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ORIGINAL ARTICLE

Effects of tool paths and machining parameters on the performance in micro-milling of Ti6Al4V titanium with high-speed spindle attachment

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Abstract The objective of the current work was to investigate the influence of tool path and micro-milling conditions on wear, surface roughness, and forces when micro-milling Ti6Al4V titanium material. The performances of raster (zigzag) and single-direction raster (zig) tool paths were evaluated. The micro-milling experiments were carried out by employing high-speed spindle attachment connected to main spindle of standard machine tool under various tool paths. The experimental studies consisted of two stages. In the first stage, the effect of spindle speed by employing high-speed spindle attachment was examined under various tool paths at low and high feed rates. In the second stage, the effect of feed rate on machining performance was investigated under various tool paths. Based on this study, the optimum cutting conditions could be determined when using high-speed spindle attachment under various tool paths.

Keywords Micro-milling · Tool path · Tool wear · Surface roughness · Force · Titanium alloy

1 Introduction

The miniaturization of products has gained more attention nowadays in a great variety of fields like optics, electronics, medicine, and aerospace [1, 2]. Micro-products have been fabricated by laser machining, electrodischarge machining, electrochemical machining, and micro-mechanical machining [3]. Micro-milling is the micro-mechanical machining method, and this method is suitable for the fabrication of 3D micro-features with high dimensional accuracy. Also, most materials have machined successfully with micro-milling [3, 4].

In this study, titanium is chosen as a workpiece material since it is extensively employed in the aerospace, aircraft, and implant industries. Titanium and its alloys have high strength-to-weight ratio, excellent physical and mechanical properties, superior corrosion resistance, and high biocompatibility. However, titanium has low thermal conductivity and the machinability of titanium is very poor due to the work hardening. To diminish the problems encountered during the micro-milling of titanium, machining parameters and strategies should be selected properly. To investigate the effect of the machining parameters, some researchers performed the micro-milling of titanium material [4–6]; however, no published work was seen for investigating the effect of tool path in surface micro-milling of titanium to the best of our knowledge.

Although some works have been carried out about the influence of different path strategies on machining performance in macro-milling [7–10], there are very few studies about tool path in micro-milling [11–13]. The performances of various strategies for micro-milling of copper material were determined by measuring surface roughness, and it was found that the "constant_load" and "follow_hardwall" strategies gave the lowest surface roughness value [12]. It was observed that the tool wear was lower in up milling than that in down milling and this result was explained with higher force when down milling was used. It was said that higher forces increased chipping and tool wear rate [11]. The boundary between two consecutive tool marks in the cross-feed direction was found to be much smoother in up milling than that in down milling. This result was due to a higher force in down milling. The increase in the surface roughness when down milling was

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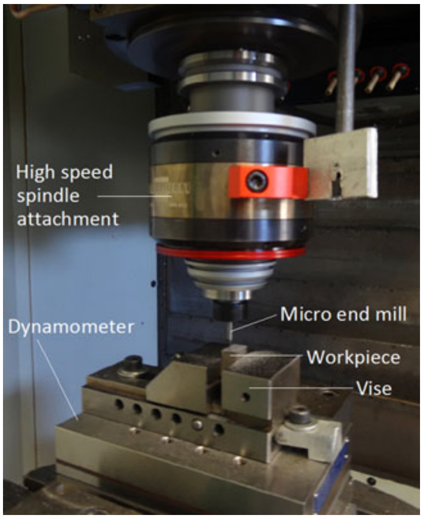

Fig. 1 Experimental setup

conducted was due to the fact that the micro-end mills bent more in down milling [12]. Cardoso and Davim [13] investigated the influence of tool path strategies and machining conditions on roughness during micro-milling of Al 2011 aluminum alloy. Three strategies, namely, parallel zigzag, parallel spiral, and constant overlap spiral, were employed and the best performances were achieved via "constant overlap spiral." The proper selection of cutter path strategies can decrease the machining time and can improve the surface quality and tool life. Therefore, this work focused the positive and negative aspects of employing various tool path strategies during micro-milling of Ti6Al4V.

It is known that when the diameter of cutting tool is decreased, higher spindle speeds are required. Higher spindle speeds need high-speed machine tools and the cost of these tools is high. Due to the current economic considerations, machining industry develops the high-speed spindle attachment and the use of this attachment has been increasing. Thus, it is necessary to determine the performance of high-speed spindle attachment. Therefore, we investigated the performance of high-speed spindle attachment under various tool paths.

This study consisted of two stages. In the first stage the effect of spindle speed on machining performance was investigated at low and high feed rates. In the second stage, the effect of feed rate by employing high-speed spindle attachment was determined. All tests were performed by employing down, up, and zigzag micro-milling strategy. Machining performance was determined by measuring surface roughness, wear, and forces.

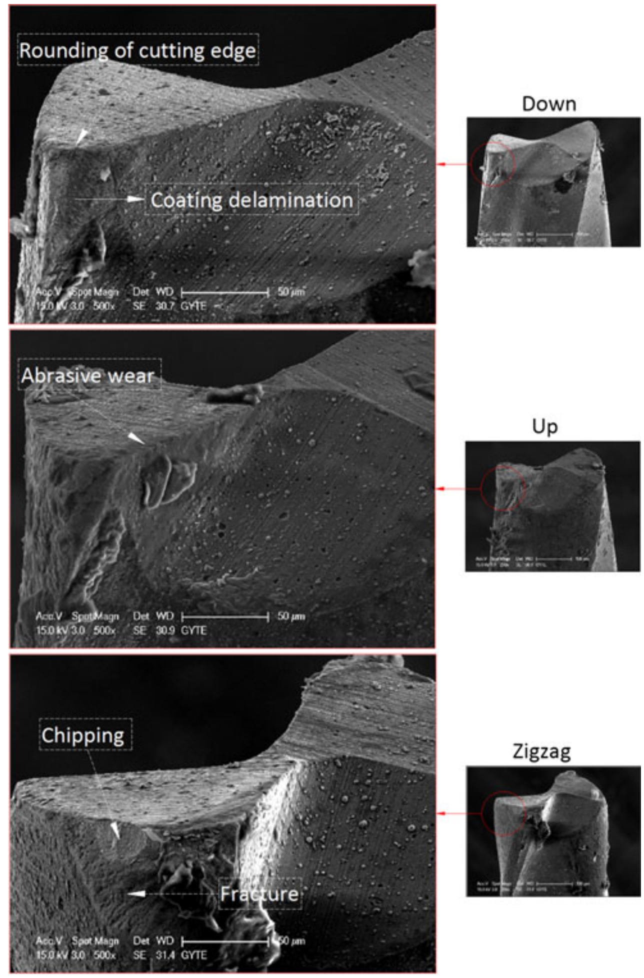

Fig. 2 The comparisons of tool wear under various tool paths (spindle speed of 12,000 rpm, feed rate of 75 mm/min)

2 Experimental study

2.1 Materials and tools

The experiments were performed on DECKEL MAHO DMU 60 P CNC. The main spindle of the machine can rotate at a maximum of 12,000 rpm; therefore, a high-speed spindle was attached on the main spindle to conduct high-speed

Table 1 Micro-milling conditions

Experiments	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (μm)	Step over (μm)
1	12,000	75	60	50
2	28,000	75	60	50
3	20,000	150	60	50
4	28,000	150	60	50

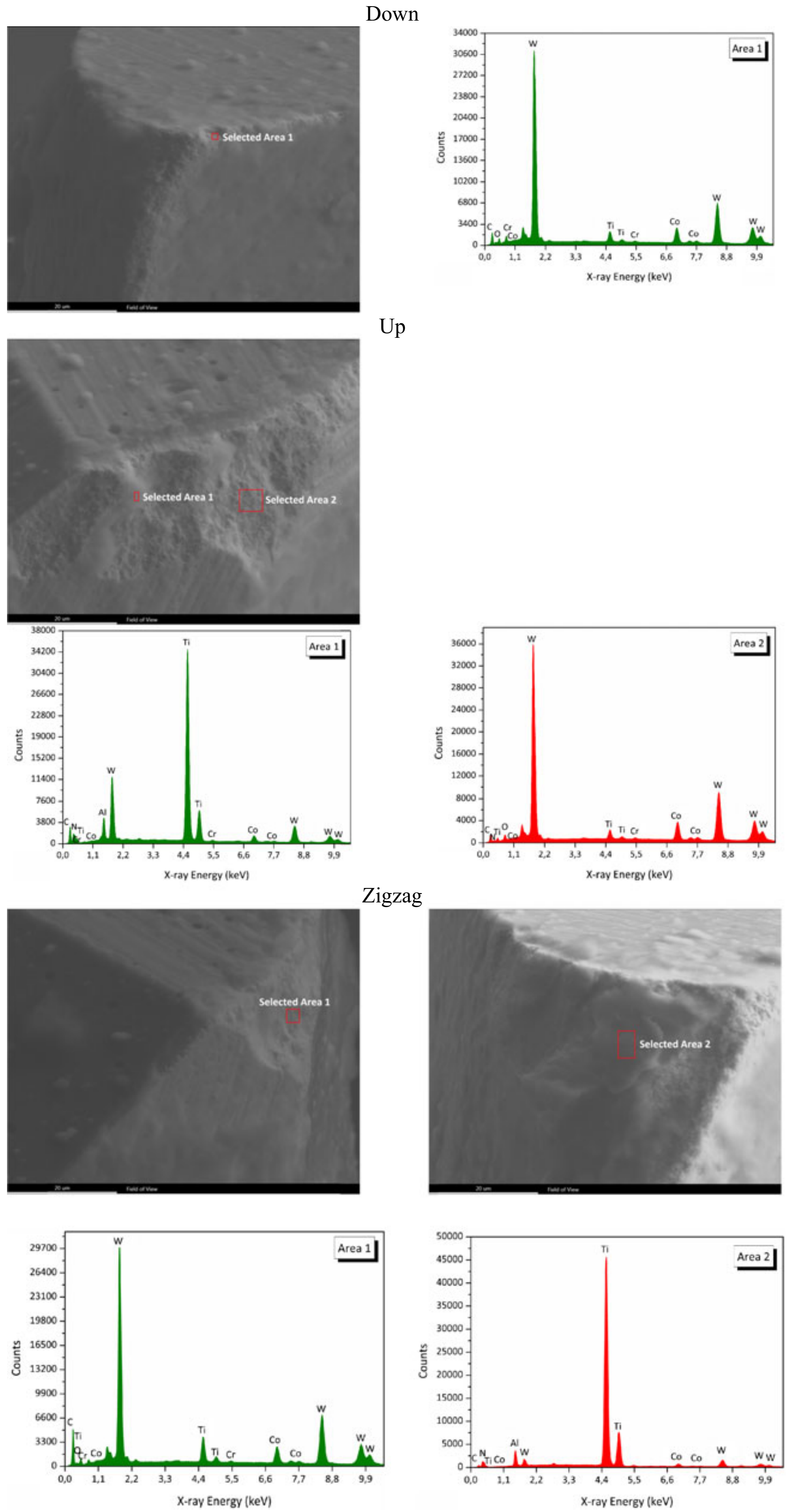

Fig. 3 EDX spectra of worn micro tools under various tool paths (spindle speed of 12,000 rpm, feed rate of 75 mm/min)

experiments. A Pibomulti X9810 attachment which has a maximum spindle speed of 40,000 rpm was used. Ti6Al4V titanium alloy (hardness of 35 HRC) was chosen as a workpiece material and dimensions of workpiece were 15 mm × 10 mm × 20 mm. Before starting the experiments, the workpiece materials were face-milled to eliminate any surface defects and to provide flatness. In the micro-milling experiments, two-flute flat-end mill with a diameter of 400 μm (Union Tool, CES3A 20040-015) was employed. Micro cutting tools were TiAlN-coated and helix angle was 20°. A new cutting tool was utilized for each test. In order to minimize the deflection and runout effect, the distance to the tool tip from the tool holder was kept constant as 20 mm during all experiments. The static runout of cutting tool was determined with dial gauge at the shaft part of tool before conducting each experiment, and the values were found to be between 4 and 6 μm. The workpiece and tools were employed from the same batch to minimize diversity in the results. All experiments were carried out at dry conditions. Surface of 15 mm × 10 mm was micro-milled at each experiment.

2.2 Measurements

In the current work, surface roughness, wear, and forces were considered to determine the performance of different tool paths at various spindle speeds and feed rates. Tool wear was observed by a scanning electron microscope (SEM, Philips XL30) at ×500 magnifications. Tool wear mechanisms were also analyzed via energy dispersive X-ray (EDX) analysis. Fx and Fy forces were measured via a dynamometer and force data was analyzed via Dynoware software. Averages of peak-to-valley (P-to-V) Fx and Fy were used for the force analysis. Owing to the small dimensions of workpiece, workpiece was attached on the vise mounting on the dynamometer (Fig. 1). The surface roughness of micro-milled surface was measured offline by employing profilometer (Mitutoyo Surf Test 301). Before the performing of the measurement, the profilometer was calibrated. In this work, roughness parameter of average surface roughness (Ra) was employed. Surface roughness was measured at ten times and average of these values was used for analysis.

2.3 Micro-milling conditions

The micro-milling parameters are given in Table 1. Three different tool paths, namely, zigzag, down, and up micro-milling, were used in all experiments. Experiments were carried out with high-speed spindle attachment.

3 Results and discussions

3.1 Influence of spindle speed

Figure 2 shows SEM micrographs of down, up, and zigzag micro-milling after machining at 75 mm/min and 12,000 rpm. Coating delamination near the cutting tool edge was seen in down micro-milling strategy, and it was reported that this was

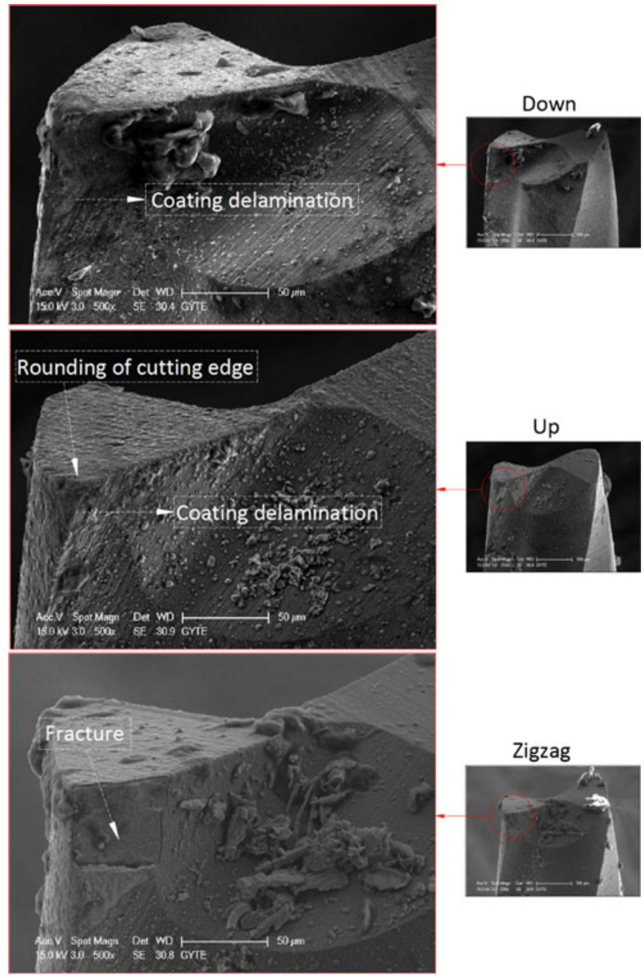

Fig. 4 The comparisons of tool wear under various tool paths (spindle speed of 28,000 rpm, feed rate of 75 mm/min)

a very common wear form for TiAlN-coated tools in the machining of titanium-based material [14]. Coating delamination was a result of some parameters such as mechanical impact, alternating thermo-mechanical stresses, residual stress of the coating, and chemical reactions [15]. It was reported that adhesion occurring at the interface of cutting tool-chip was the initiator of the delamination during machining of Ti6Al4V [16]. Furthermore, interrupted nature of milling process induced high-frequency interrupted cutting force at the cutting edges [17] and under these circumstances, the coating chipped off easily. In addition, rounding of the cutting edges was observed, which indicated abrasive wear. For up micro-milling, abrasive wear was observed and it was known that it led to rounding of the cutting tool following initial fracture of the cutting edges. In abrasive mechanism, rubbing was more dominant during machining than shearing. Abrasive wear increased cutting edge radius, changed the tool geometry, and caused the reduction in cutting tool diameter [18]. Chipping was observed in zigzag micro-milling due to the excessive stresses on the cutting edges. The higher chemical affinity between the tool coating and workpiece material resulted in

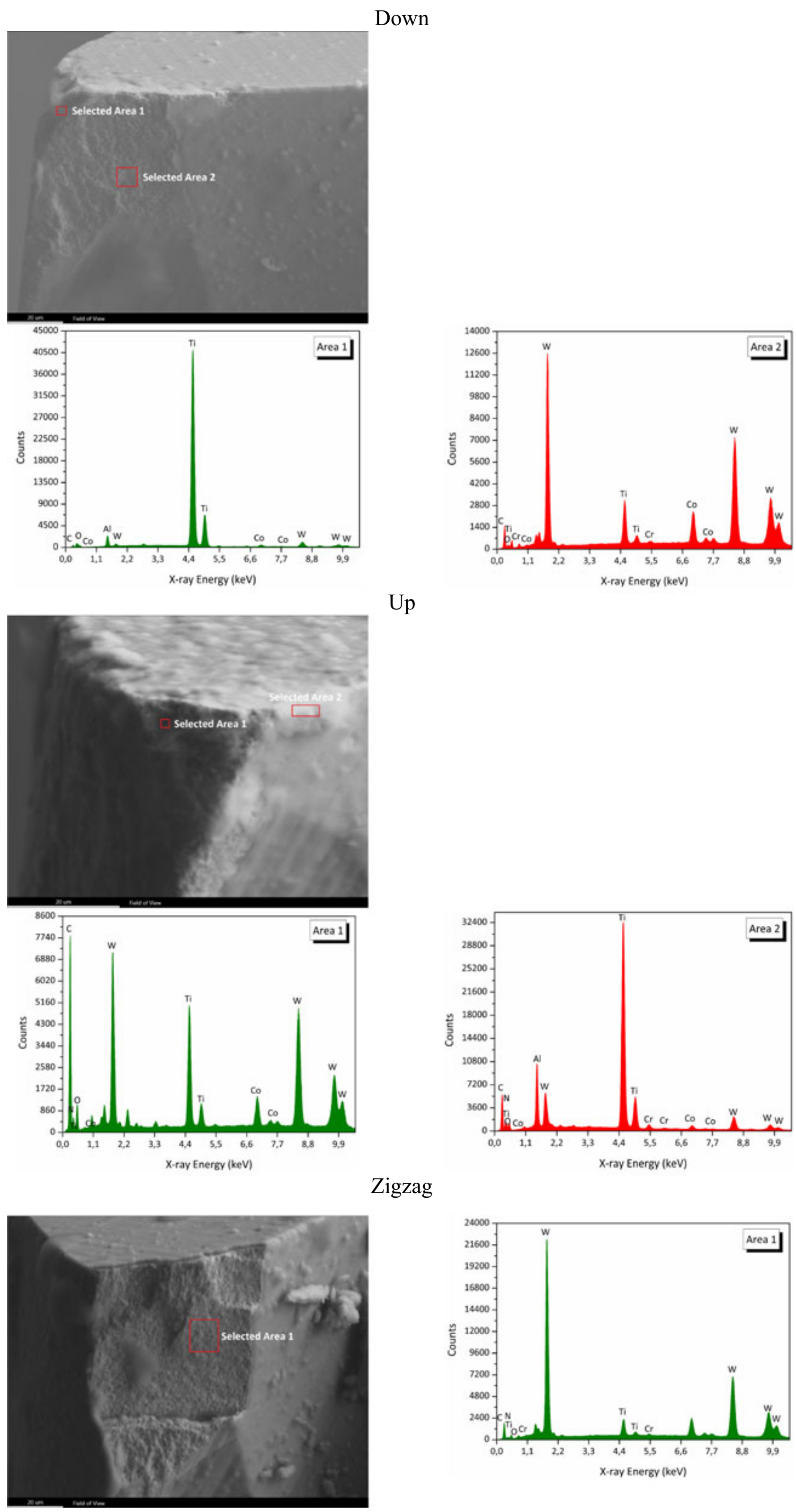

Fig. 5 EDX spectra of worn micro tools under various tool paths (spindle speed of 28,000 rpm, feed rate of 75 mm/min)

an excessive reaction. This reaction during machining induced the removing of the coating from the cutting edge. This is the reason why cutting tool suffered from chipping. Also, intermittent nature of milling process resulted in cyclic impacts which could initiate chipping. For zigzag micro-milling, fracture was also observed. The formation of fracture was

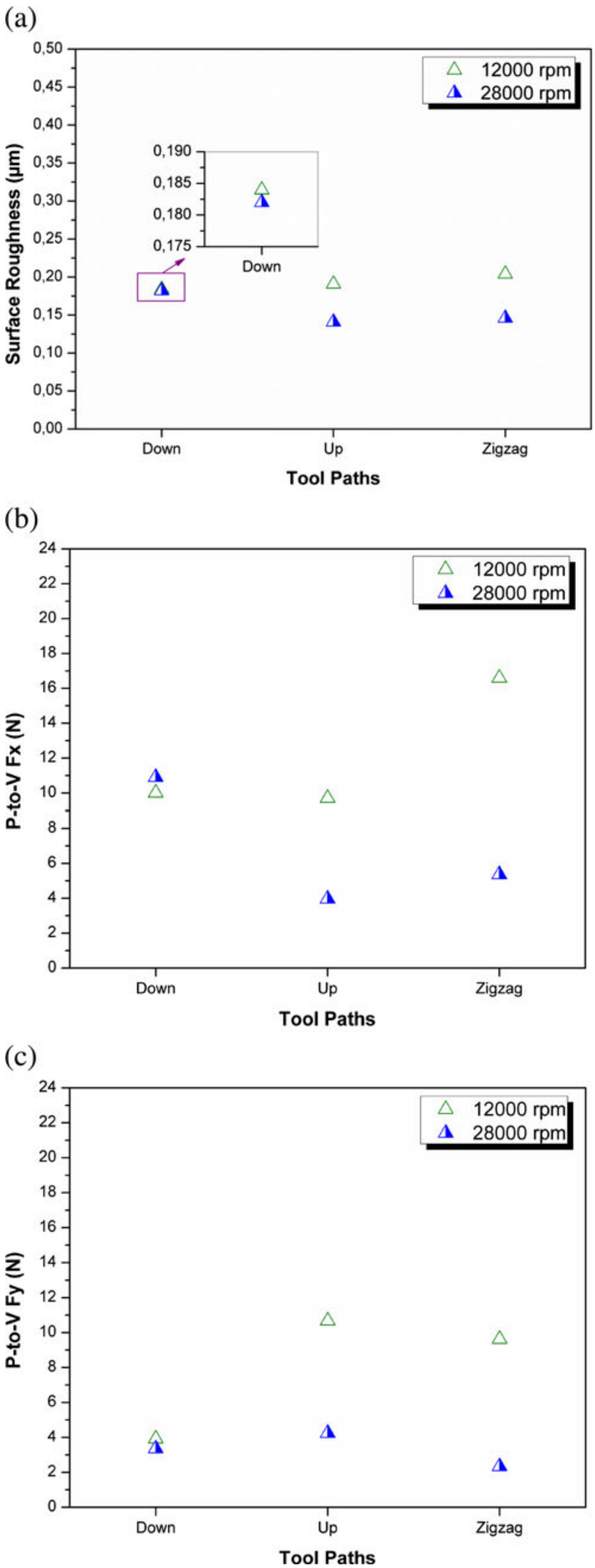

Fig. 6 The comparisons of **a** surface roughness, **b** P-to-V Fx, and **c** P-to-V Fy values under various tool paths and spindle speeds at the feed rate of 75 mm/min

owing to high stress and impact between the cutting edge and workpiece material [19]. Following coating delamination, the cyclic impact started small cracks on the cutting tool. As cutting continued, the micro-chipping changed to fracture of the cutting tool tip, which diminished the effective diameter of the cutting tool [18]. It was also reported that the built up edges (BUE) formation could lead to fracture of the cutting edge during removal of BUE [18].

It was found that up micro-milling was the best strategy in terms of tool wear when micro-milling was conducted at 75 mm/min and 12,000 rpm. The worst performance was obtained with zigzag micro-milling.

EDX spectra of worn micro cutting tools under various tool paths at the spindle speed of 12,000 rpm and feed rate of 75 mm/min are presented in Fig. 3. For down micro-milling, a higher tungsten (W) content was achieved at the selected area 1. This result was an indication of a coating (TiAlN) delamination during down micro-milling. The presence of oxygen (O) was observed on the surface of worn cutting tool indicating existence of oxide layers. For up micro-milling, it was detected a significant removal of TiAlN coating from micro-tool as shown in selected areas 1 and 2. At selected areas 1 and 2, there was W element. But, at selected area 1, the presence of titanium (Ti) indicated the partial coating delamination or BUE formation. For zigzag micro-milling, coating delamination was observed. It was also seen that a higher presence of Ti element was found for zigzag micro-milling, which confirmed the transfer of this element from workpiece material to cutting tool.

SEM micrographs of down, up, and zigzag micro-milling after machining at 75 mm/min and 28,000 rpm are presented in Fig. 4. Coating delamination was found to be the main wear mechanism of cutting tool in down micro-milling. The observed wear mechanisms were coating delamination and rounding of cutting edge when up micro-milling was used. In zigzag micro-milling, fracture of cutting tool was observed. The lowest tool wear was obtained with up micro-milling under the conditions investigated in current study.

EDX spectra of worn micro cutting tools under various tool paths at the spindle speed of 28,000 rpm and feed rate of 75 mm/min are given in Fig. 5. For down micro-milling, a higher Ti content was obtained at the selected area 1, indicating the formation of BUE. At the selected area 2, it was said that the coating delamination was found due to a higher presence of W element. The presence of O was observed on the surface of worn cutting tool indicating existence of oxide layers. For up micro-milling, it was detected a removal of TiAlN coating from micro tool as shown in selected area 1. At selected area 2, the presence of Ti indicated BUE

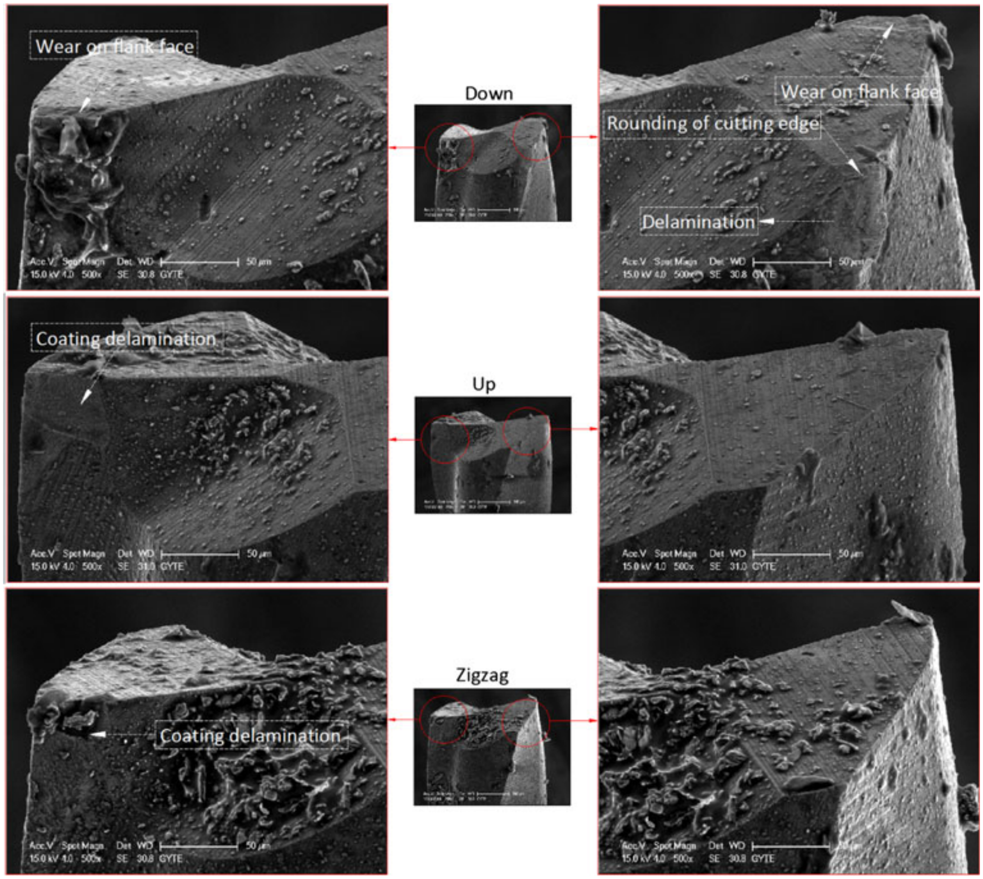

Fig. 7 The comparisons of tool wear under various tool paths (spindle speed of 20,000 rpm, feed rate of 150 mm/min)

formation. For zigzag micro-milling, coating delamination was observed.

To determine the effect of speed on tool wear when machining with low feed rate, results in Fig. 2 was compared with Fig. 4. The increment in spindle speed gave lower tool wear in down and zigzag micro-milling. However, tool wear deteriorated with the increase in spindle speed when up micro-milling was used.

The influence of speed on surface roughness and forces at the feed rate of 75 mm/min is given in Fig. 6 for down, up, and zigzag micro-milling. The increment in spindle speed resulted in the decrement in surface roughness values for all tool paths; however, this decrement was found to be low for down micro-milling. The decrement in the surface roughness was 26.2 % for up micro-milling and 28.4 % for zigzag micro-milling with the increasing spindle speed. The lowest surface roughness was obtained with up micro-milling at the spindle speed of 28,000 rpm. The increasing of spindle speed from 12,000 rpm to 28,000 rpm resulted in 59.1 and 67.6 % decrement in P-to-V Fx for up and zigzag micro-milling, respectively, however 9 % increment in down micro-milling. Up micro-milling gave the lowest P-to-V Fx for both spindle speeds. The increasing spindle speed induced the decrement in P-to-V Fy for all tool paths. When spindle speed increased from 12,000 to 28,000 rpm, 14.5, 60.2, and 75.7 % decrement in P-to-V Fy were found for down, up, and zigzag micro-milling, respectively. The lowest P-to-V Fy was achieved with down micro-milling at 12,000 rpm and zigzag micro-milling at 28,000 rpm.

Figure 7 shows SEM micrographs of down, up, and zigzag micro-milling after machining at 150 mm/min and 20,000 rpm. At 20,000 rpm for down micro-milling, coating delamination, wear located at flank face, rounding of the corner due to the abrasive wear, and the adherence of workpiece material to the cutting tool were observed. Coating delamination was also observed in up and zigzag micro-milling of Ti6Al4V material. In the case of down micro-milling, wear area was found to be lower than in the case of up and zigzag micro-milling. It was concluded that down micro-milling was the best strategy in terms of tool wear when micro-milling was carried out at 150 mm/min and 20,000 rpm.

EDX spectra of worn micro cutting tools under various tool paths at the spindle speed of 20,000 rpm and feed rate of 150 mm/min are shown in Fig. 8. At the selected area 1, a high concentration of Ti element was observed, indicating adhesion of workpiece material to the micro cutting tool. For up micro-milling, W was the major element detected at the selected area 1. The presence of this element was the indicator of coating delamination from micro tool. The EDX spectra of zigzag micro-milling revealed the presence of W element due to the coating delamination.

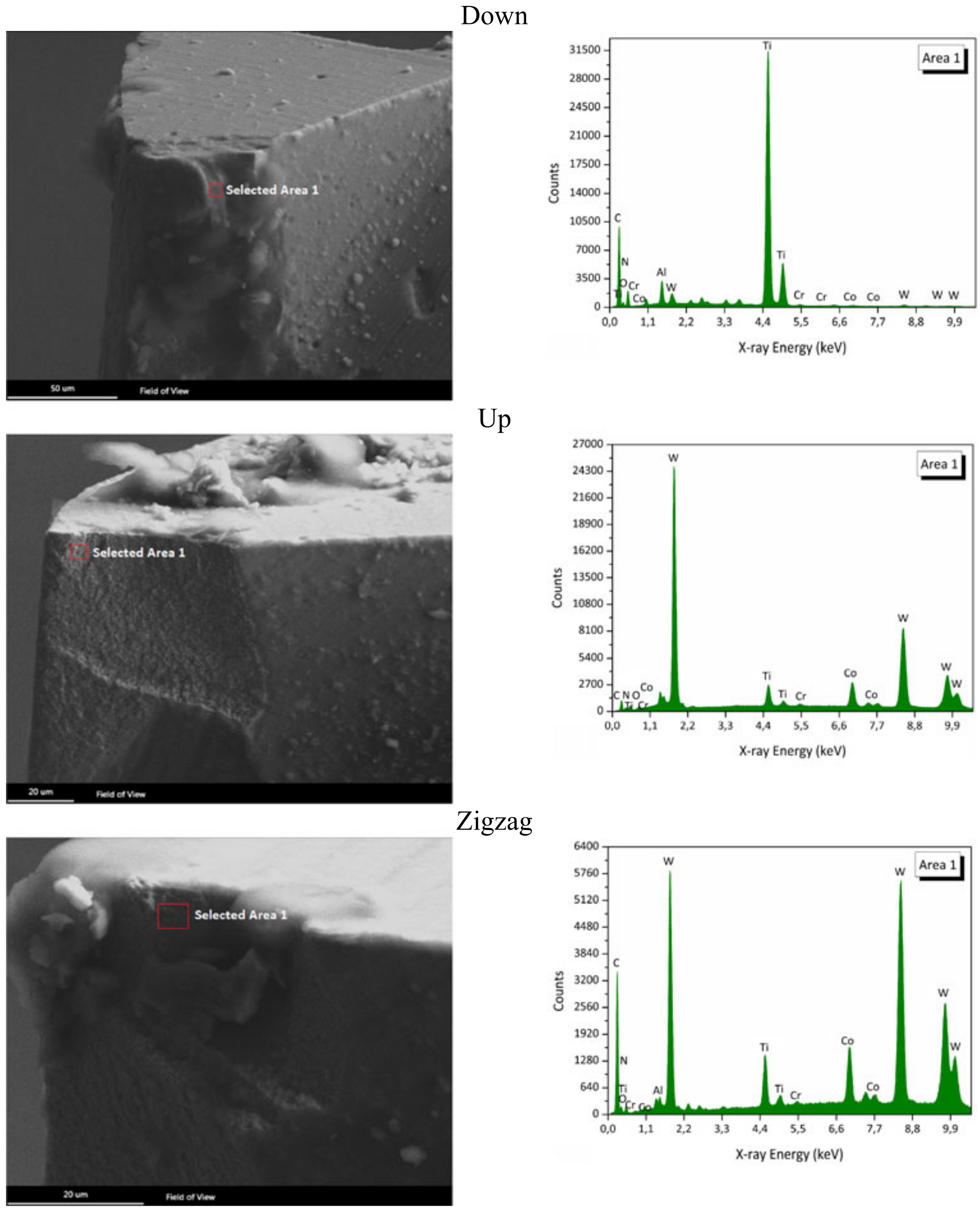

Fig. 8 EDX spectra of worn micro tools under various tool paths (spindle speed of 20,000 rpm, feed rate of 150 mm/min)

Tool wear results for down, up, and zigzag micro-milling at 150 mm/min and 28,000 rpm are given in Fig. 9. At the spindle speed of 28,000 rpm for down micro-milling, coating delamination, wear located at flank face, and chip adhesion on the cutting edge were seen. In up micro-milling, rounding of the corner owing to the abrasive wear was seen. It was also observed that the workpiece material adhered to the cutting tool. Coating delamination and fracture in up micro-milling were found to be more serious. In zigzag micro-milling, the original cutting edge was damaged and a new cutting edge formed. This was due to the excessive abrasive wear mechanism. Coating delamination and wear located at rake face were also seen in zigzag micro-milling. It was found that in down micro-milling, wear area was lower than in up and zigzag micro-milling.

EDX spectra of worn micro cutting tools under various tool paths at the spindle speed of 28,000 rpm and feed rate of 150 mm/min are depicted in Fig. 10. For down micro-milling, Ti and Al elements were found at the selected area 1 owing to the adhesion of workpiece material. A higher W element was achieved at the selected area 2. This result was an indication of a coating delamination during down micro-milling. The presence of O element was observed on the surface of worn cutting tool indicating existence of oxide layers. For up micro-milling, a removal of TiAlN coating from micro tool was observed as shown in selected area 1. For zigzag micro-milling, coating delamination was observed due to the presence of W element.

When considering Figs. 7 and 9 together, the higher spindle speed caused the higher tool wear for all machining strategies.

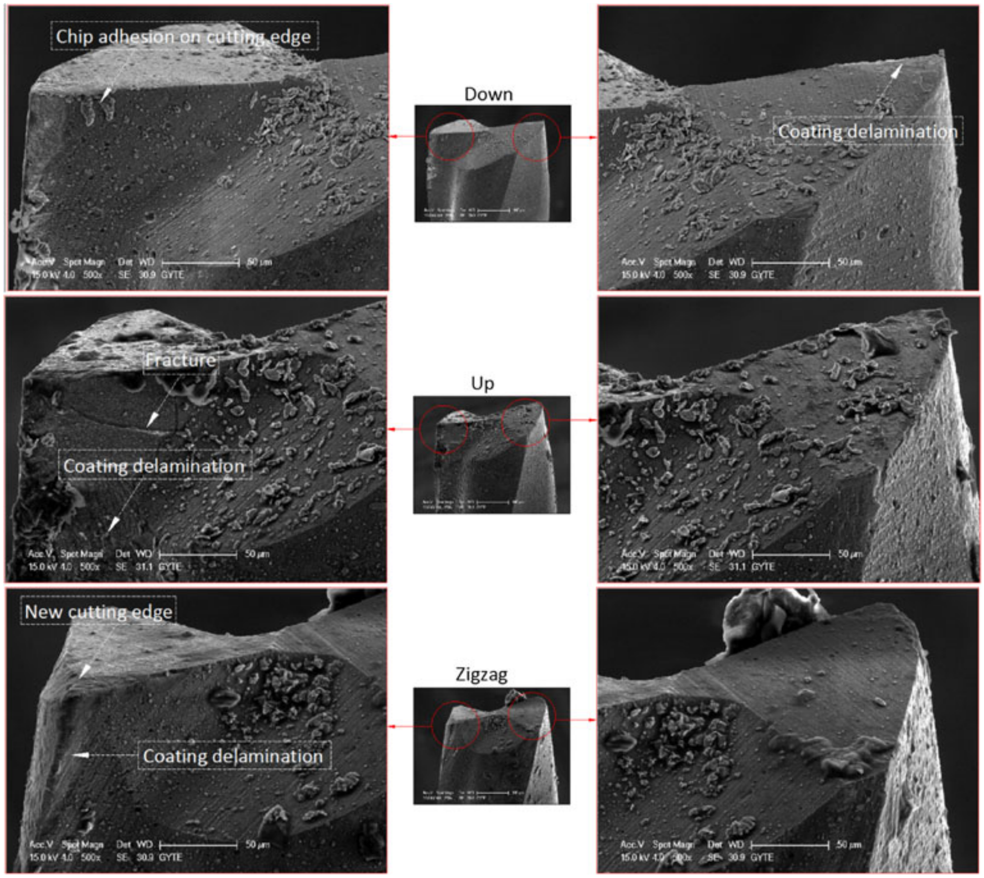

Fig. 9 The comparisons of tool wear under various tool paths (spindle speed of 28,000 rpm, feed rate of 150 mm/min)

In macro-milling, similar result was found when using zigzag milling strategy [20]. When the spindle speed increased, the time of contact between the workpiece and cutting tool increased and this induced in the rising of temperature at the contact area. This might be the reason why tool wear deteriorated with an increasing of speed.

The effect of spindle speed on roughness and forces at the feed rate of 150 mm/min can be seen in Fig. 11 for down, up, and zigzag micro-milling. The best performance in terms of surface roughness was found for both spindle speeds at down micro-milling strategy. For the spindle speed of 28,000 rpm, down micro-milling decreased surface roughness by 6.7 % compared to up micro-milling and 14.5 % compared to zigzag micro-milling. When the speed decreased from 28,000 to 20, 000 rpm, roughness in down micro-milling reduced by 12.5 and 16.7 % compared to up and zigzag micro-milling. By an increment at the spindle speed, surface roughness decreased for all tool paths. However, for up micro-milling, the influence of speed on the roughness was to be less prominent. At higher spindle speeds, cutting temperature increased and this induced the softening of the material. The softening of the material resulted in a smoother surface finish and lower surface roughness [21]. The surface roughness of down milling was found to be smaller than that of up milling. In up milling, chip thickness is zero when the cutting tool enters the workpiece and increases from zero to maximum when the cutting tool exits the workpiece. At the beginning of the cut, there will be sliding and rubbing between the cutting tools and the milled surface, which cause higher cutting temperature and an excessively work-hardened layer in the workpiece and damage to the smoothness of the milled surface. Whereas, in down milling, chip thickness decreases from maximum to zero and no sliding and rubbing phenomenon occur [21]. Therefore, the surface roughness of down milling was smaller.

In general, both P-to-V Fx and P-to-V Fy forces decreased with an increase of speed owing to the increase in cutting temperature in the shear region. Higher temperature induced the reduction of the strength of the workpiece material [22]. At low spindle speed, the cutting temperature is not high enough and the workpiece maintains its hardness. High mechanical load increases the force. By increasing of speed, the temperature in the shear zone reaches a relatively high value. Higher cutting temperature leads to decrease in shear strength and hardness of the workpiece material in the shear zone [21, 23]. This was the reason why force was small at higher spindle speed.

At the spindle speed of 20,000 rpm, P-to-V Fx force altered little under different strategies; however, minimum P-to-V Fx was recorded at down micro-milling. At the spindle speed of 28,000 rpm, P-to-V Fx force for down micro-

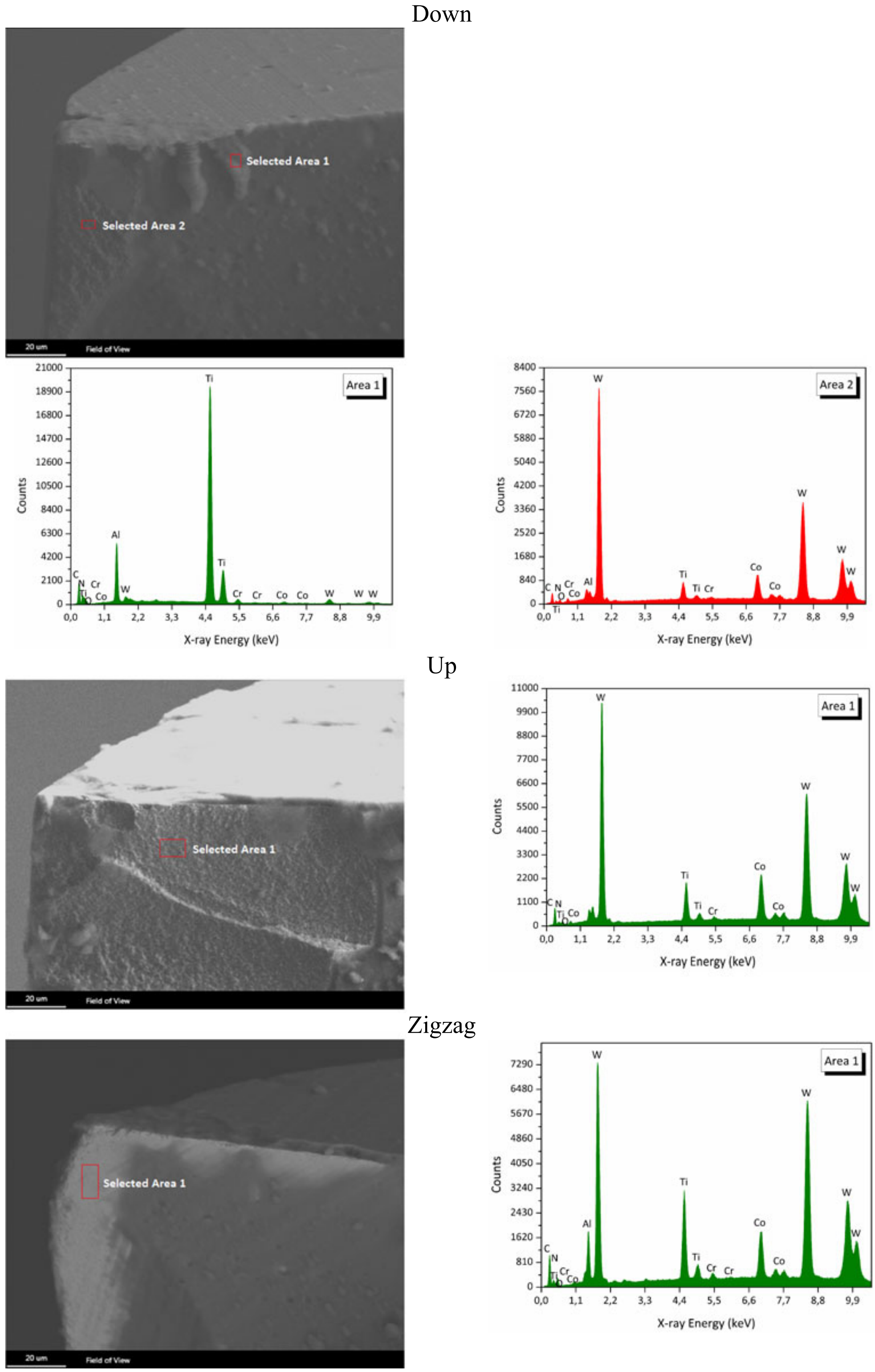

Fig. 10 EDX spectra of worn micro tools under various tool paths (spindle speed of 28,000 rpm, feed rate of 150 mm/min)

milling decreased by 35.1 % over up micro-milling and 37.3 % over zigzag micro-milling. As the spindle speed was decreased from 28,000 to 20,000 rpm, the reduction in P-to-V Fx force for down micro-milling was 1.3 and 2.6 % compared to up and zigzag micro-milling. As a result, the minimum P-to-V Fx force was achieved with down micro-milling strategy at the spindle speed of 28,000 rpm. Higher force under up milling was due to the fact that there was sliding and rubbing when cutting tool entered the workpiece material [21].

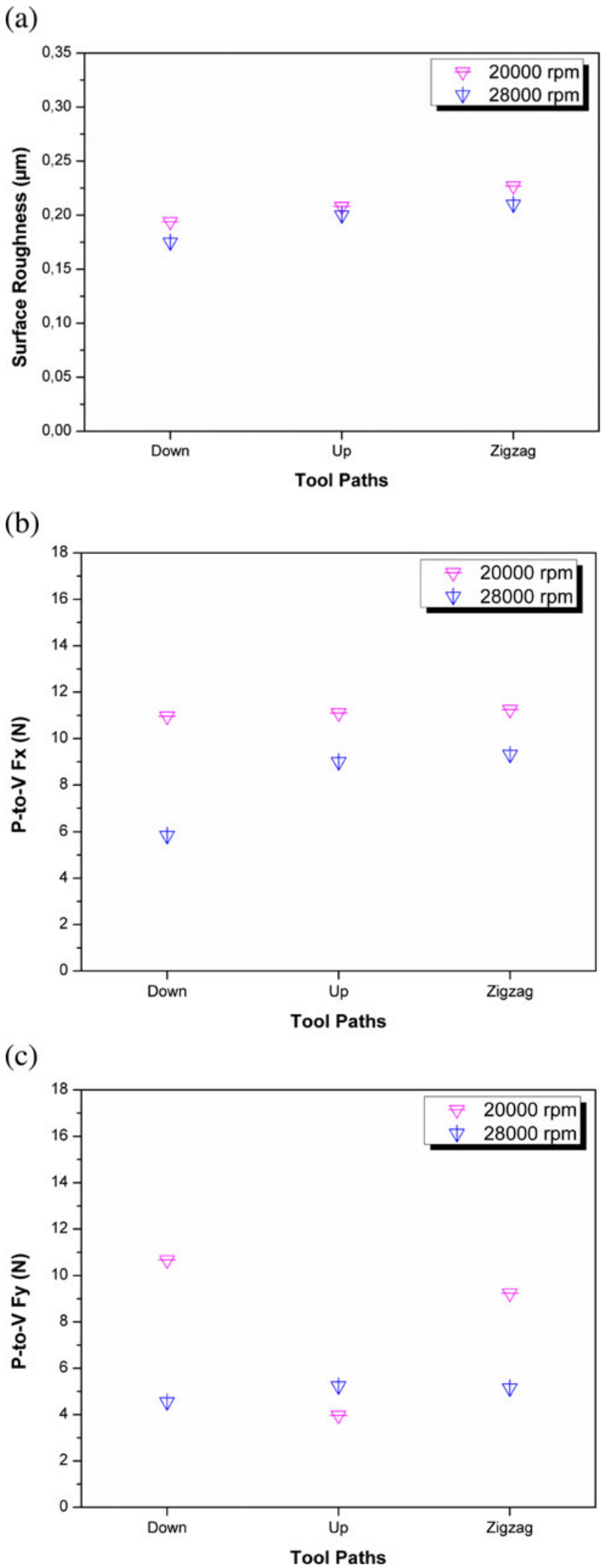

Fig. 11 The comparisons of **a** surface roughness, **b** P-to-V Fx, and **c** P-to-V Fy values under various tool paths and spindle speeds at the feed rate of 150 mm/min

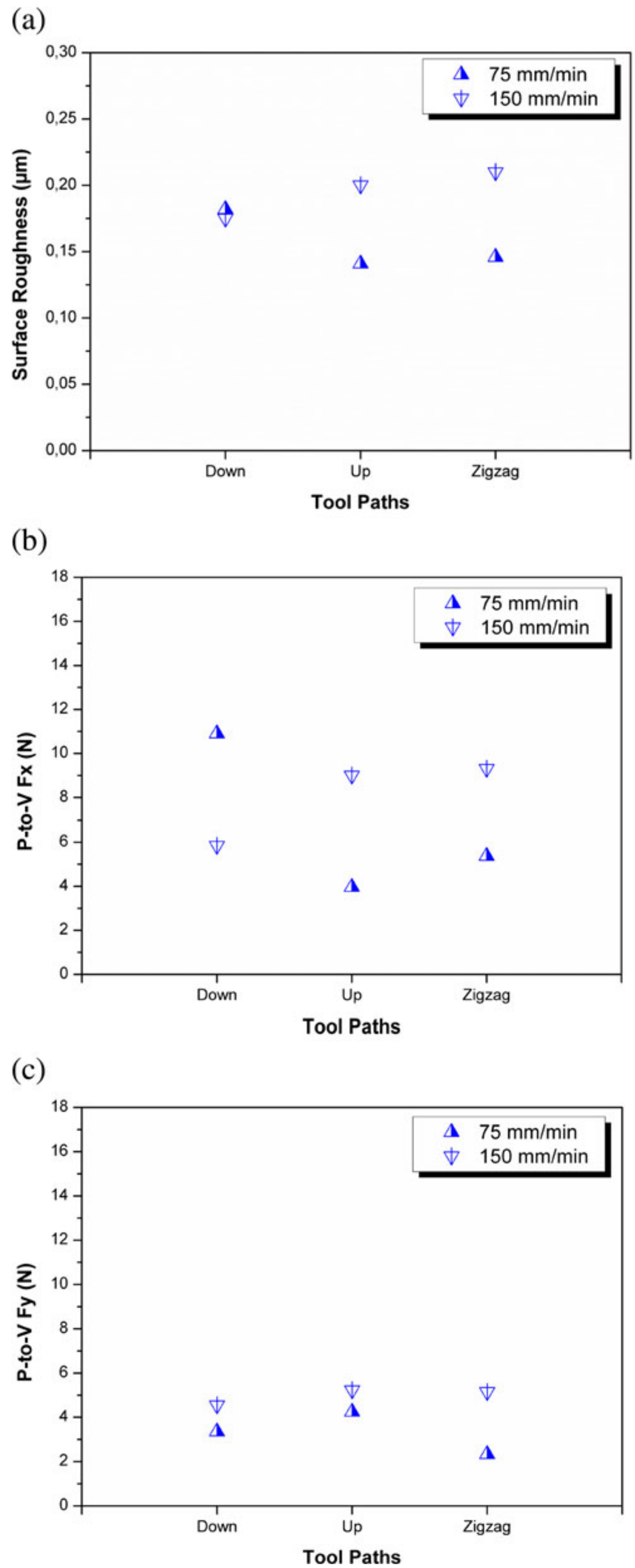

Fig. 12 The comparisons of **a** surface roughness, **b** P-to-V Fx, and **c** P-to-V Fy values under various tool paths and feed rates at the spindle speed of 28,000 rpm

When the spindle speed was 20,000 rpm, P-to-V Fy force in up micro-milling was lower than that in down micro-milling, while as the spindle speed was 28,000 rpm, P-to-V Fy force in down micro-milling was lower than that in up micro-milling.

3.2 Influence of feed rate

When Figs. 4 and 9 were compared, for all tool paths, it was found that tool wear increased with the increment in feed rate.

The influence of feed rate on forces and surface roughness at 28,000 rpm is given in Fig. 12 for down, up, and zigzag micro-milling. Up micro-milling strategy gave the lowest surface roughness value. It was found that roughness values deteriorated with an increase of feed rate for all tool paths except for down micro-milling. However, no significant change in surface roughness for down micro-milling was found with increasing of the feed rate from 75 to 150 mm/min. It was reported that the feed marks left by cutting tool could be seen in the surface topography at higher feed rate [24].

Up micro-milling gave the lowest P-to-V Fx at 75 mm/min. When feed rate rose from 75 to 150 mm/min, down micro-milling gave the lowest P-to-V Fx. It was also found that P-to-V Fx values increased with increasing feed rate for all tool paths except for down micro-milling.

At 28,000 rpm, P-to-V Fy increased with increasing feed rate. The lowest P-to-V Fy values was obtained with down micro-milling at 150 mm/min and zigzag micro-milling at 75 mm/min, respectively.

4 Conclusions

The influences of tool paths, feed rates, and spindle speeds on wear, surface roughness, and forces in micro-milling of Ti6Al4V material were investigated. Results were summarized as follows:

- Coating delamination, rounding of the cutting edges, abrasive wear, chipping, and fracture were the observed wear mechanisms at 75 mm/min and 12,000 rpm. It was also found that up micro-milling was the best strategy in terms of tool wear when micro-milling was conducted at the spindle speed of 12,000 rpm. The worst performance was obtained with zigzag micro-milling. The lowest surface roughness, P-to-V Fx, and P-to-V Fy were obtained with down, up, and down micro-milling, respectively.
- At 75 mm/min and 28,000 rpm, the coating delamination, rounding of cutting edge, and fracture were observed on cutting tools and up micro-milling gave the lowest tool wear, surface roughness and P-to-V Fx values. The lowest P-to-V Fy was obtained with zigzag micro-milling strategy.
- At 150 mm/min and 20,000 rpm, the coating delamination, wear on flank face, rounding of the corner, and adhesion were observed. The lowest tool wear, surface roughness, and P-to-V Fx were achieved with down micro-milling strategy; however, the lowest P-to-V Fy was obtained with up micro-milling.
- When micro-milling experiments were conducted at 150 mm/min and 28,000 rpm, the coating delamination, wear on flank face, adhesion, rounding of corner, and fracture were observed. At this condition, the lowest tool wear, surface roughness, P-to-V Fx, and P-to-V Fy were found at down micro-milling.
- At low feed rate, the increment in spindle speed gave lower tool wear in down and zigzag micro-milling. However, tool wear increased with the increment in spindle speed when up micro-milling was used. Under these circumstances, surface roughness and P-to-V Fy for all tool paths decreased with increasing spindle speed. P-to-V Fx decreased with increasing spindle speed for all tool paths except for down micro-milling.
- Under high feed rate conditions, tool wear increased with spindle speed for all tool paths. In general, the increase in spindle speed induced the decrease in surface roughness, P-to-V Fx and P-to-V Fy.
- At 28,000 rpm, tool wear and P-to-V Fy increased with feed rate for all tool paths and surface roughness and P-to-V Fx increased with increasing feed rate for all tool paths except for down micro-milling.
- In summary, it was concluded that up or zigzag micro-milling gave the best performance at high spindle speed and low feed rate. The best performance was achieved with down micro-milling at high spindle speed and high feed rate.
- EDX analysis confirmed the coating delamination and the presence of BUE in TiAlN coated micro cutting tools during down, up, and zigzag micro-milling of Ti6Al4V workpiece material.

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