Reduction of tool tip vibration in single point diamond turning using an eddy current damping effect

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Abstract

Titanium alloys are regarded as difficult to cut materials because of their low thermal conductivity at the elevated temperature, the elastic recovery of machined surface near the clearance face of cutting tool in single point diamond turning (SPDT) is unavoidable, causing an extensive tool tip vibration. The tool tip vibrates at a high frequency with small amplitudes in SPDT, resulting of poor surface integrity. Focusing on the problematic tool tip vibration occurred in SPDT, in this paper, the intensive work was conducted on investigating the influence of eddy current damping effect on the tool tip vibration in SPDT, showing the reduction of the tool tip vibration. In the experiments, titanium alloys were rotated in between of two permanent magnets and suffered from an eddy current damping effect. The experimental results showed that tool marks caused by the small tool movements in tool tip vibration were highly reduced, resulting of improvements of surface roughness and surface profile. Moreover, because of the dissipation of kinetic energy of tool tip vibration by the additional eddy current damping factor, the characteristic peak ratio (CPR) decreased too, which it accurately predicted that surface roughness of machined surface decreased with the CPR increase and magnetic field intensity increase. The intensive work from this study provides an effective machining technology to reduce the unsolvable tool tip vibration in SPDT by using an eddy current damping effect.

Keywords: Single point diamond turning; Titanium alloys; Eddy current damping effect; Tool tip vibration; Ultra precision machining

1. Introduction

Owing to the excellent material properties of two-phrase (α+β) titanium alloys Ti6Al4V(TC4) such as high strength-to-weight ratio, excellent heat resistance and extraordinary corrosion resistance, they have been selected as materials for manufacturing highly precise products especially in the aerospace and medical industries[1–4]. However, titanium alloys are difficult-to-cut materials because of their low thermal conductivity, ultimately causing negative effects to machinability of the materials[5,6]. In machining, cutting tools wear off quickly because of high machining temperature and noteworthy adhesion between tool edges and melted titanium alloys, which highly degrade the physical strength of tool. On the other hand, low elastic modulus of titanium alloys generates a high level of material recovery in machining processes, which further introduces tool tip vibration at the tool/workpiece, resulting of the wavy machined surface and high surface roughness[7–10].

In previous researches, the works related to ultra-precision machining (UPM) of titanium alloys displayed poor surface finishing due to the low machinability of materials. The machined products and components made with titanium alloys are difficult to fulfil the requirement of UPM which the final products are required in nanometric surface finishing[11]. Therefore, UPM of titanium alloys is now still in a nascent stage and various machining technologies should be modified to fill this research gap. Researchers commonly construct the simulation model by applying involved machining parameters, tool geometry to predict surface roughness of machined surface. However, the tool tip vibration in single point diamond turning (SPDT) is rarely considered in the element of modelling which highly affects the final machined surface, and thus no related solution is provided for controlling that tool tip vibration in UPM up to now. Also, previous studies mostly focus on the vibration with low frequency ranges in machining, for the vibrations with frequency more than

10 kHz, which are the main vibration mode generated by the tool tip vibration in SPDT, are underestimated in previous works[12]. The problematic tool tip vibration has not been resolved up to now and it inputs undesired machining outcomes to the final machined components especially for the surface integrity.

In this paper, an eddy current damping effect was applied into SPDT in order to suppress the tool tip vibration in SPDT of titanium alloys. The tool tip vibration would be treated as the simple harmonic motion with the small amplitude and low frequency. Considering an application of the eddy current damping effect into SPDT, experimental results showed that the tool tip vibration in the turning process was minimized through dissipating the oscillation energy as a form of heat in generating eddy current, they also validated the strong correlation between the ratio of characteristic peak's amplitude and surface roughness in SPDT. This study provided a novel machining technology to reduce the degree of the tool tip vibration and the induced surface damage in SPDT.

2. Theory

Reduction of turning vibration using an eddy current damping effect

When a conductive metal exposes to a magnetic field and it has a motion in between of the magnetic field, an eddy current is generated through a stationary magnetic field or time varying magnetic field inside the conductor. The eddy current will create its own magnetic field with the opposite direction of the applied magnetic field, the interaction of the magnetic fields leads a force to against the change in magnetic flux [13]. As there is an existence of the internal resistance of the conductor, an eddy current is dissipated in the form of heat energy from the kinetic energy of vibration in the mechanical system. The kinetic energy of the oscillating system would convert to the heat energy which dissipates to heat up the conductor. The processes of creating and dissipating of the eddy current lead the system to act as a function of a viscous damper [14–17].

In the proposed research, an eddy current damping was applied into SPDT of titanium alloys. In the experiments, titanium alloys were placed and rotated in between of two magnets in the turning process. Titanium alloys acted as the moving conductor in a static magnetic field, and an eddy current was induced inside the titanium alloy. Therefore, a viscous damper was added into the SPDT system, which successfully minimized an unsolvable tool tip vibration in SPDT.

3. Material and methods

Two-phrase titanium alloys, Ti6Al4V(TC4), were used as materials for the experiments. Ti6Al4V contains 6% aluminium, 4% beta phrase stabilizer vanadium, 0.25% iron, 0.2% oxygen and the remaining parts of titanium. Titanium alloys were cylindrical shape with length 40mm and diameter 15mm. Titanium alloys were placed in between of two permanent magnets and underwent single-point diamond turning. One group of samples underwent SPDT in the presence of magnetic field, named as MFS (magnetic field sample) while another group of samples underwent SPDT in the absence of magnetic field, named as NMFS (non-magnetic field sample). The magnetic field intensity was simply adjusted by replacing the magnets with different intensity. Depth of cut, feedrate and spindle speed were set as 4μm, 8mm/min and 1500rpm respectively and were unchanged throughout the experiments. The magnetic field intensity was adjusted as 0.01T and 0.02T. The detail experimental setup is shown in Figure 1. The radius and height of diamond tools used in the experiments were 1.468mm and 10.172mm respectively. Moore Nanotech 350FG (4-axis Ultra-precision machine) was used as equipment for diamond turning. The surface roughness was measured by the Wyko NT8000 Optical Profiling System.

Figures 1. Experimental setup of SPDT under an eddy damping effect

4. Results and Discussion

4.1 Characteristic twin peaks in the FFT generated in SPDT

The material swelling effect is the well-known problem that worsens the surface quality of machined surface in SPDT, the ragged materials cause an uneven machined surface and therefore increase surface roughness. The ragged materials on the machined surface become a damping source that delays the movement time of tool tip vibration. The dynamic model of tool tip vibrations with the material swelling effect is similar to an impacted pendulum system with a damping factor[9,10], an illustration graph of tool tip vibration with process damping by recovered materials is shown in Figure 2.

The overall orbit of object in the pendulum with a barrier being an excitation is the summarization of the orbit equations of oscillating object with a barrier $h_1(t)$ and without barrier $h_2(t)$:

$$h(t) = h_1(t) + h_2(t) = H_1 \sin(\omega_1 t + \varphi_1) + H_2 \sin(\omega_2 t + \varphi_2) \quad (1)$$

$$\omega_2 = \frac{2\pi}{T_2} \quad (2)$$

where ω_1 and ω_2 are the vibration frequency of the simple pendulum system with and without an impact respectively. φ_1 and φ_2 are the phase shift of the simple pendulum system with and without an impact respectively. Appling the scenario of tool vibration into the above pendulum model, the orbit of tool vibration induced by the impact between tool and the chip root can be expressed as equation (1) too.

Due to the material swelling behind the tool edge, time T_2' for tool moving backward in the vibration motion is lengthened and longer because of the ragged surface. Therefore, the swing frequency with damping effect $\omega_2'$is smaller than ω_2, in the meantime, $T_2' > T_2$. The orbit of object $h(t)'$ in the impacted pendulum system with a damped factor is expressed as

$$h'(t) = h_1(t) + h_2'(t) = H_1 \sin(\omega_1 t + \varphi_1) + H_2' \sin(\omega_2' t + \varphi_2') \quad (3)$$

Therefore, for the frequency spectrum analysis of SPDT, the tool vibration could be identified by twin peaks in FFT; the peak with the smaller frequency would be the back-shift movement of tool vibration caused by the ragged materials on the machined surface, while the peak with the higher frequency would be the forward movement of tool tip vibration toward the chip root of machined surface.

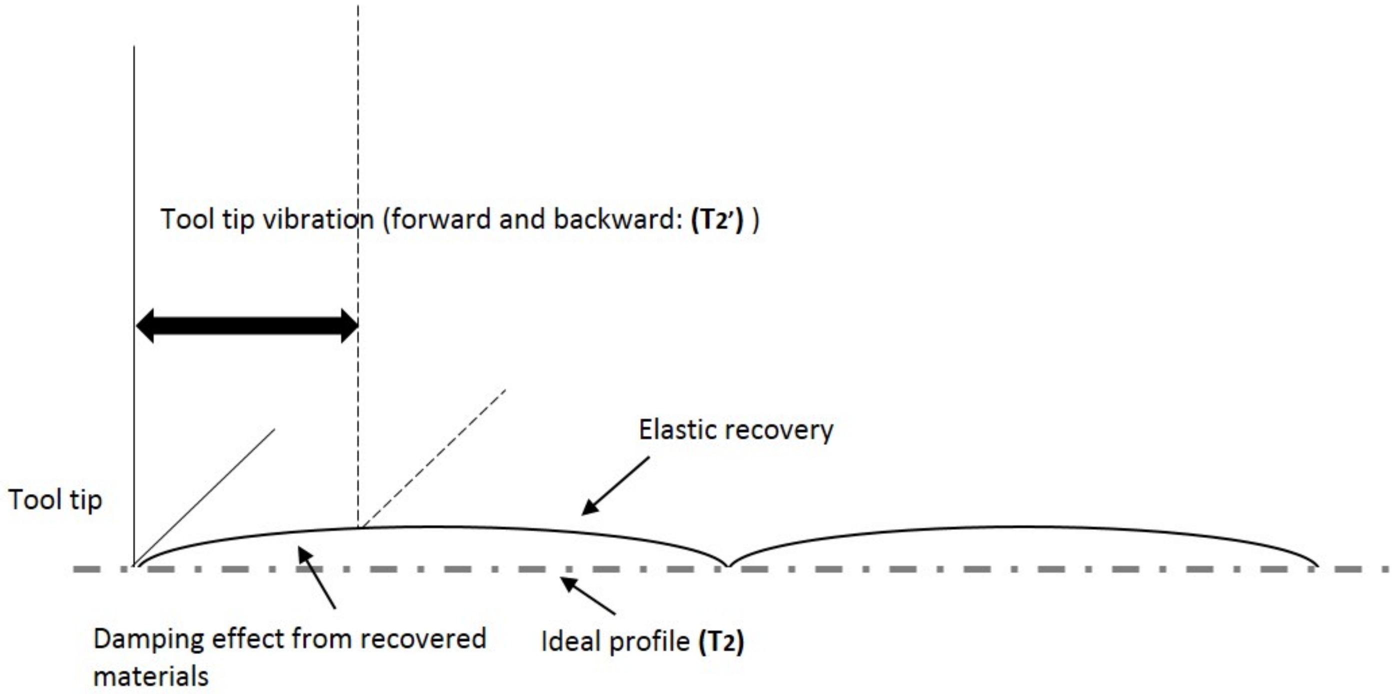
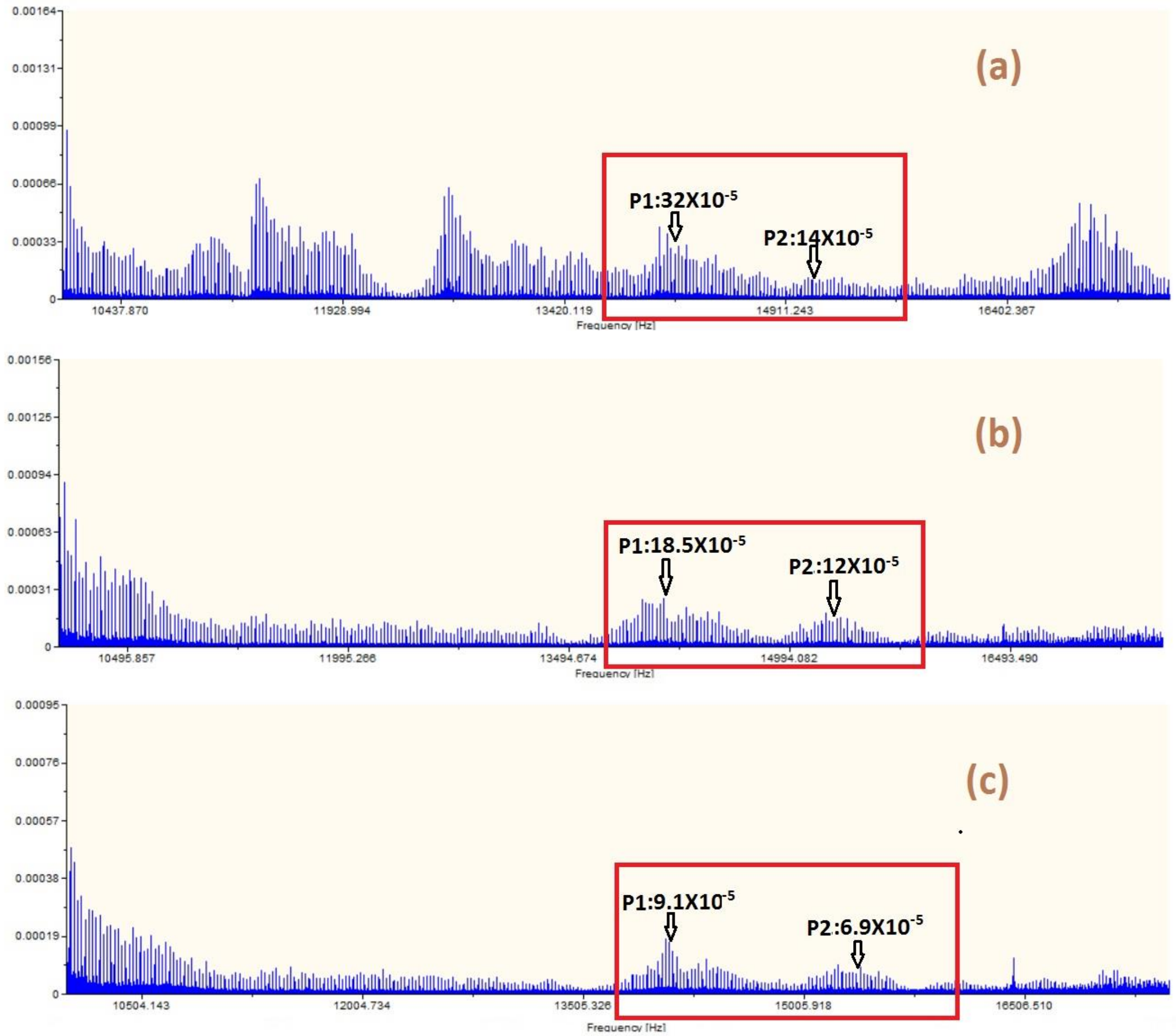


Figure 2. Illustration graph of tool tip vibration with process damping by recovered materials

4.2 Influence of eddy current damping effects on the tool tip vibration and surface roughness

In the experiments, the natural frequency of turning motion in SPDT is determined as 14.4KHz. According to Figures 3, the peak P2 within the particular twin peaks appeared at around 15.2kHz, therefore, the twin peaks P2 and P1 are identified as the excited natural frequency induced by SPDT process and the back-shift of tool tip vibration with the damping effects induced by recovered materials respectively. According to Figures 3, The peak amplitudes P2 and P1 generated in the presence of magnetic field intensity 0.01T – 0.02T were obviously lower than that of in the absence of magnetic field intensity. The peak amplitudes P2 and P1 generated at the magnetic field intensity 0.02T even decreased about 50.7% and 71.6% respectively in comparison to that of zero magnetic field intensity, suggesting the suppression of tool tip vibration induced by material recovery in SPDT.



Figures 3. FFT of thrust force generated at magnetic field (a) 0T, (b) 0.01T and (c) 0.02T

Table 1. Amplitude of characteristic twin peaks and CPR of SPDT under 0 – 0.02T magnetic field intensity

H	Amplitude (N)		CPR
	P1	P2	
0	0.00032	0.00014	0.4375
0.01	0.000185	0.00012	0.6486
0.02	0.000091	0.000069	0.7582

In SPDT, tool marks are induced on the machined surface due to the tool tip vibration. When the tool tip vibration happens, the vibrated tool moves forward and backward on the machined surface and obvious tool marks are resulted because of the tool shift. As shown in Figure 4, the tool shift causes the overlap and discontinuity of two adjacent tool marks. The tool shift forward leads to the discontinuity of two adjacent tool marks and therefore there are uncut materials left on the surface, while the tool shift backward causes overcutting of surface materials and thus the machined surface appears concave areas which the height of the concave area is below the machined surface. The ragged and concave areas generated by the tool shift display on the machined surface in every turning cycle and therefore the surface finishing is poorer when the tool tip vibration is presence [15]. For an ideal profile without any tool tip vibration, the tool radius is large enough to produce tool marks which contribute to small surface roughness, the ideal machined surface is always little wavy as well as containing blur tool marks. As shown in Figure 4, because of the suppression of tool tip vibration using an eddy current damping effect, the tool shift distance of MFSs was reduced, and hence the amounts of overcut and uncut machined area were lower for MFSs as shown in Figures 5. On the contrary, many uncut and overcut materials displayed on the machined surface of NMFS, which were possibly induced by the forward and backward shifts of tool in the tool tip vibration.

As the suppression of turning vibration by an eddy current damping effect, the tool shift distance of MFSs is believed to reduce, so the tool marks of machined surface of MFSs were shallower and narrower consequently in comparison to that of NMFS. The machined surface profiles of MFSs and NMFS are shown in Figures 6(a-c). Comparing between Figures 6(a-c), the tool marks produced in the absence of magnetic field were clearly displayed on the machined surface, they were distributed distinctly and obviously with clear crests and valleys in between two adjacent tool marks, while the tool marks were found to be blur and indistinctive in the presence of magnetic field intensity 0.01T and 0.02T. Surface integrity of machined surface was highly improved under the influence of eddy current damping effect.

On the other hand, as the CPR index is directly obtained from the cutting force during the SPDT process, while surface roughness is the main machining outcome of SPDT, therefore, the CPR index has a close connection with the value of surface roughness and the tool tip vibration. The CPR is denoted as a prediction tool of surface roughness in SPDT encountering with the tool tip vibration[9]. A higher value of CPR means a stronger reduction of tool tip vibration in SPDT. According to the results in Figure 6, the tool marks of NMFS are obvious, and each tool mark has longer width, it represented that surface roughness of machined titanium alloys decreased with an increase in the CPR, which matched the results of CPR shown in Table 1.

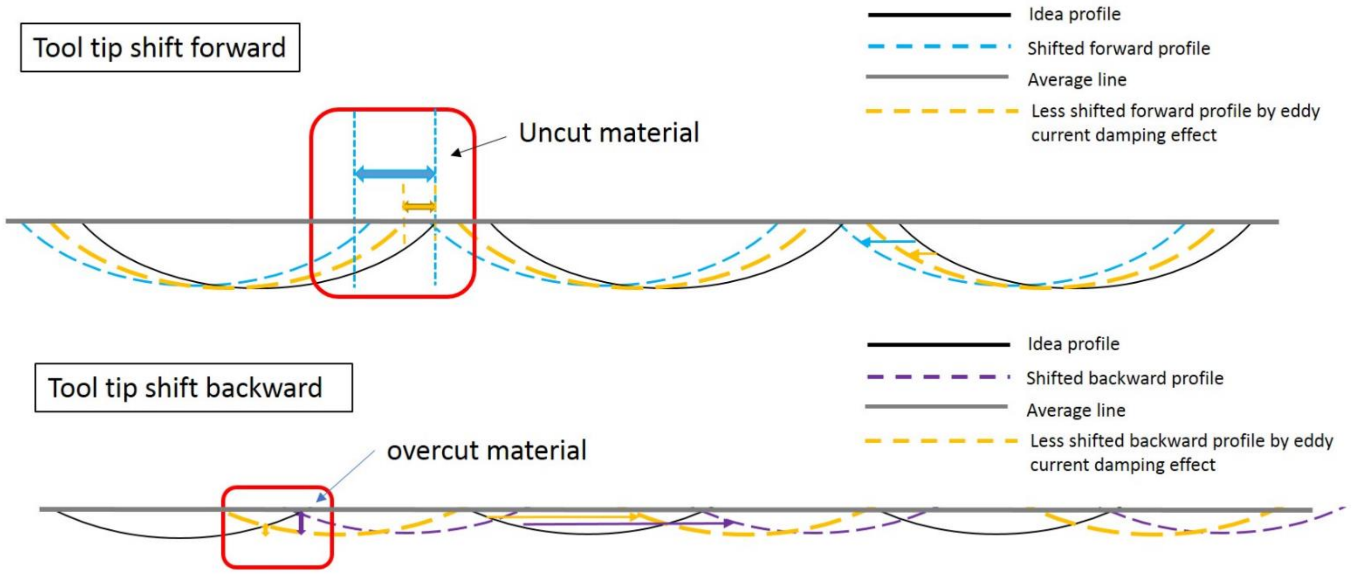
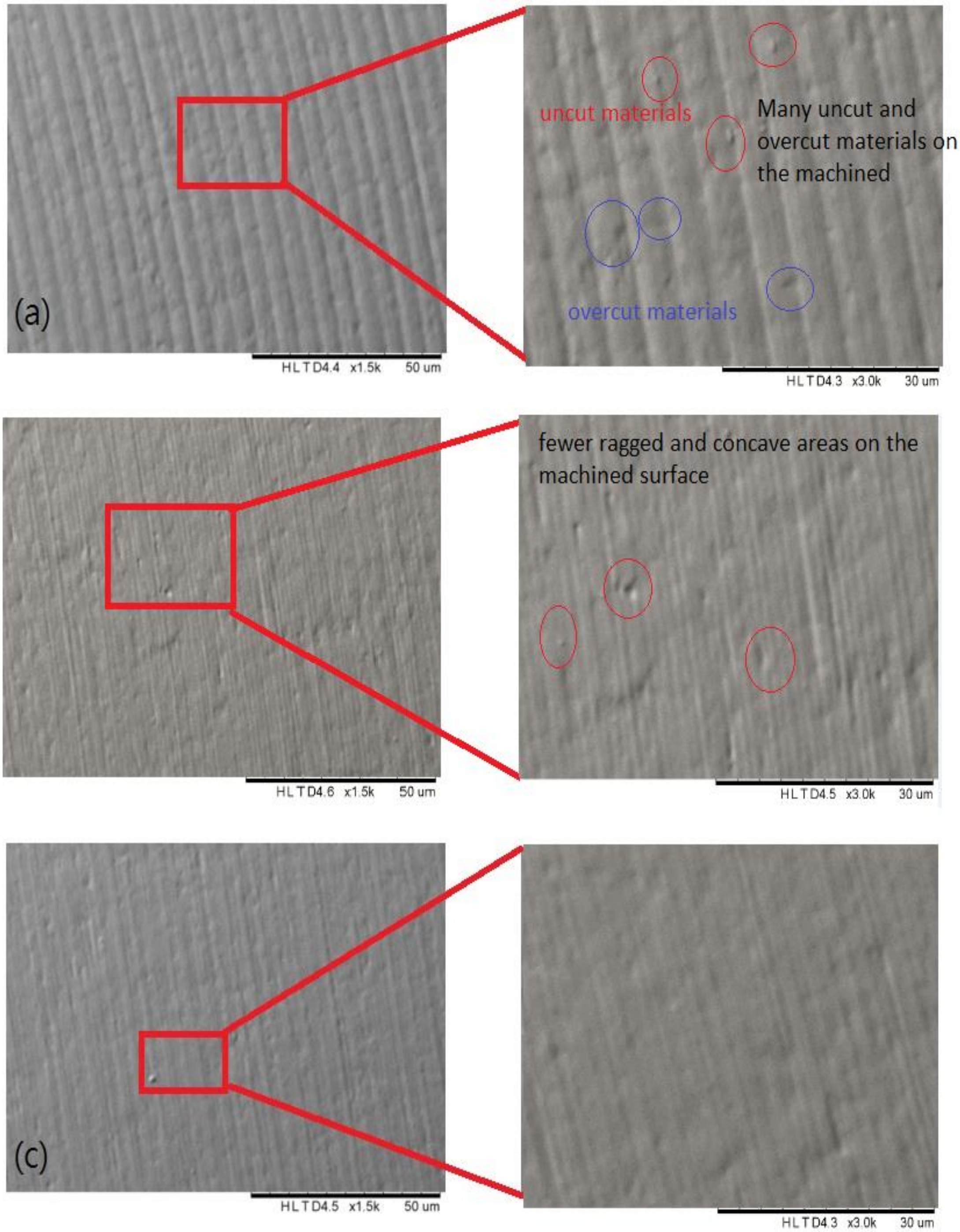
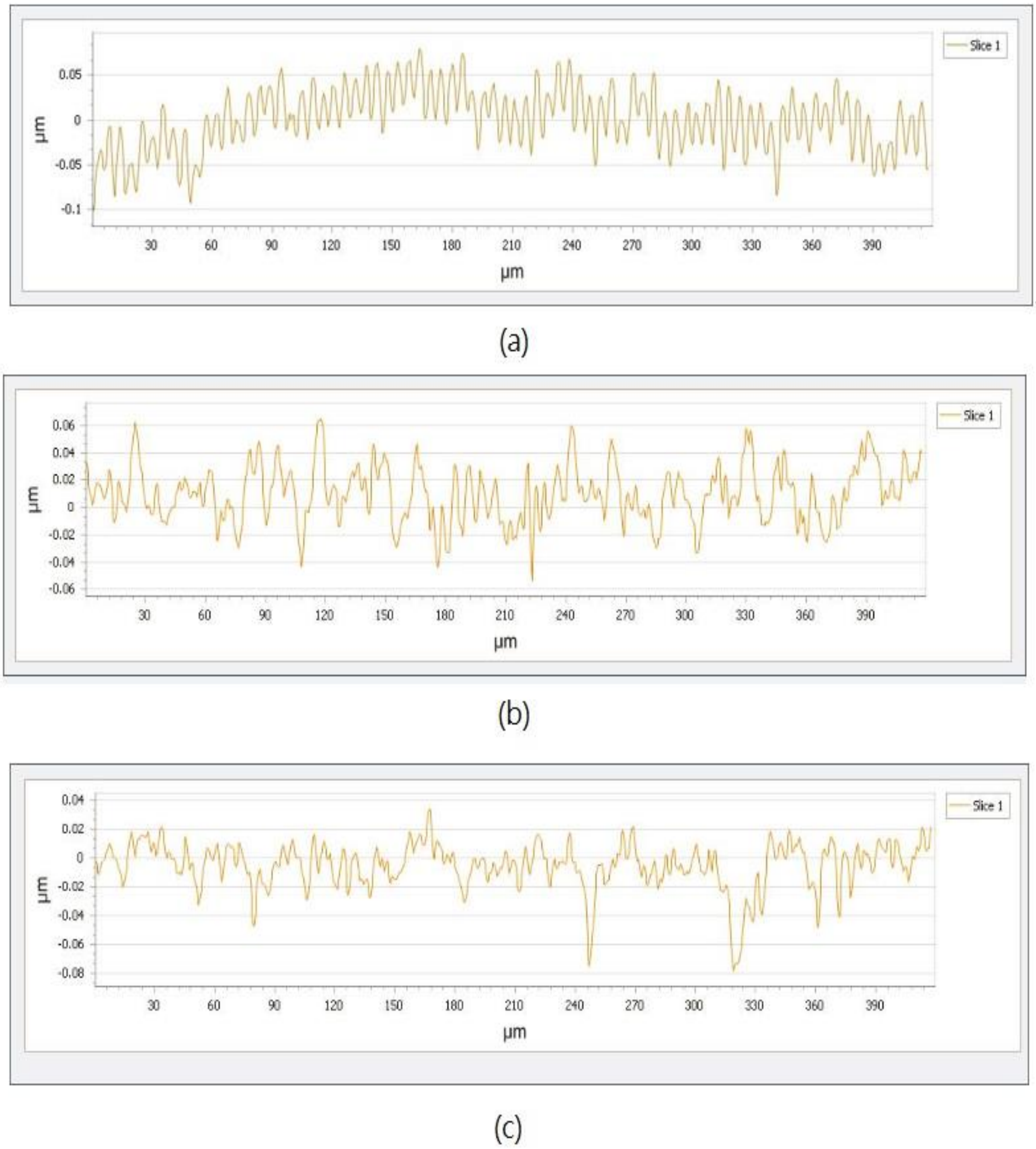


Figure 4. Illustration graph of tool marks caused by tool vibration



Figures 5. Tool marks on the machined surface of (a) NMFS, (b) MFS at 0.01T magnetic field intensity and (c) MFS in 0.02T magnetic field intensity



Figures 6. Surface profiles of (a) NMFS, (b) MFS at 0.01T magnetic field intensity and (c) MFS at 0.02T magnetic field intensity

5. Conclusions

In this study, the works on the positive influences of SPDT using an eddy current damping effect were conducted, which focusing on minimizing the problematic tool tip vibration in SPDT. The reduction of vibration amplitudes regarding to the tool tip vibration were proven by the comparisons of the twin peak amplitudes in the FFT between MFSs and NMFS. Moreover, the CPR of SPDT adding with an eddy current damping effect increased, providing the evidence of effectiveness of dissipating oscillation energy of tool tip vibration through an eddy current damping effect, thus decreased surface roughness of machined surface. The experimental results showed an improvement of surface roughness and a reduction of tool marks induced by tool tip vibration under the influence of eddy current damping effect, which validated the prediction capability of CPR on surface roughness. The tool tip vibration was successfully suppressed by the eddy current damping effect which the proposed approach is firstly introduced to minimize the tool tip vibration in UPM area.

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