DIW) and paraffin oil-water emulsion (PO+DIW). The surfactant was dissolved in soybean oil/paraffin oil by stirring (0.25 mL emulsifier in 5 mL oil) for 30 minutes with a magnetic stirrer. This mixture was then added to a 100 mL deionized water volume and agitated for 30 minutes using a magnetic stirrer. After that, it underwent 2 h of additional sonication using an ultrasonic probe sonicator (manufacturer: Ultra Autosonic India Pvt. Ltd., India). Different emulsions utilized in MQL assisted micromilling of the workpiece are shown in Fig. 6.2. Additionally, dynamic light scattering (DLS) is used to determine the particle size distribution and average size of particles in emulsions, as illustrated in Fig. 6.3. The average particle size for soybean oil-water emulsion and paraffin oil-water emulsion is 248.77 ± 0.65 nm and 269.57 ± 34.28 nm, respectively. During micromilling, a straight slot of 20 mm length has been machined for each condition. Cutting forces were measured using a piezoelectric type mini dynamometer (Kistler, 9256C2) with an accessory of charge amplifier (Kistler 5070A) and data acquisition system (Kistler, 5697) by keeping the sampling frequency at 25 kHz.

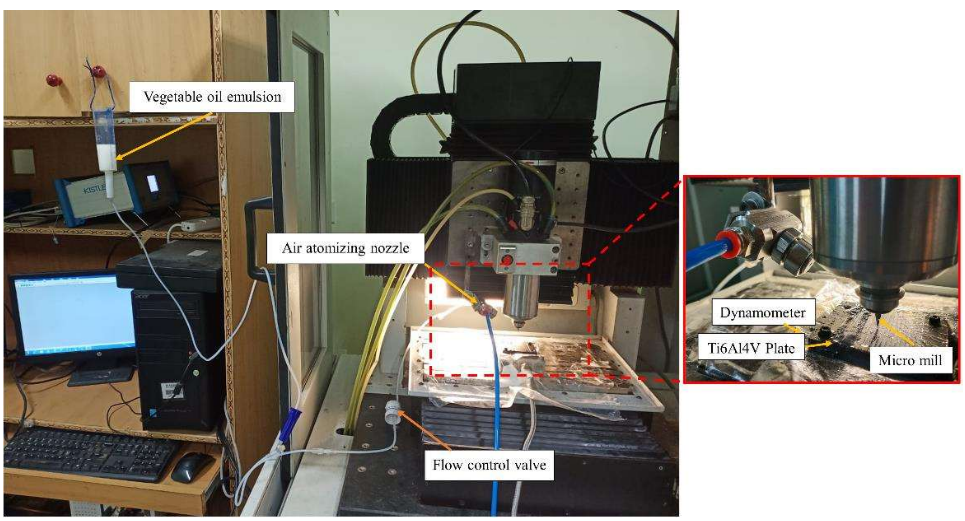

Fig. 6.1 DT110 micromachine with a close view of the MQL setup

Table 6.1 Micromilling and MQL parameters

Experimental parameters	Value
Rotational speed	10000 and 35000 rpm
Micro end-mill diameter	200 μm
Feed per tooth	3 μm/tooth
Depth of cut	60 μm
Lubricant	Soybean oil-water emulsion (SO+DIW) and paraffin oil-water emulsion (PO+DIW)
Nozzle diameter	0.8 mm
Nozzle angle	30°
Nozzle distance	30 mm
Pressure	4 bar
MQL flow rate	60, 125, and 250 ml/h
Total machining length	20 mm

Surface roughness was measured using a non-contact Zegage optical profilometer (Zygo) with a 140 μm × 140 μm closure area. The areal surface roughness value (S_a) was calculated by averaging the data obtained from three locations within the channel. A scanning electron microscope (SEM) captures images of the burrs and surface morphology. The top burr width was measured using ImageJ software.

Table 6.2 Physical properties of soybean oil

Properties	Density (kg/m^3)	Viscosity (Pa-s)	Pour point (°C)	Flash point (°C)
Soybean oil	923	0.048	-24	240

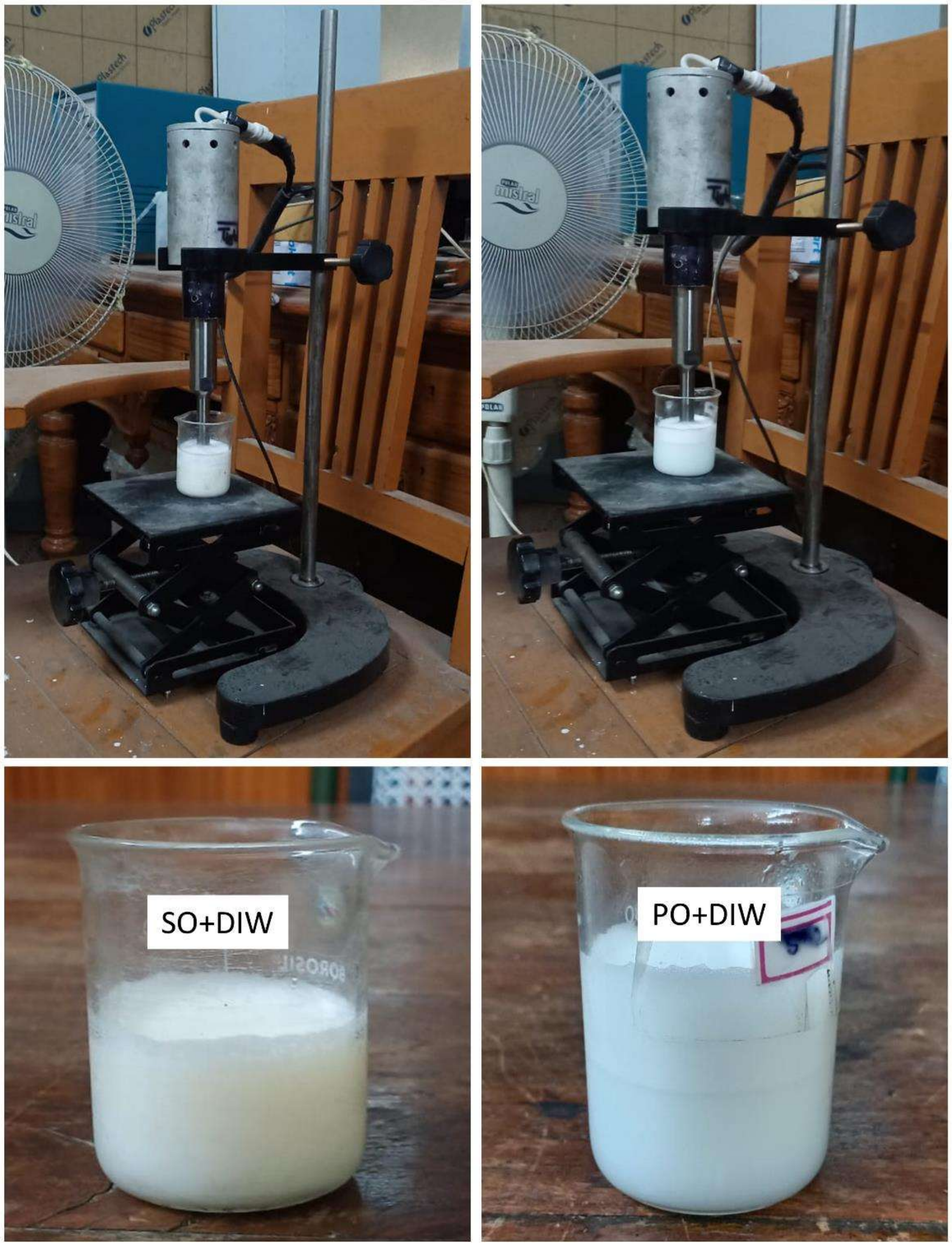

Fig. 6.2 Prepared emulsions of soybean oil-water and paraffin oil-water

6.2 Results and discussion

6.2.1 Tribology tests and micromilling forces

Tribology studies have been carried out using a ball-on-disk tribometer to evaluate the coefficient of friction of soybean and paraffin oil-water emulsions. In Fig. 6.4, the test rig is displayed. The MQL parameters for micromilling are the same as the utilized atomizing air pressure and MQL flow rates for tribology tests indicated in Table 6.1.

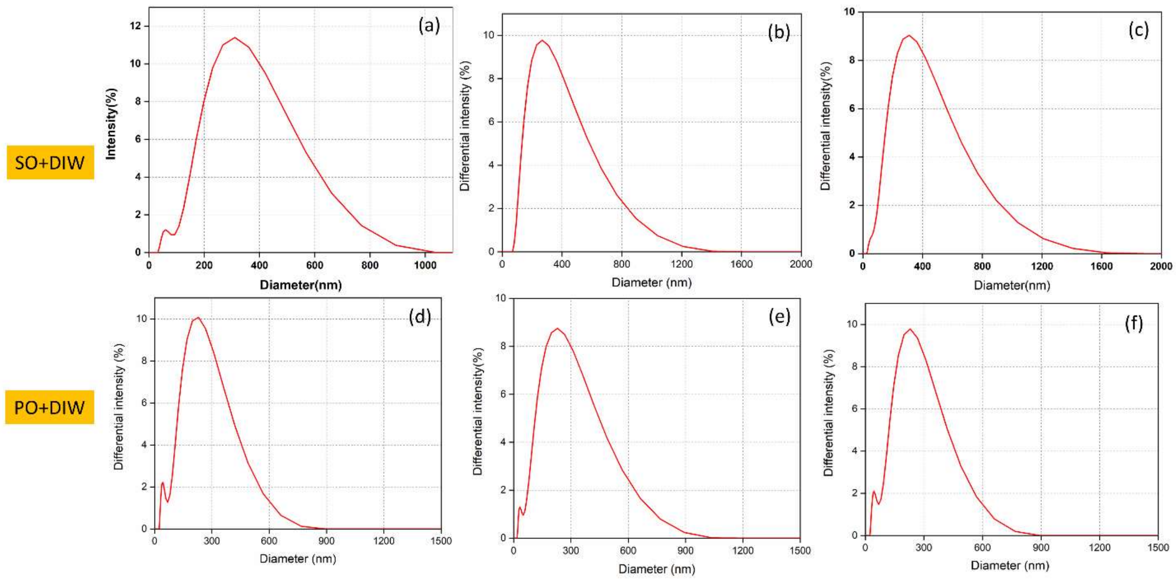

Fig. 6.3 Particle size distribution for (a)-(c) soybean oil-water emulsion and (b) paraffin oil-water emulsion

The flat Ti6Al4V plate was 30 × 30 mm^2 in size, and the polished WC ball with a 6 mm diameter was employed in the experiment. Under an applied normal load of 10 N, the Ti-6Al-4V disc was rotated at 200 rpm opposite to the WC ball. The wear track diameter is considered 10 mm, which corresponds to a sliding speed of 6.28 m/s (cutting velocity at 10000 rpm for 200 µm diameter micro mill is also 6.28 m/s). The sliding region is located 30 mm away from the nozzle, and the nozzle angle is 30^o. The tests were conducted at room temperature for a sliding time of 30 min. At various MQL flow rates, the variation in the coefficient of friction (COF) for dry, soybean oil-water emulsion, and paraffin oil-water emulsion are shown in Fig. 6.5. The dry condition shows the highest COF owing to the absence of lubrication and rubbing of pair surfaces. The viscosity of vegetable oil is more than paraffin oil; hence vegetable oil-water emulsion forms a stable tribofilm layer and reduces friction significantly. Fig. 6.6 shows the RMS value of the resultant cutting force at different lubricating conditions obtained by vector summation of planar forces. The changes in cutting forces are mainly related to the coefficient of friction under various lubricating cutting conditions; however, it also differs due to unexpected tool wear characteristics in micromilling. From Fig. 6.6, it has been observed that the cutting force at 35000 rpm spindle speed is lower than 10000 rpm in case of dry condition. An increase in temperature has a little thermal softening effect on the shear flow stress, altering the sliding friction coefficient and reducing the friction stress in the secondary machining zone, which in turn results in a drop in cutting force due to an increase in rotating speed.

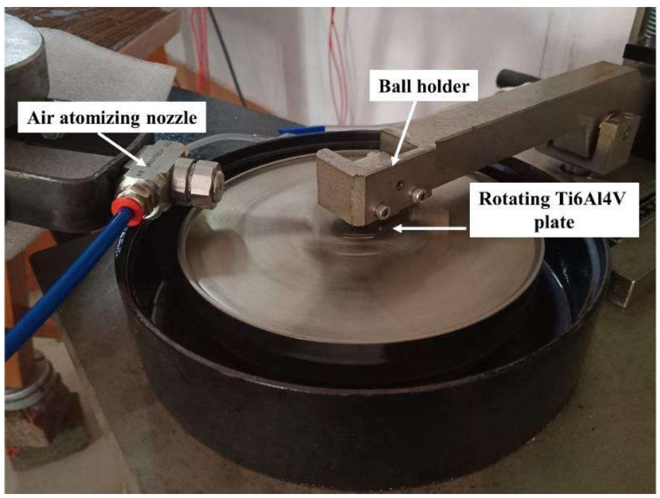

Fig. 6.4 Tribology setup

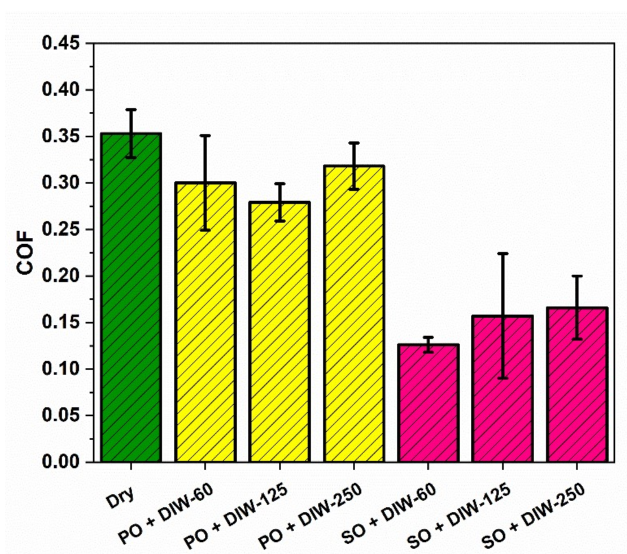

Fig. 6.5 Variation in the coefficient of friction at different lubricating conditions

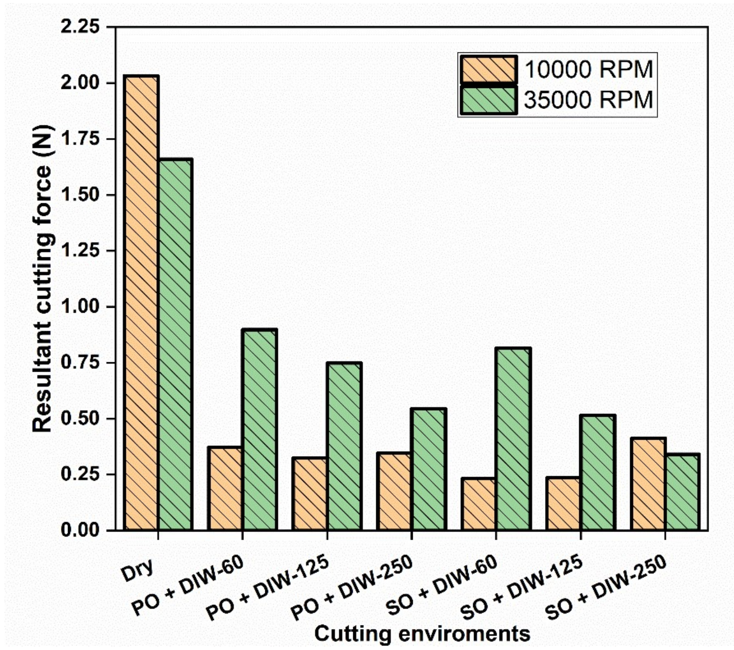

Fig. 6.6 Variation of cutting forces with different cutting environments

At 10000 rpm spindle speed, for paraffin oil-water emulsion, reduction of cutting force takes place up to 125 ml/h, then enhancement of cutting force is observed, whereas, in the case of soybean oil-water emulsion, increments in cutting force are observed with the increased flow rates. Therefore, 125 ml/h and 60 ml/h flow rates are adequate for PO+DIW and SO+DIW, respectively. No significant variation was observed when the flow rate attained a specific volume due to boundary lubrication conditions. The boundary lubrication condition depends not only on the amount of lubricant but also on the properties of the oil, like viscosity and wettability, the material properties of the workpiece, and the tool. The maximum effective flow rate of lubricant is to fill the peak and valley of the tool-workpiece contact area. The viscosity of soybean oil is higher than paraffin oil, so at 10000 rpm spindle speed, a 60 ml/h flow rate is sufficient for soybean oil-water emulsion MQL. On the other hand, the 125 ml/h flow rate is adequate for paraffin oil-water emulsion MQL at 10000 rpm spindle speed. This suggests that the fluid infiltration could reach a critical point when the capabilities of excess fluid are no longer as effective because it is challenging to enter into the cutting zone.

Similarly, cutting forces decreased for both paraffin oil-water and soybean oil-water emulsions at 35000 rpm spindle speed when MQL flow rates increased; nevertheless, 125 ml/h flow rate is adequate for soybean oil emulsion as less cutting force variation was noticed from 125 ml/h to 250 ml/h. At 35000 rpm spindle speed, the cutting force is reduced with an increase in emulsion flow rate owing to the number of droplets entering the tool–chip's contact zone increases. Higher spindle speed makes it more challenging for MQL fluid to access the chip-tool boundary because there is more rotational velocity and less time for infiltration. For a 35000 RPM spindle speed, it is anticipated that a greater MQL fluid flow rate would be preferable [119]. Fig. 6.7 and 6.8 denote the feed force vs. time variation with different lubricating conditions at 10000 rpm and 35000 rpm spindle speeds. At 10000 rpm spindle speed, as shown in Fig. 6.6, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the resultant cutting force by 81.67%, 83.99%, and 82.94%, respectively. Whereas SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the resultant cutting force by 88.5%, 88.38%, and 79.67% compared to dry conditions. At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the resultant cutting force by 45.86%, 54.89%, and 67.21%, respectively, relative to dry conditions, while SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the resultant cutting force by 50.82%, 68.96%, and 79.42% compared to dry conditions.

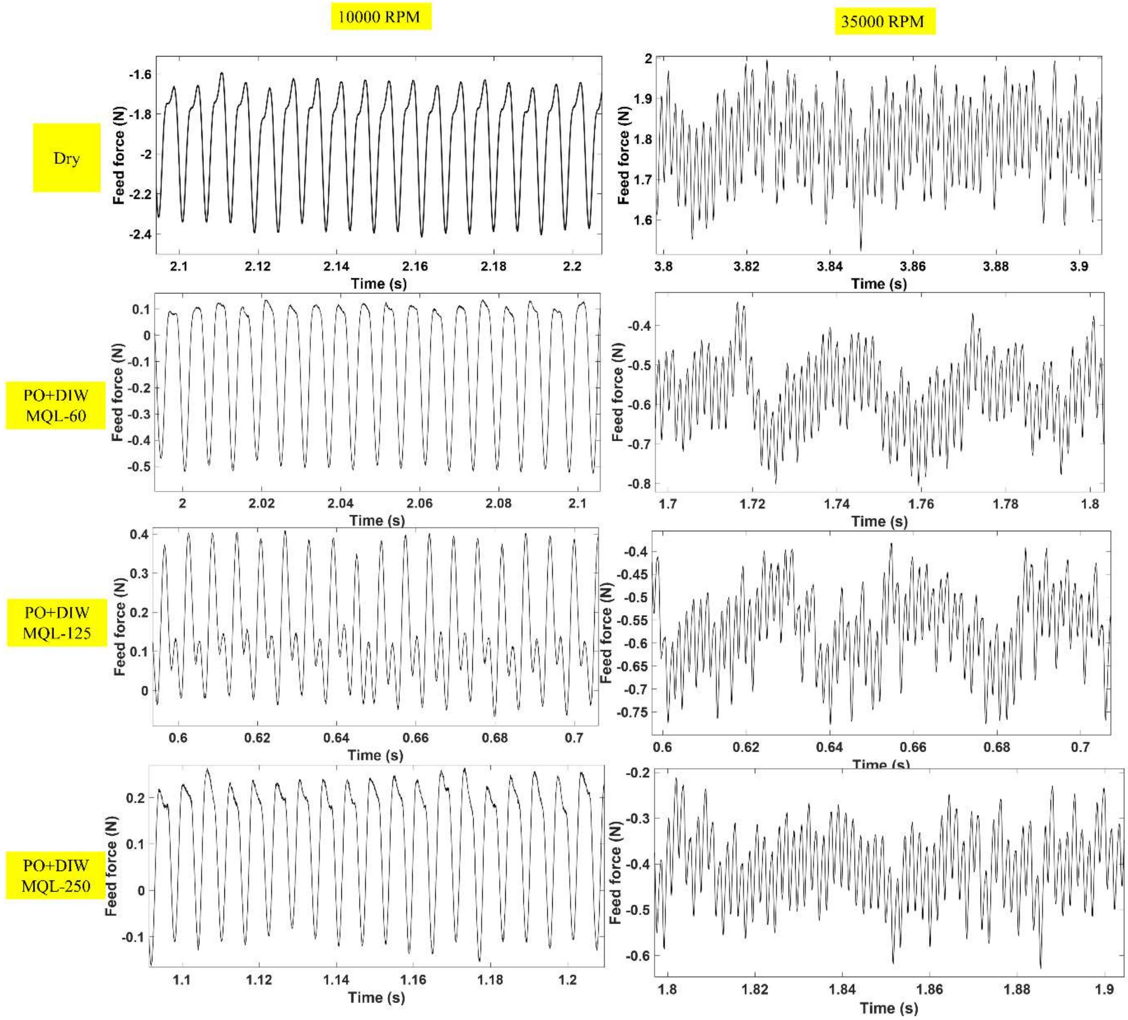

Fig. 6.7 Feed force variation for dry and paraffin oil-water emulsion with different MQL flow rates

6.2.2 Analysis of surface quality

The top burr width and surface roughness of the Ti6Al4V alloy micro slots produced by uncoated WC micro-mills under dry, paraffin oil-water emulsion, and soybean oil-water emulsion conditions at various MQL flow rates have been investigated. These results are shown in Figs. 6.10–6.12 and Figs. 6.13–6.15. Fig. 6.9 illustrates the measurement of top burr width in down milling side of the typical microchannel with burr formation.

Fig. 6.10 and 6.11 show that significant burr reduction occurs using paraffin oil-water emulsion and soybean oil-water emulsion at different flow rates.

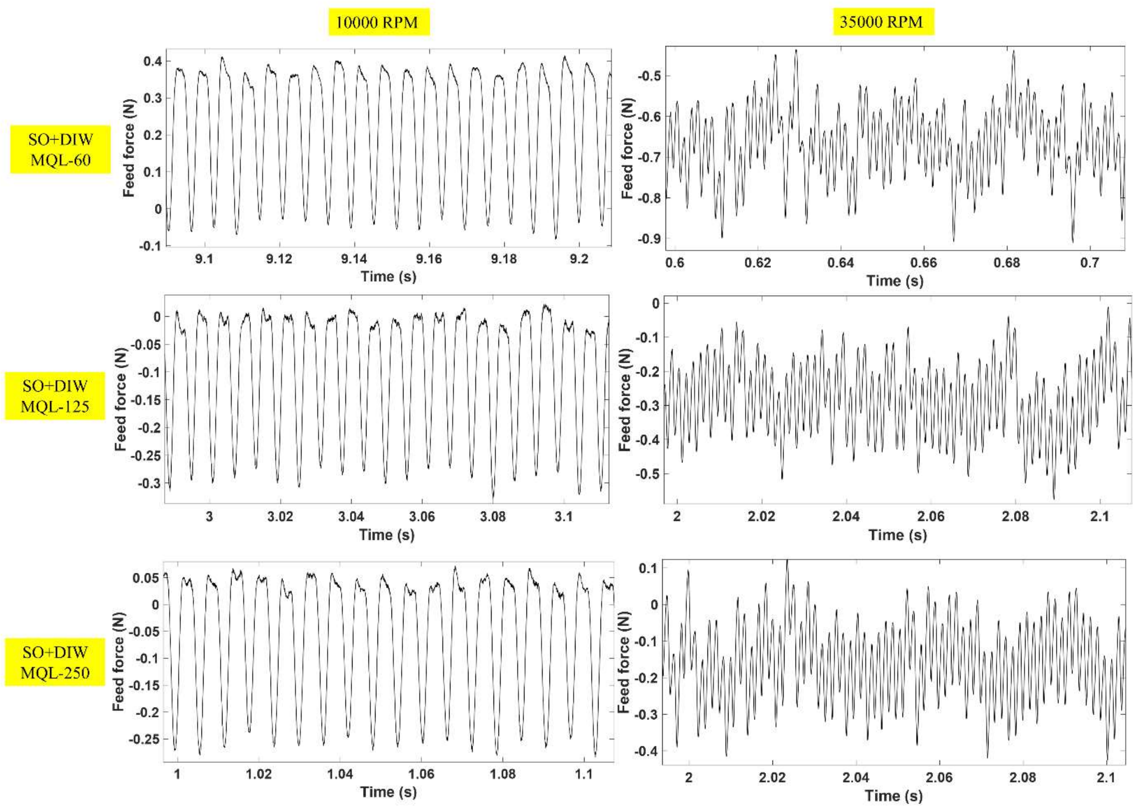

Fig. 6.8 Feed force variation for soybean oil-water emulsion with different MQL flow rates

It has also been observed in Fig. 6.12 for top burr width in up and down milling. It can be seen from Fig. 6.12 that the least top burr width was obtained for paraffin oil-water emulsion at 125 ml/h flow rate and soybean oil-water emulsion at 60 ml/h flow rate for both spindle speeds, respectively. In contrast, the largest is formed in dry conditions. Paraffin oil-water emulsion at a higher speed shows few burr formations for different flow rates. However, compared to dry conditions, a significant burr reduction was obtained. At 10000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the top burr width by 76.04%, 76.87%, and 65.08%, respectively, on up milling side while 78.84%, 87.04%, and 61.44% respectively in down milling compared to dry conditions. Similarly, SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the top burr width by 71.25%, 66.03%, and 62.72% for up milling operations while 86.78%, 82.01%, and 84.77% respectively in down milling compared to dry conditions. Hence it has been revealed that MQL flow rates of 125 ml/h and 60 ml/h are more viable options for reducing burr formation in the case of paraffin oil-water emulsion and soybean oil-water emulsion, respectively.

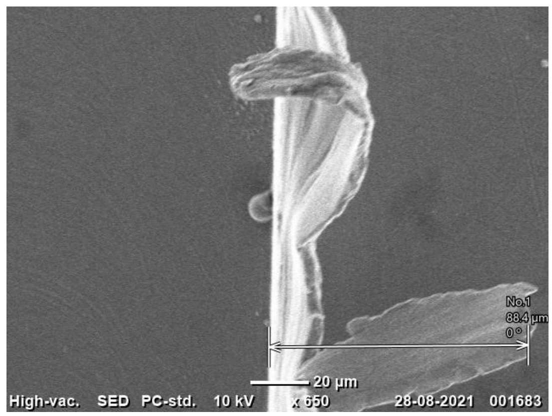

Fig. 6.9 Typical SEM image denoting burr width measurement in down milling

At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the top burr width by 47.56%, 83.11%, and 84.18%, respectively, on the up milling side while 79.08%, 84.90 and 73.56% respectively in down milling compared to dry conditions. Similarly, SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the top burr width by 58.17%, 70.77%, and 69.92% for up milling operations while 86.36%, 86.47%, and 88.53% respectively in down milling compared to dry conditions.

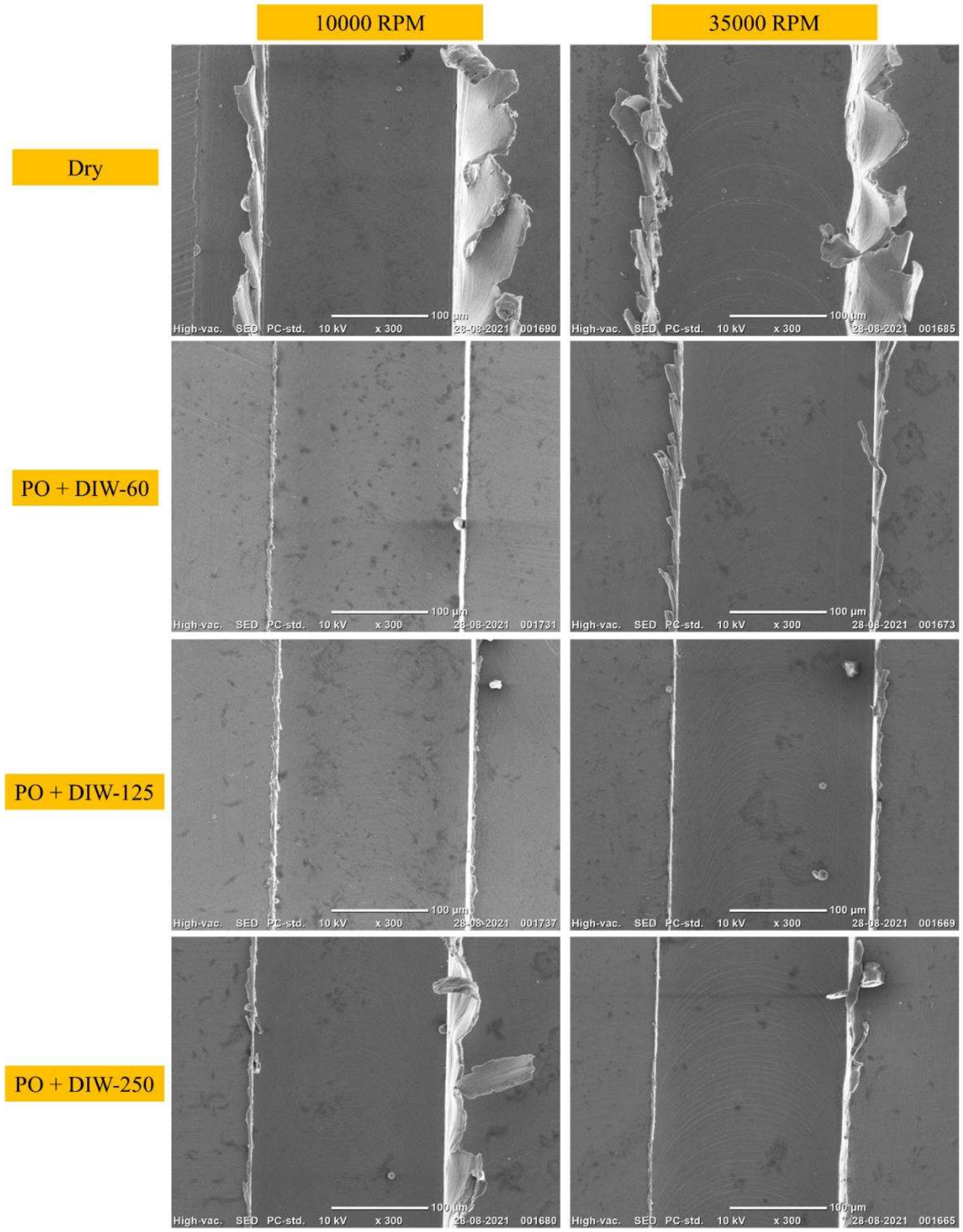

Fig. 6.10 SEM images of top burr formation after up or down milling under dry conditions and paraffin oil-water emulsion with different MQL flow rates at 10000 rpm and 35000 rpm spindle speed

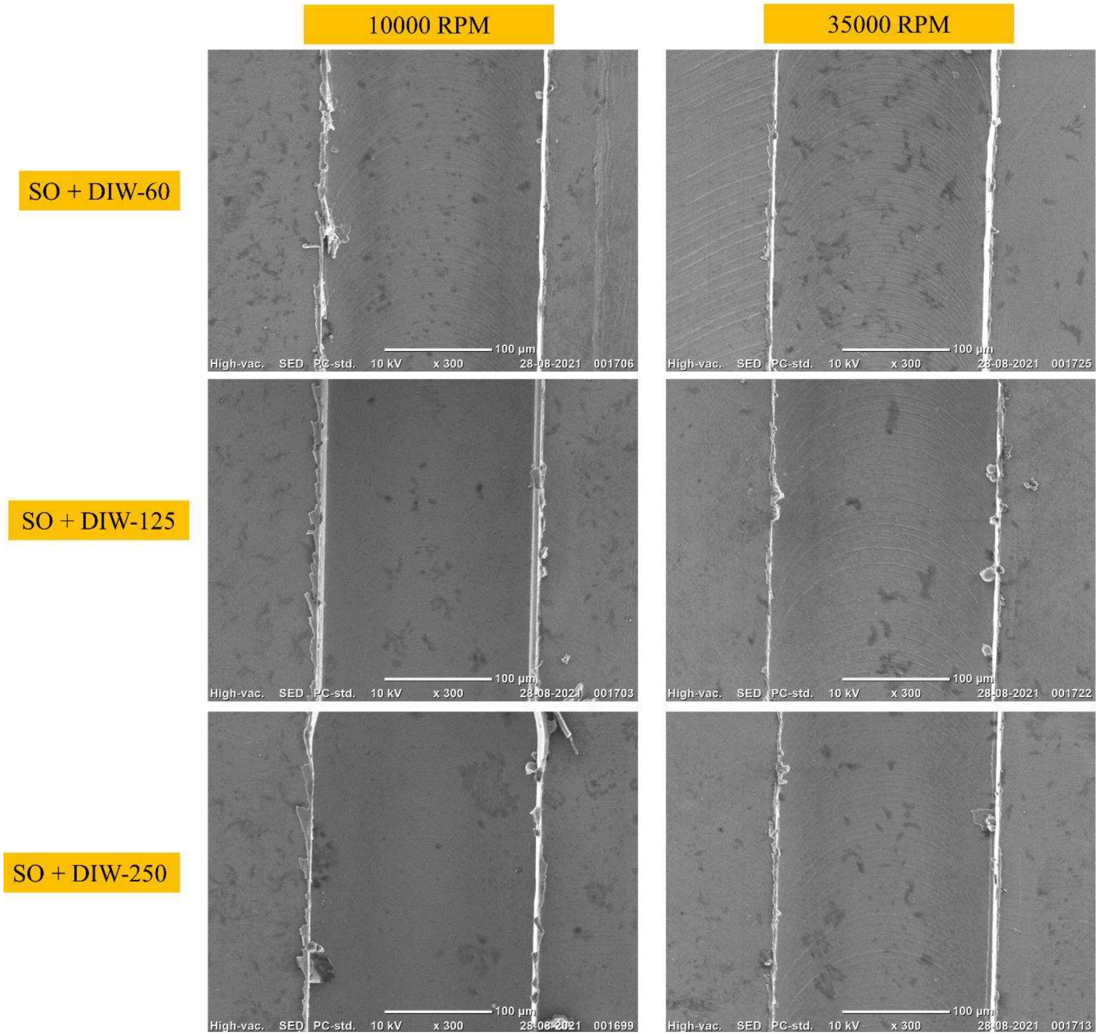

Fig. 6.11 SEM images of top burr formation after up or down milling under soybean oil-water emulsion with different MQL flow rates at 10000 rpm and 35000 rpm spindle speed

The smoothness of the machined surface is crucial in precision machining. Evaluating the manufactured part's surface finish is essential to produce a superior result. Shearing and plowing zones are present at the beginning, end, and center of the micromilling channel. As a result, the average arithmetic height of an area (S_a), a measure of area surface roughness, was employed in this research. It has been discovered that cutting conditions have an analogous impact on surface roughness as cutting force in dry conditions. For dry conditions, surface roughness often decreases with increased spindle speed, as shown in Fig. 6.13.

Due to easier mist impingement caused by lower viscosity and a larger surface area of lubricating film generation in machining zones, paraffin oil-water emulsion MQL improves surface quality. Surface roughness for MQL flow rate at 60 ml/h contributed to the best surface finish for 10000 rpm spindle speed. Further increase in MQL flow rate is not found effective for surface roughness. Once it achieves adequate lubrication conditions, the additional surplus amount of cutting fluid volume is not fruitful for lubrication. Another reason for an increase in surface roughness with higher MQL flow rates is larger droplets reduce the infiltration into the concise micromachining zone [94]. Higher rotational speed (35000 rpm) in MQL results in more surface roughness values due to inadequate lubrication spurred on by the tool's high rotating speed and the mismatch between MQL flow rate and rotational speed. More droplets enter the cutting zone and create tribofilm with an increased MQL flow rate [120]. Even so, it was discovered that lubrication had a more significant impact at low spindle speeds.

A similar improvement in surface finish observed by SO+DIW MQL is shown in Fig. 6.14. Based on their chemical composition and high viscosity, vegetable-based cutting fluids provide a thin, durable, and long-lasting lubrication film in the machining zone [121]. Surface roughness for MQL flow rate at 60 ml/h contributed to the best surface finish for 10000 rpm spindle speed. Surface roughness was enhanced at 10000 rpm spindle speed, increasing MQL rates from 60 ml/h to 250 ml/h. In contrast, for 35000 RPM, when MQL flow rates rise, the surface roughness reduces at a higher spindle speed.

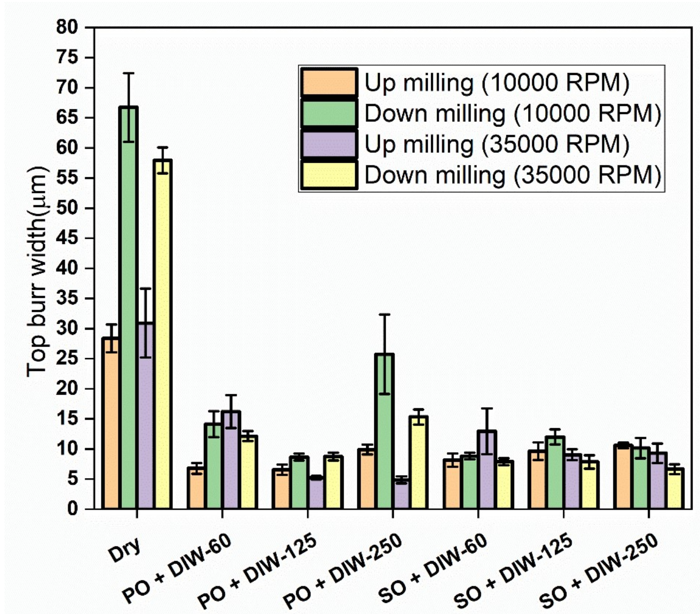

Fig. 6.12 Variations in down milling and up milling burr width at different spindle speeds under various lubricating conditions

At 10000 rpm spindle speed, as shown in Fig. 6.15, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the areal surface roughness by 74.67%, 70.67%, and 44.67%, respectively. Whereas SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the areal surface roughness by 72%, 62%, and 67.33% compared to dry conditions. At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the areal surface roughness by 21.32%, 20.59%, and 30.51%, respectively, relative to dry conditions, while SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the areal surface roughness by 10.29%, 20.59%, and 25.73% compared to dry conditions.

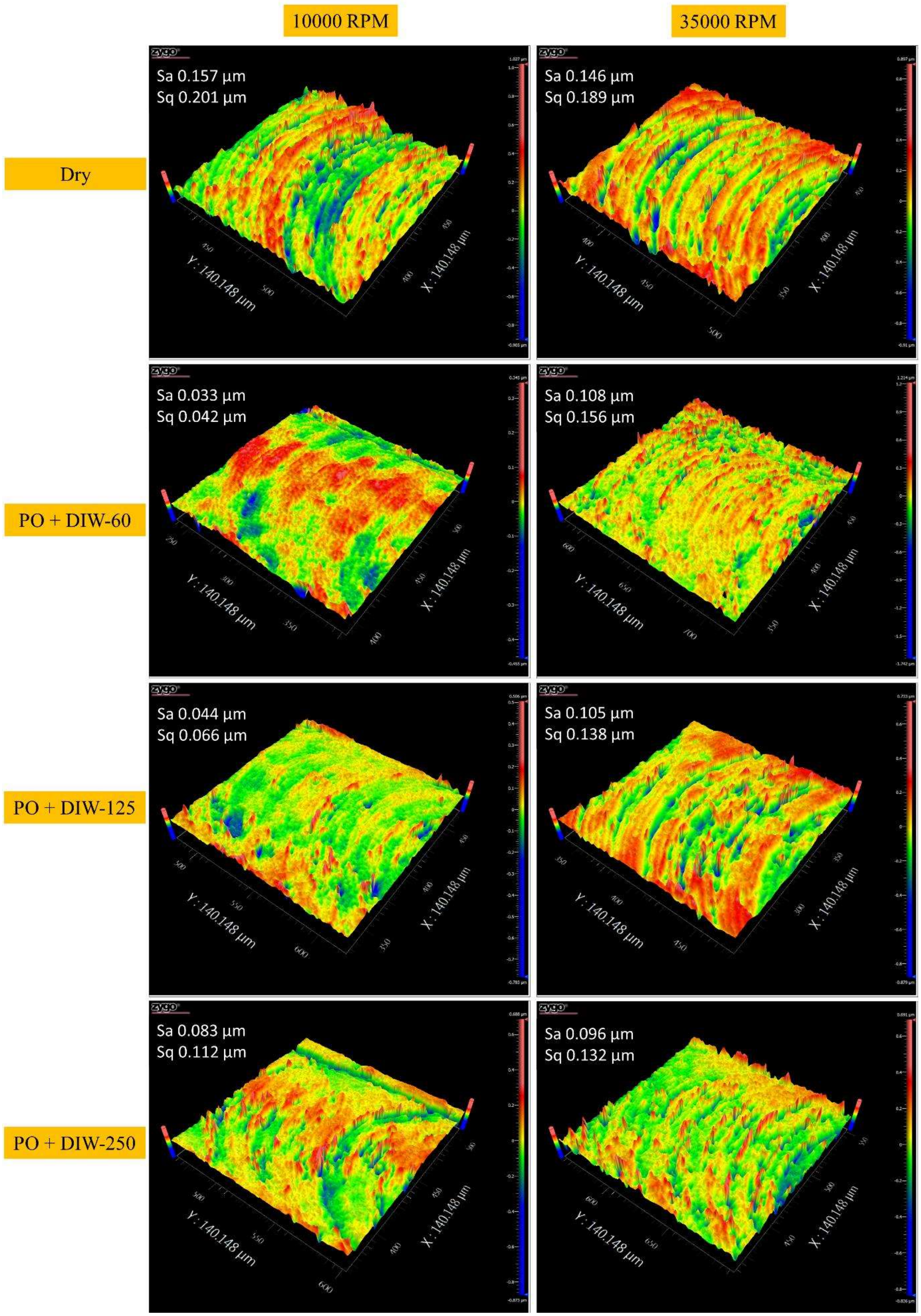

Fig. 6.13 Surface profile of the machined channel for dry and paraffin oil-water emulsion environments with different MQL flow rates

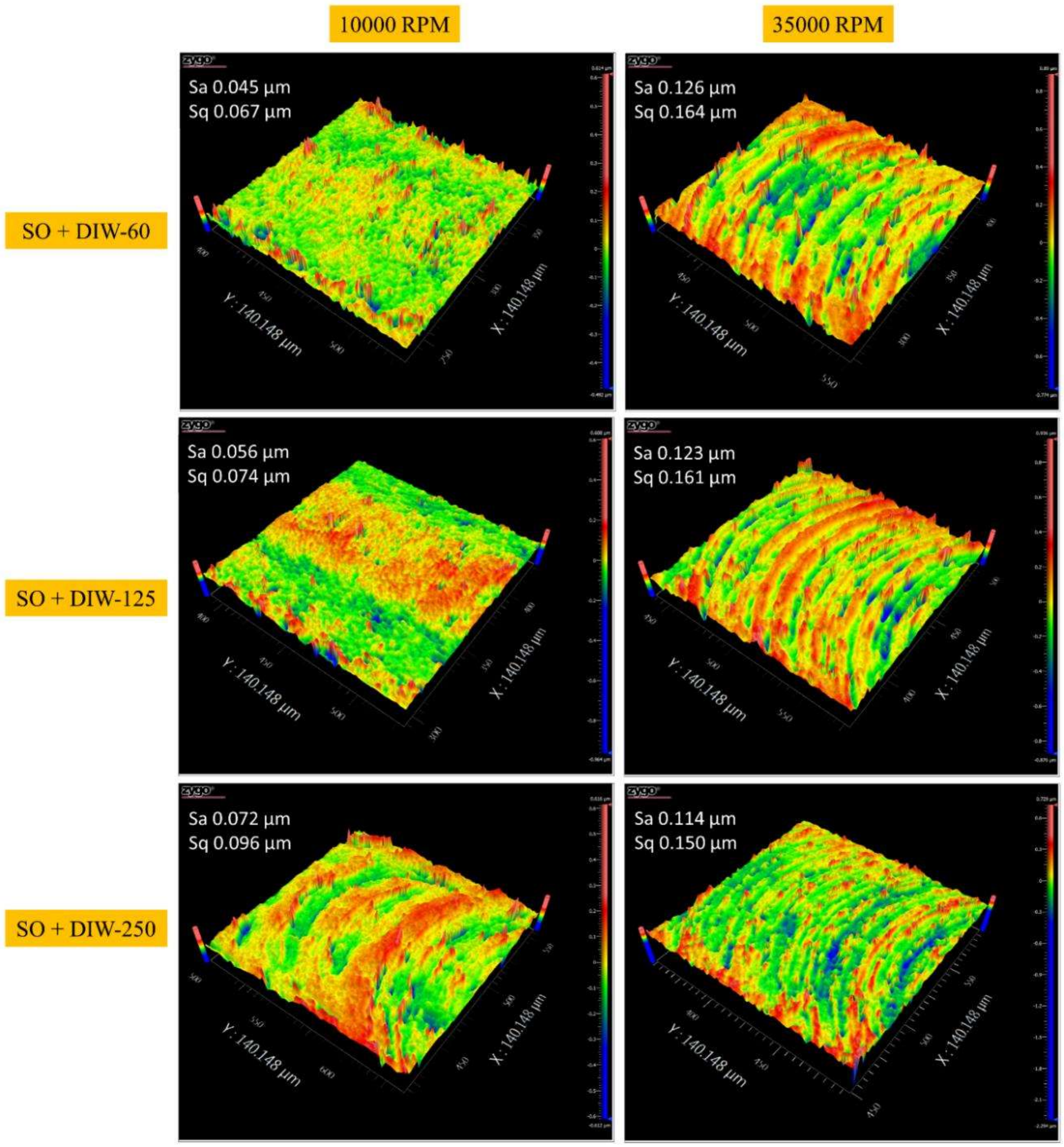

Fig. 6.14 Surface profile of the machined channel for soybean oil-water emulsion environment with different MQL flow rates

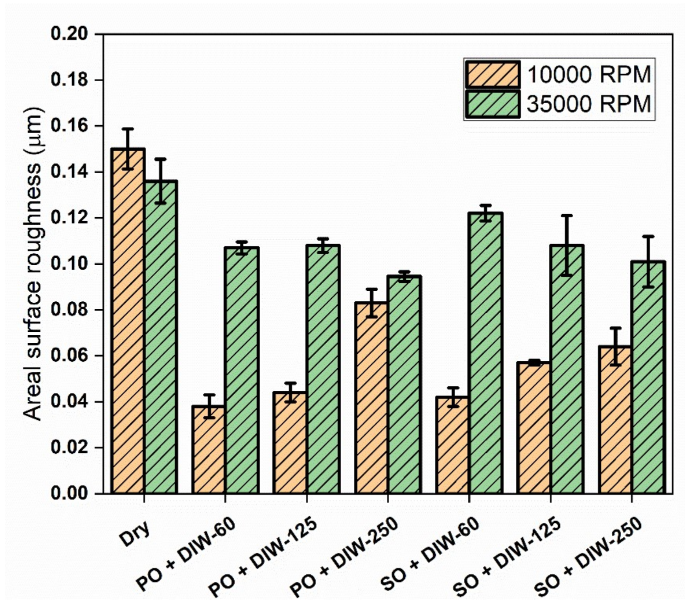

Fig. 6.15 Variation of surface roughness with cutting environments

6.3. Summary

This chapter aims to identify the appropriate emulsion at a particular flow rate at different spindle speeds that can be used for efficient micromilling of Ti6Al4V alloy and to evaluate micromilling performance in terms of cutting force, burr formation, surface roughness, and surface topography. From the study, the key findings can be summed up as follows:

- The largest magnitude of cutting forces and surface roughness is obtained in dry conditions, although increased spindle speed reduces cutting forces and surface roughness due to thermal softening from high heat generation.
- At 10000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the resultant cutting force by 81.67%, 83.99%, and 82.94%, respectively. Whereas SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the resultant cutting force by 88.5%, 88.38%, and 79.67% compared to dry conditions. At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the resultant cutting force by 45.86%, 54.89%, and

67.21%, respectively, relative to dry conditions, while SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the resultant cutting force by 50.82%, 68.96%, and 79.42% compared to dry conditions.

- At 10000 rpm spindle speed, 125 ml/h and 60 ml/h flow rates are sufficient for cutting force reduction and tribofilm stability by paraffin oil water-emulsion (PO+DIW) and soybean oil water-emulsion (SO+DIW), respectively. At 35000 RPM spindle speed, 250 m/h MQL flow rate of paraffin oil-water and soybean oil-water emulsion is more effective for cutting force reduction.
- It has been observed that significant burr reduction occurs using paraffin oil-water emulsion and soybean oil-water emulsion at different flow rates. At 10000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the top burr width by 76.04%, 76.87%, and 65.08%, respectively, on up milling side while 78.84%, 87.04%, and 61.44% respectively in down milling compared to dry conditions. Similarly, SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the top burr width by 71.25%, 66.03%, and 62.72% for up milling operations while 86.78%, 82.01%, and 84.77% respectively in down milling compared to dry conditions. At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the top burr width by 47.56%, 83.11%, and 84.18%, respectively, on the up milling side while 79.08%, 84.90 and 73.56% respectively in down milling compared to dry conditions. Similarly, SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the top burr width by 58.17%,70.77%, and 69.92% for up milling operations while 86.36%, 86.47%, and 88.53% respectively in down milling compared to dry conditions.

- The least top burr width was obtained for paraffin oil-water emulsion at 125 ml/h flow rate and soybean oil-water emulsion at 60 ml/h flow rate for both spindle speeds, respectively.
- Since soybean oil-water emulsion has a higher viscosity and a more stable lubricant film than paraffin oil-water emulsion at 10000 rpm spindle speed, it performs better for surface roughness reduction; however, at 35000 rpm spindle speed, paraffin oil-water emulsion with a lower viscosity allows for quick penetration into the cutting zone.
- At 10000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the areal surface roughness by 74.67%, 70.67%, and 44.67%, respectively. Whereas SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the areal surface roughness by 72%, 62%, and 67.33% compared to dry conditions. At 35000 rpm spindle speed, PO+DIW-60, PO+DIW-125, and PO+DIW-250 reduce the areal surface roughness by 21.32%, 20.59%, and 30.51%, respectively, relative to dry conditions, while SO+DIW-60, SO+DIW-125, and SO+DIW-250 reduce the areal surface roughness by 10.29%, 20.59%, and 25.73% compared to dry conditions.
- Surface roughness was enhanced at 10000 rpm spindle speed, increasing MQL rates from 60 ml/h to 250 ml/h. In contrast, for 35000 RPM, when MQL flow rates rise, the surface roughness reduces at a higher spindle speed.