An application of eddy current damping effect on single point diamond turning of titanium alloys

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Abstract

Titanium alloys Ti6Al4V (TC4) have been popularly applied in many industries. They hold superior material properties including an excellent strength-to-weight ratio and corrosion resistance. However, they are regarded as difficult to cut materials; serious tool wear, a high level of cutting vibration and low surface integrity are always involved in machining processes especially in ultra-precision machining (UPM). In this paper, a novel hybrid machining technology using an eddy current damping effect was firstly introduced in UPM to suppress the machining vibration and improve machining performances of titanium alloys. A magnetic field was superimposed on samples during single point diamond turning (SPDT) by exposing the samples in between of two permanent magnets. When titanium alloys rotated within a magnetic field in SPDT, an eddy current was generated through a stationary magnetic field inside titanium alloys. An eddy current would generate its own magnetic field with the opposite direction of external magnetic field leading a repulsive force, compensating the machining vibration induced by the turning process. The experimental results showed a remarkable improvement on cutting force variation, a significant reduction of adhesive tool wear and an extreme long chip formation in comparison to normal SPDT of titanium alloys, suggesting the enhancement of machinability of titanium alloys using an eddy current damping effect. An eddy current damping effect was firstly introduced in UPM area to deliver the results of outstanding machining performances.

Keywords: Eddy Current damping effect; Ultra-precision machining; Titanium alloys; Machining vibration; Single point diamond turning

1. Introduction

Owing to the excellent material properties of two phase (α+β) titanium alloys Ti6Al4V (TC4) including high strength-to-weight ratio, heat resistance and extraordinary corrosion resistance, they are widely employed in the aerospace and automobile industries [1-2]. Titanium alloys are difficult to cut materials because of low thermal conductivity, which is not favourable in the machining [3]. Low thermal conductivity of titanium alloys prevents heat transfer from a cutting zone in machining, the heat generated in the turning process cannot be dissipated from the machined surface effectively. Hence, the localized heat at the tool flank surface deteriorates the tool life [4], leading a poor surface finish and surface integrity. The machining cost unavoidably increases due to the rapid tool wear and the resulting low surface integrity.

Apart from the problematic high cutting temperature, the machining vibration is another main factor that worsens the surface quality and machining performances in machining of titanium alloys. Vibration is unavoidable in machining processes. Basically, the vibration in the turning process can be categorized as two types, they are forced vibration and self-excited vibration. Normally, the forced vibration is causes by the insertion of periodic cutting force at the tool/workpiece interface. Because of the periodic cutting force, the cutting tool vibrates at the frequency of the cutting force, which the vibration amplitude is depended on the frequency ratio of the cutting force to the natural frequency of the cutting tool [5-6]. On the other hand, the vibration receptively occurs because of an inevitable self-excited vibration between the workpiece and tool, which is induced by the formation of cyclic force as well as the localized shearing, causing dynamic instability in the turning process [7-8]. The machining vibration generates wavy surface on the machined components, causing an advanced cutting force variation and discontinuous chips, generating an extensive machining vibration at the tool/workpiece interface. Moreover, the waviness regeneration occurs if the tool vibration is not in phase with the surface waviness, causing the enlargement of tool vibration and instability in machining processes. In addition, chatter vibration exists in the turning process, it increases with the depth of cut increase in machining processes [9-10]. Chatter vibration is magnified at the particular combination of depth of cut and spindle speed, therefore, the strategies of changing spindle speed and reducing depth of cut are implemented in order to suppress chatter vibration which lead to sacrifice the material removal rate. The machining vibration causes adverse effects on the machined components of titanium alloys, causing poor surface integrity of machined products and a high machining cost, the applications of these excellent alloys are thus limited. Therefore, the suppression of machining vibration of titanium alloys becomes the main issue for enhancing machining performances of titanium alloys.

Single Point Diamond Turning (SPDT) is one of machining technologies in ultra-precision machining (UPM) and is substantially used for producing an optical grade surface finishing within 10 nm surface roughness. Titanium alloys have excellent properties such as high strength to weight ratio, so the uses of titanium alloys are commonly in the optical and medical applications with precise specifications, which are manufactured by diamond turning to achieve the excellent surface quality. Diamond turning of titanium alloys has been extensively investigated by the researchers. Ruibin and Wu [11] studied the optimum machining parameter for diamond cutting of titanium alloys, they verified that low feedrate and small depth of cut should be adopted in machining in order to provide better surface quality of machined components. Zareena and Veldhuis [12] examined the tool wear mechanisms involved in diamond turning of titanium alloys, they obtained results that the serious adhesive diamond tool wear occurred on the rake face due to high localized cutting temperature. Hu and Zhou [13] conducted tests on diamond cutting of titanium alloys and reported the wear pattern, showing the uniform wear and chemical wear because of trapping high cutting temperature at the cutting zone. The reported reason for serious adhesive tool wear in diamond turning of titanium alloys was mainly low thermal conductivity, which caused high cutting vibration, cutting friction and strong adhesion of materials on the tool. Researchers focused on resolving the problematic tool wear. Zhang et al. [14] indicated that the tool vibration induced from the high cutting friction as well as the high cutting heat was the dominant factor to affect the tool wear, therefore, they proposed ultrasonic vibration diamond turning to lower the cutting force and vibration in machining. Sales et al. [15] proposed different cooling approaches to lower the cutting temperature in diamond machining of titanium alloys, the results showed that the use of cryogenic cooling would alter the tribological behaviour of machining interface, contributing to the lower tool wear and surface roughness. They also showed that adhesive titanium alloys would result in plucking out of hard diamond materials from the tool, causing abrasive wear. According to previous literature, the high cutting vibration and adhesive tool wear in diamond turning of titanium alloys should be resolved in order to uplift the machinability of titanium alloys.

Research on machining technologies related to physical fields has been getting attention. Several studies had showed the successful applications of a magnetic field to machine different materials. Li et al. [16] demonstrated an amelioration of machining performance of TC4 by a pulsed magnetic field treatment, the phase transformation from beta to alpha of titanium alloys was facilitated and the dislocation density decreased under the influence of magnetic field intensity 4T. El Mansori et al. [17] confirmed the tool wear was significantly reduced by an application of coaxial electromotive force which was explained by the principle of magnetic alignment induced by an irreversible rotation of domain wall of ferromagnetic materials.

Up to now, machining titanium alloys reported in literature showed poor surface finishing on machined components due to the low machinability of materials, also, the subsequent problematic tool wear has not been solved yet. Machining titanium alloys is still under a progressing stage and different machining technologies should be adopted in order to fill up the research gap. An eddy current damping has never been applied in the machining area especially in UPM to provide exceptional effects to increase the machining performances of difficult to cut materials in SPDT. In the presented work, under employing an eddy current damping effect in SPDT, a suppression of cutting force variation, continuous chip formation and a reduction of adhesive tool wear were demonstrated in comparison to the normal SPDT. Furthermore, the proposed technique is cost efficient and flexible for the modification, only two permanent magnets which are extremely low cost are used additionally. Small size of magnets enables them to be installed inside the ultra-precision machine; The proposed technology overcomes the restriction of insufficient space of ultra-precision machine.

2. Material and methods

Two phase titanium alloys, Ti6Al4V(TC4) were used as the materials for the experiments. Ti6Al4V contains 6% aluminum, 4% of beta phase stabilizer vanadium, 0.25% of iron, 0.2% of oxygen and remaining parts of titanium. Titanium alloys were in cylinder shape with length 40mm and diameter 15mm. One group of titanium alloys NMFS (non-magnetic field sample) processed normal SPDT in absence of magnetic field, while another group titanium alloys MFS (magnetic field sample) processed SPDT in presence of magnetic field. The self-developed fixture for holding permanent magnets was installed in the ultra-precision turning machine. MFSs were placed in the middle of two magnets during SPDT in order to suffer from an eddy current damping effect. The particular part of the fixture was made by steel which is a ferromagnetic material, they aimed to provide an uniform magnetic field strength passing through titanium alloys so that the steady magnetic torque could be generated in SPDT. The radius and height of diamond tool were 1.468mm and 10.172mm respectively. The chip formation was observed under scanning electron microscopy (SEM) machine Hitachi HT3030. The force sensor Kistler 9256C was used to measure the cutting force. Moore Nanotech 350FG (4 axis Ultra-precision machine) was used as the equipment for diamond turning.

The magnetic field intensity provided in the experiment was adjusted for three values as 0.01T, 0.02T and 0.03T. Feedrate, depth of cut and spindle speed were set as 8mm/min, 4μm and 1500rpm respectively and unchanged throughout the whole experiments. The tool conditions at the cutting distances 75m and 150m were observed under SEM. The experimental setup is shown in Figure 1.

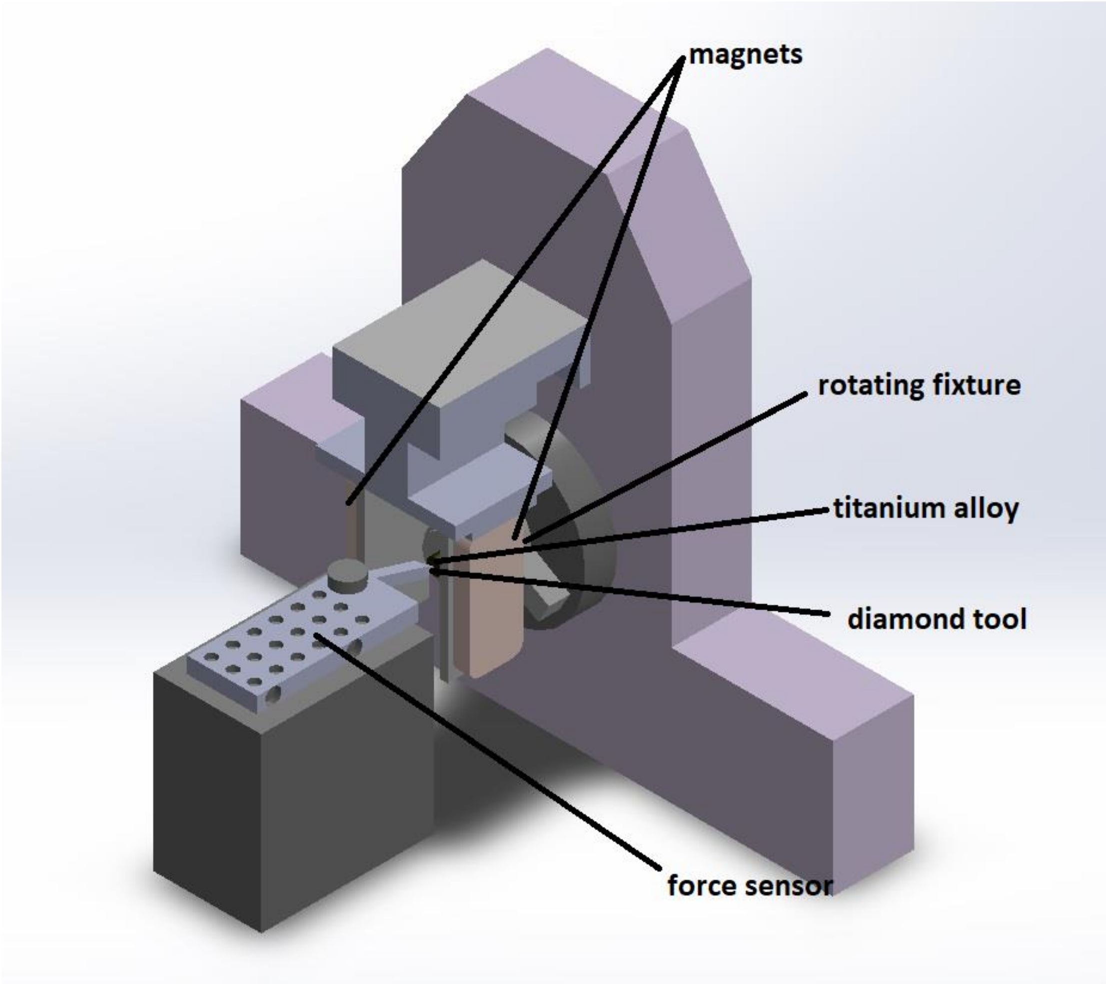


Figure 1. Experimental setup of magnetic assisted diamond turning

3. Theory

3.1 Suppression of system vibration using an eddy damping effect

When a conductive metal rotates within a magnetic field, an eddy current is generated through a stationary magnetic field inside the conductor. An eddy current will create its own magnetic field with the opposite direction of external magnetic field leading the repulsive force called Lorentz force [18-21]. Ebrahimi et al. [22] made a claim that the repulsive force generated by an eddy current was proportional to the velocity of the moving conductor, therefore the magnet and moving conductor acted as a viscous damper system. The phenomenon of acting force reduction by the repulsive force induced from an eddy current is called "eddy current damping effect". Lorentz force F is termed as

$$F = E \times q + q \times V_e \times B \quad (1)$$

where V_e is the turning velocity of the conductor, q is the charge carried by the conductor, E is the electric field and B is magnetic field.

$$F \; \alpha \; V_e \; and \; F \; \alpha \; B (2)$$

Lorentz force is proportional to the turning velocity of rotating titanium alloys and the magnetic field intensity.

On the other hand, the machining parameters involved in SPDT process are in small scale, the depth of cut and feedrate used in the experiments were 4μm and 8mm/min respectively. Hence, the cutting force as well as the turning vibration generated was small. In this case, the eddy current damping force was used to suppress millimeter range vibration force. Therefore, the magnetic field intensity was set as 0.01T - 0.03T in the experiments in order to generate a proper Lorentz force to suppress the small vibration force in the experiments.

There were literature concerns that an eddy current damping effect enabled to reduce the vibration of mechanical system. Bae et al. [23] showed the theoretical and experimental results that the vibration of beam structure was remarkably suppressed using an eddy current damper effect. Matsuda and Hashitani [24] discussed the method of active vibration control using a moving-coil-type actuator based on an eddy current damping principle. They determined the velocity of driving current and confirmed a reduction of system vibration. Matsuzaki et al. [25] proposed a new vibration control system which successfully suppressed the vibration of partially magnetized beam using the electromagnetic force. In the practical applications, an eddy current damping effect has already been applied in the automobile and elevator systems. Liu et al. [26] designed an eddy current retarder for automobiles and it decreased the brake torque and enhanced the braking efficiency of main brake system. Jou et al. [27] designed the upright magnetic braking system, applying permanent magnets for elevators to reduce the inside vibration and hence to enhance the elevator safety. Titanium alloys were rotated in between of two magnets in this study, Lorentz force was generated which caused the opposite force acting on the rotating direction and compensated the vibration force of unstable turning system. The damping effect functionally suppressed the turning vibration induced by the interaction between tool and workpiece in SPDT.

4. Results and Discussion

4.1 Chip formation analysis

Figures 2 (a-d) show the SEMs of chip formation generated in SPDT at the magnetic field intensity 0 - 0.03T with different magnifications. Refer to Figure 2(c), the long, flat and continuous chips were generated at the magnetic field intensity 0.02T. The free surface of chips showed entire and glossy with unserrated side tips. This type of chip suggests the steady cutting mode as well as non-interrupted turning. In the contrast, discontinuous chips were generated from the NMFS. The discontinuous chips implied the formation of defects on the machined surface due to the tool vibration, and the small movement of tool vibration initiated the tensile cracks and shear cracks at the chip. This kind of chip formation normally happens in machining materials with low modulus elasticity such as titanium alloys. The integral effects of low elastic modulus of titanium alloys and the small step removal mechanism in SPDT lead to decrease the chip stiffness at the high cutting temperature, finally the chips melted and caused the generation of segment chips of NMFS. On the other hand, the NMFS generated the chip edges with classical saw tooth tips. For the MFSs at the same machining condition, the chip edges showed flat without appearing saw tooth shape, their free surface displayed lamellae layers with even width. It suggested the diamond tool lid easily with long dislocation distance during diamond turning process, demonstrating less vibration characteristic. In order to capture the entire chip of MFS at magnetic field 0.02T, a lower magnification of MFS chip was applied in order to provide the clear view of whole chip and make the macro comparison between that of NMFS and MFS. The contrast of chip formation between NMFS and MFSs was magnified in term of macro view as shown in Figures 3(a-b). The length of chips generated from MFS at the magnetic field intensity 0.02T was surprisingly long while the powder and fragment chips were formed from NMFS due to the extensive turning vibration in SPDT.

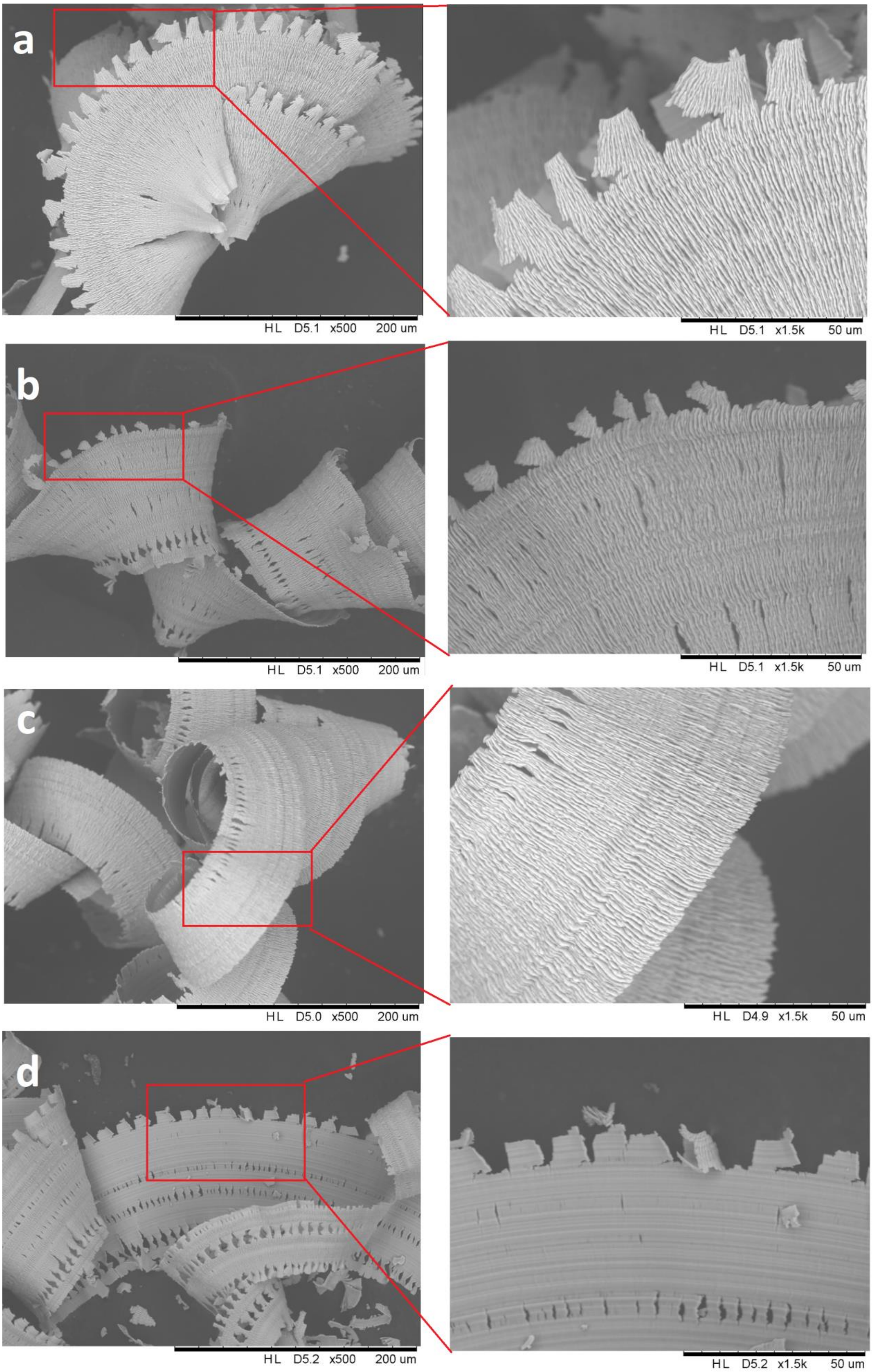
Faraday’s law explained that an electromagnetic force (EMF) ε is generated within a conductor when there is a change in the magnetic field, and EMF is highly related to the change rate of magnetic field, which is expressed as:

$$\epsilon = -\frac{d\emptyset_B}{dt} \quad (3)$$

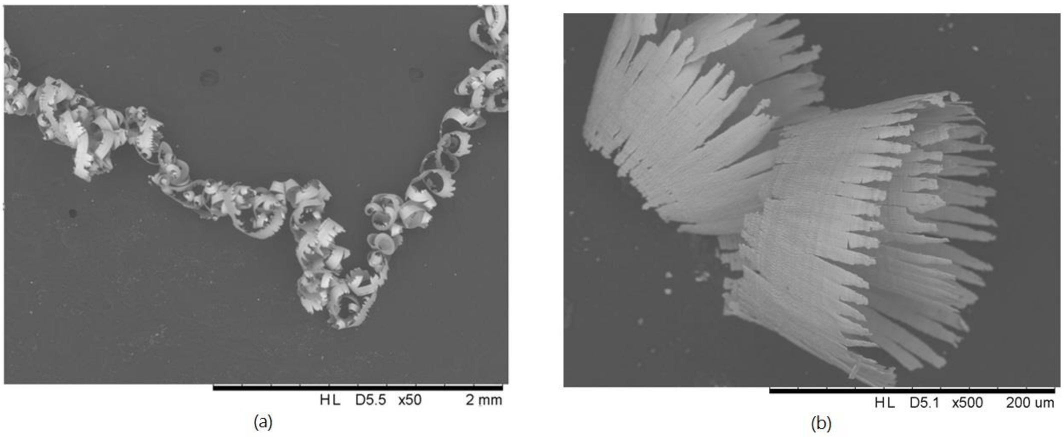
where $\emptyset_B$ is the magnetic flux density. The EMF creates a current I which is inversely proportional to the resistance R of moving conductor. The current is expressed as:

$$\mathrm{I} = \frac{\epsilon}{R} \quad (4)$$

A higher magnetic field results a higher EMF and current, consequently, MFS at the magnetic field intensity 0.03T suffered the higher current among the other two MFSs. Under the influence of relatively higher temperature at the magnetic field intensity 0.03T, the ductile fracture occurred inside the chips generated at magnetic field 0.03T, more voids was observed on the free surface of chips. On the other hand, a reduction of turning vibration lessened the tool tip shift during SPDT, thus minimized the chip breaking in the chip removal process and the chips would be continuous. Therefore, the chip generated at the magnetic field intensity 0.03T was still continuous with a few voids. In this study, the EMF generated was very small in MFSs. Therefore, although the induced eddy current would place negative effects on the machining performance in SPDT, the significance of that influence is exceptionally small. On the other hand, as UPM involves high machining accuracy, the depth of cut and feedrate are normally in micron range and millimeter displacement per second respectively, small tool vibration enables to affect the surface integrity of components. Therefore, the effect of tool vibration would be dominant in diamond turning. The induced eddy current affects the machined surface negatively, however, as an eddy current damping effect is dominant over the induced eddy current effect in SPDT. Hence, the overall machining performance was still improved for MFS at magnetic field intensity 0.03T.



Figures 2. SEM of chip generated in (a) magnetic field 0T (an absence of magnetic field), (b)magnetic field 0.01T, (c) magnetic field 0.02T, and (d) magnetic field 0.03T



Figures 3. SEMs of chip generated in (a) magnetic field 0.02T, (b) magnetic field 0T(an absence of magnetic field) in a lower magnification

4.2 Tool wear reduction

The low thermal conductivity and high elastic recovery capability of titanium alloys cause the heat trapping at the cutting zone during machining, results in an extensive tool vibration during SPDT which damages the diamond tool [28]. In machining of titanium alloys, a sizable chipping of cutting edge occurs as the vibration in the machining system enlarges, causing chip tangling and welding at the tool edge [29]. Adhesive tool wear is dominated in machining processes of titanium alloys; actually, adhesive wear is caused by the micro welding of workpiece materials. The soldering of materials is related to the high cutting force at the cutting zone which the cutting force shears the metallic junction between the cut materials and workpiece; powder forms of chip and material particle are released at the moment of breaking the metallic junction. The metallic junction is much earlier broken because of the tool vibration and eventually more chips are welded on the cutting edge [30], the turning vibration especially the tool vibration facilities adhesive tool wear in SPDT of titanium alloys.

Titanium alloys are classified as difficult to cut materials and proven to be low machinability due to their low thermal conductivity, which restricts the dissipation of cutting heat from the tool/workpiece interface [31-33]. In comparison to other materials, the temperature at the tool/workpiece interface during machining of titanium alloys is extremely high [34], and tends to localize at the tool edge. Hence, during machining processes, the tool wears very speedily due to the high cutting temperature and the strong adhesion of materials at the tool/chip interface and tool/workpiece interface [35]. Therefore, mainly, the tool wear in machining of titanium alloys is due to adhesive wear mechanism on the rake face [36]. Adhesive wear was reported to be the dominant wear mechanism in machining of titanium alloys [37-39]. Park et al. [40] indicated the same that titanium adhesion was the dominant factor for the tool wear during drilling of composite containing titanium. Combining the effects of extremely high cutting temperature and tool vibration, short chips remain contacts with the tool rake and flank surface, finally they stick to the tool tip and cause serious tool wear. Therefore, the significance of adhesive wear is one of the indicators to display the intensity of tool vibration in machining processes.

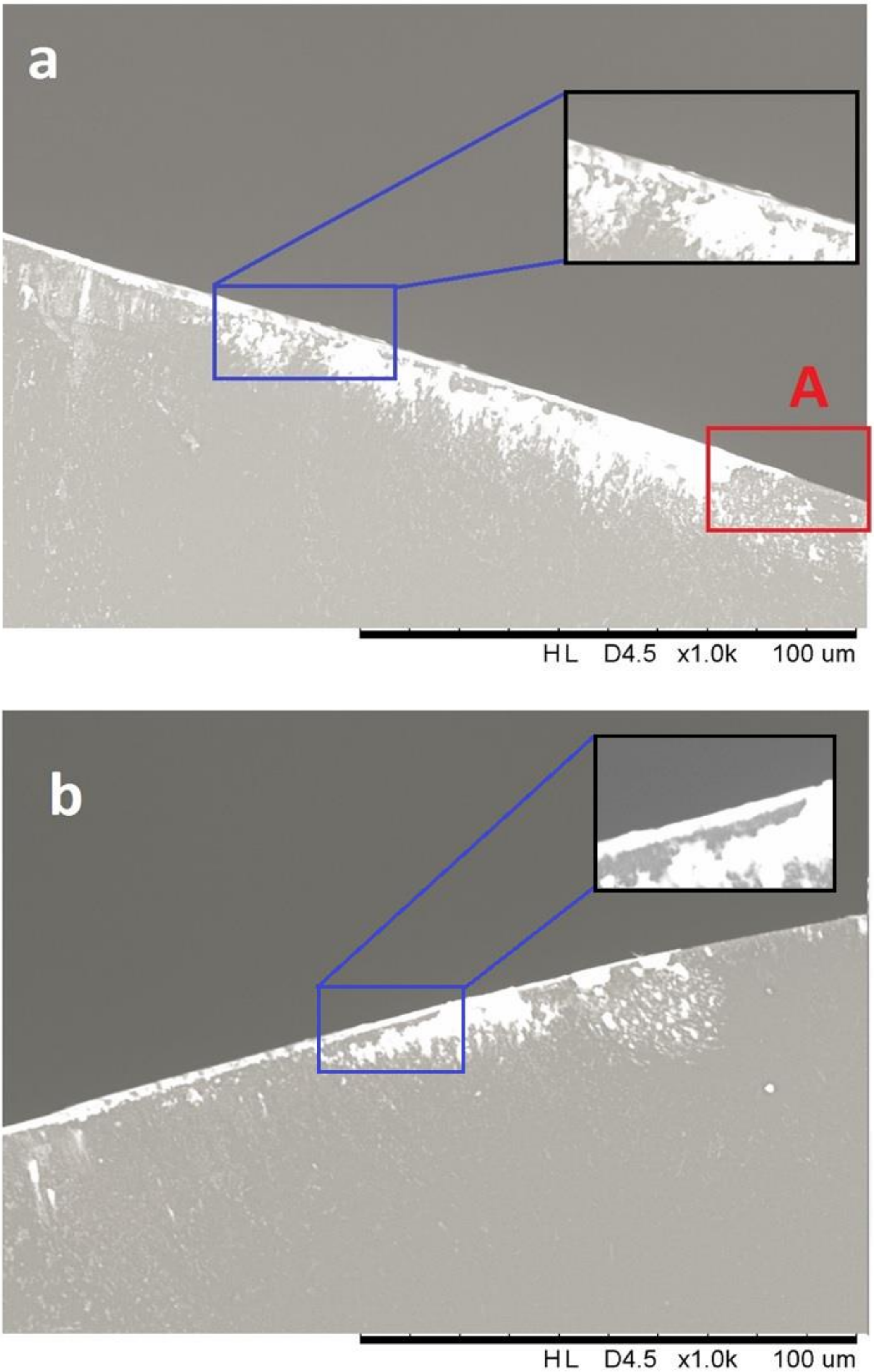
Refer to the above reports, adhesion wear would be the main focus of tool condition in SPDT of titanium alloys. In order to show the clear difference between the cutting distances 75m and 150m for NMFS tool , Figures 4 and Figures 5 showed the size and thickness of adhesive layer which are the main indicators for adhesive wear. Although the area of welded titanium alloys in the rake surface enables revealing adhesive wear, the welded titanium alloys on the rake surface do not contribute to the cutting motion as they are not located at the cutting edge. Therefore, the adhesive titanium alloys located at the cutting edge and near the cutting edge would be accounted for the tool wear and would affect the machined surface quality, we would focus on investigating the adhesive layer close to the cutting edge. Refer to Figures 4 (a-b), the adhesive/diffusive wear occurred at the tool tip regardless of a presence of magnetic field, shiny melted titanium alloys stuck to the cutting edges of both diamond tools.

Although the tool wear mechanism between MFS and NMFS was the same, the significance of tool wear was much different between NMFS and MFS tools. For NMFS tool, the area and width of welded titanium alloys at the tool tip were found to be larger and more breadth, more titanium alloys were dissolved on the tool tip in absence of magnetic field. The adhesive layer of titanium alloys of NMFS tool displayed much denser than that of MFS tool, which is showed in the larger magnification inside the Figures.

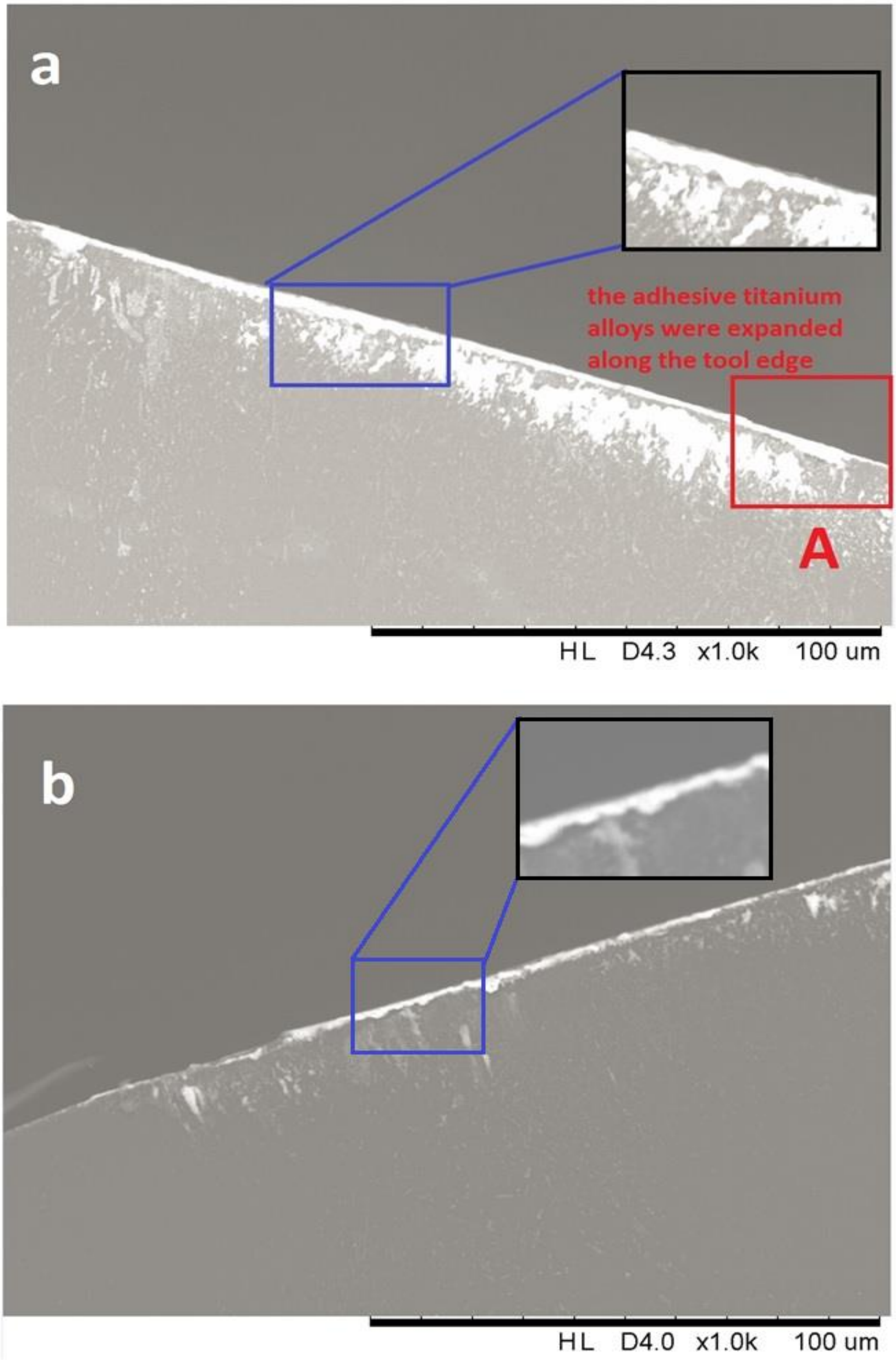
When the cutting distance increased to 150m, the characteristic of tool wear between NMFS and MFS tools was started to be dissimilar, adhesive wear was minimized under the influence of magnetic field intensity 0.02T, which is shown in Figure 5(b). Once the junction between titanium alloys and the diamond tool was formed in presence of magnetic field, the turning vibration were suppressed by an eddy current damping effect. As a result, fewer powder chips and material particles were welded on the tool tip firmly, reducing adhesive wear in SPDT of titanium alloys. In addition, the continuous turning motion further provided the harmony and offered the extra force to take off the stuck chips. When the chips melted again in the further turning process (cutting distance 150m), the melted chips lost the adhesion and were flushed away from the working gap because of the magnetic torque and aerodynamic force of turning motion. In comparison to the tool edge of NMFS, the area of adhesive wear at the tool tip came to be larger and wider when the cutting distance increased to 150m. The length of adhesive titanium alloys on the tool tip at the cutting distance 150m was longer than that at the cutting distance 75m, the adhesive layer at NMFS tool tip was expanded along to the tool edge as shown in area A of Figures 4(a) and 5(a). The small fragments of titanium alloys were welded and attached into the tool tip, that adhesive titanium alloys were deformed and enlarged to the lateral tool edge. They integrated to the tool edge and became the entire part, which contributed to disruptive turning motion and further enhanced the tool wear.

According to ISO 3685, the useful tool life is considered as end when a tool is not able to produce workpieces in the desired size and surface quality, or when it is physically incompetent for conducting further cutting [41-42]. Ultra precision machining aims to fabricate components with high surface quality, which the surface roughness of UPM products has reached up to the nanometer level. In practice, the crack of tool edge usually has the most essential influence on the quality of the produced parts. Therefore, the appearance of crack on the tool edge is used as a tool life criterion in this study.

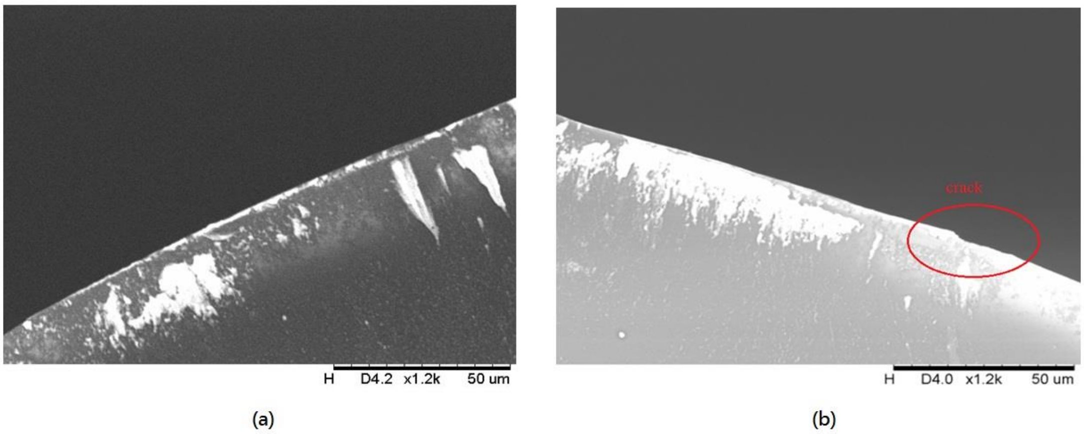
The tool wear at the longer cutting distance 750m was observed in order to observe the difference of tool wear significance between using an eddy current damping effect and without using an eddy current damping effect. As adhesive materials weaken the physical strength of diamond tool, the hard diamond materials are plucked out from the tool after adhesive tool wear in the longer cutting distance. Consequently, NMFS tool appeared a crack on the cutting edge as shown in Figure 6(b). Therefore, the tool life of NMFS tool was likely end at the cutting distance of 750m, the tool life of NMFS tool was 79.4min. In contrast to MFS tool, MFS tool was still in the stage of adhesive tool wear at this cutting distance, more titanium alloys covered on the tool edge of MFS tool but no observation of obvious crack. The tool life of MFS tool at magnetic field 0.02T would be longer than 79.4min.



Figures 4. SEMs of tool edge at cutting distance 75m (a) absence of magnetic field and (b) 0.02T of magnetic field



Figures 5. SEMs of tool edge at cutting distance 150m (a) absence of magnetic field and (b) 0.02T of magnetic field



Figures 6. The tool edge at cutting distance 750m (a) MFS and (b) NMFS

4.3 Suppression of cutting force variation using an eddy current damping effect

Kong et al. [43] stated that the thrust force F_t caused material deep swelling during SPDT, it induced obvious tool marks on the final workpiece, therefore, the thrust force F_t of NMF and MFSs was measured in the experiments. The duration was 55 seconds.

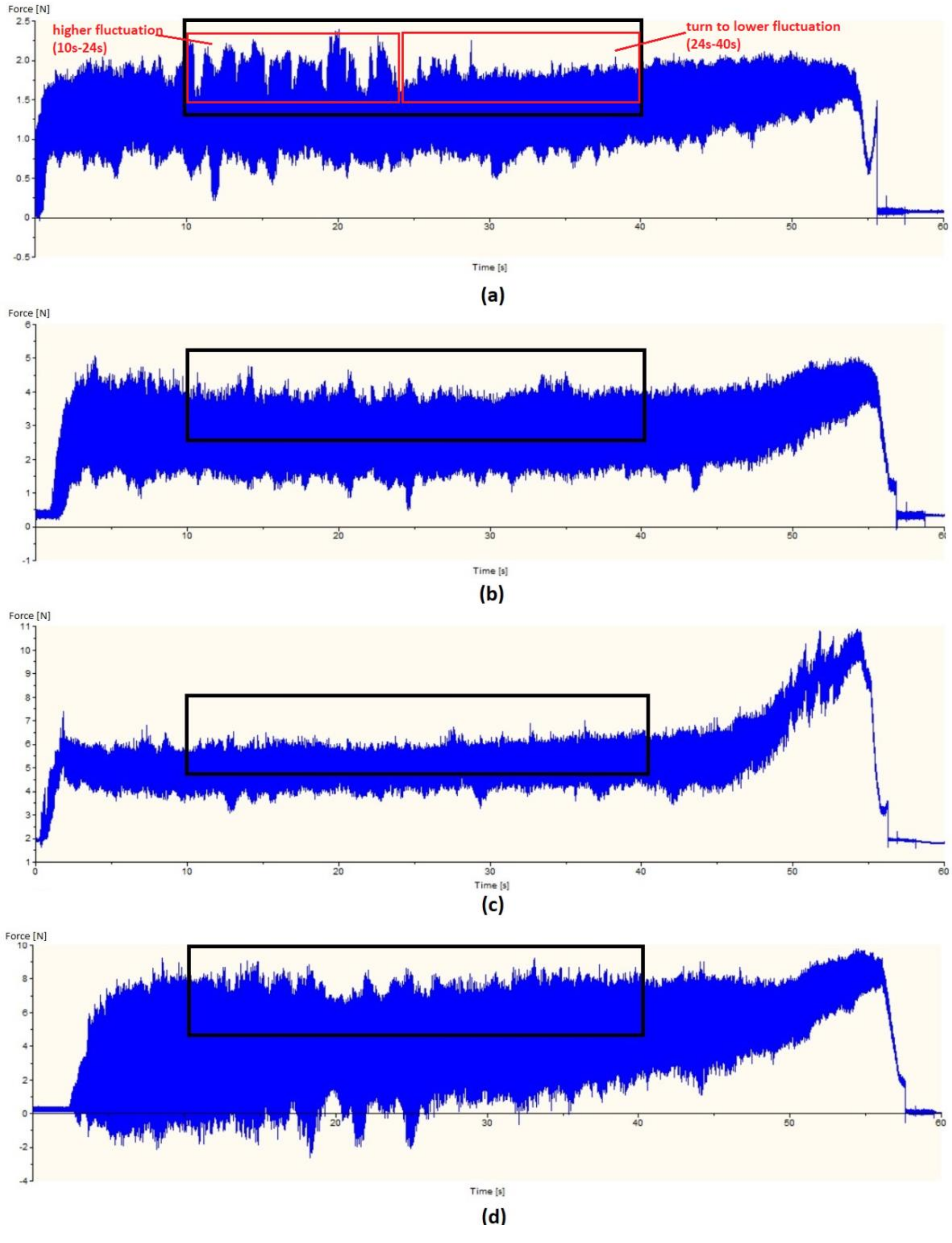
According to Table 1, the F_t magnitude of NMFS was the lowest in comparison to that of MFSs at the magnetic field intensity 0.01T - 0.03T. The mean F_t of NMFS was 1.37N while 2.92N, 5.24N and 6.28N were for the MFSs at the magnetic field intensity 0.01T, 0.02T and 0.03T respectively. The larger F_t of MFSs was caused by adding the repulsive force and magnetic torque in the direction of shear surface under an eddy current damping effect; the repulsive force increased with the magnetic field intensity increase according to Equation (1), therefore, the mean F_t increased with the magnetic field intensity increase. Although the mean F_t of all MFSs were larger than the NMFS, the F_t variation was in the contrast. The higher magnification of F_t of both NMFS and MFSs is shown in Figures 8 for the visual comparison of F_t variation. According to Figure 8(a), the crests at the F_t curve of NMFS displayed solid and clear, each crest was shown as individual and separate. At the cutting time 10s - 24s, the F_t variation of NMFS was large, it fluctuated and showed many sharp crests, At the later cutting time 24s - 40s, the F_t variation was reduced, it was much stable that the height and width of the crests became smaller. The sudden change of F_t variation (from 10s-24s to 24s-40s) resulted in much higher force variation in the overall cutting process, which was unfavorable to the tool life as well as the surface integrity. For the F_t of all MFSs, the crests at the F_t curve were blur with a smaller height and width in comparison to NMFS. Also, there was no dramatic increase/decrease of F_t throughout the whole turning process, implying more stable turning motion under the influence of an eddy current damping effect.

To compare the F_t variation between MFSs and NMFS in the statistical aspect, the parameter named Coefficient of variation (CV) was used and is defined as:

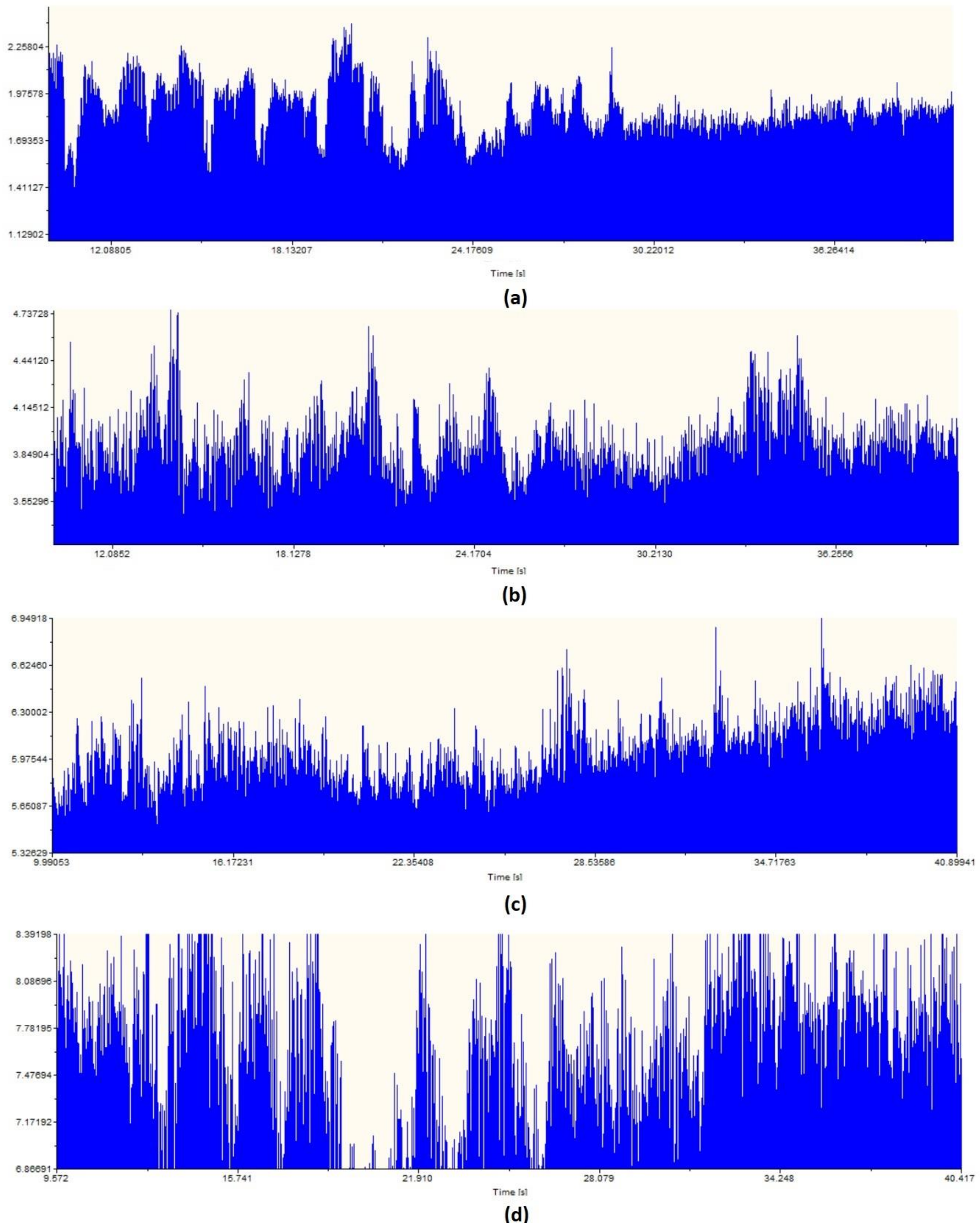
$$CV = \frac{\sigma}{\mu} \quad (5)$$

Where σ is the standard deviation and μ is the mean of all measured data values. The standard deviation is not used here for the explanation of F_t variation because the standard deviation gives a distorted interpretation when the mean value of dataset is different. CV is expressed as percentage normally. In this section, the data of F_t captured at the beginning (0-4s) and the end (44s-55s) was excluded in the CV calculation for removing the effects of instability of tool motion in the stages of tool entry and exit.

From Table 1, the CVs of MFSs at the magnetic field intensity 0.02T and 0.03T were only 5.38% and 5.48% while the NMFS was 15.77%. The CVs of MFSs at the magnetic field intensity 0.02T and 0.03T were improved by 65.88% and 65.25% respectively, suggesting less dispersive of F_t values from the mean value under the influence of an eddy current damping effect. A reduction of cutting force variation was implied.



Figures 7. The F_t of (a) 0T (an absence of magnetic field), (b) 0.01T magnetic field, (c) 0.02T magnetic field and (d) 0.03T magnetic field



Figures 8. The F_t of (a) 0T (an absence of magnetic field), (b) 0.01T magnetic field, (c) 0.02T magnetic field and (d) 0.03T magnetic field in higher magnification (10s-40s)

Table 1. Mean, standard deviation and Coefficient of variation of thrust force in magnetic field 0T-0.03T.

	H=0	H=0.01T	H=0.02T	H=0.03T
Mean Ft (N)	1.37	2.92	5.24	6.28
Standard Deviation	0.22	0.25	0.28	0.34
Coefficient of variation (%)	15.77	8.42	5.38	5.48

4.4 Surface roughness analysis

The surface roughness of MFSs and NMFS was measured, the six areas of the machined surface were measured and averaged. The corresponding results are shown in Table 2. According to the results of surface roughness of MFSs and NMFS, the lowest surface roughness was achieved at the magnetic intensity 0.02T, which is 13nm, this further provided the proof that the optimum magnetic field intensity was 0.02T in the experiments. On the other hand, the surface roughness of other MFSs (0.01T and 0.03T) was also lower than that of NMFS. Therefore, an application of eddy current damping effect in SPDT successfully improved the surface roughness of machined surface.

Table 2. Average surface roughness of MFSs and NMFS

	0	H=0.01T	H=0.02T	H=0.03T
Surface roughness(nm)	29	22	13	19.5

5. Conclusions

In the proposed study, SPDT of titanium alloys assisted with an eddy current damping effect was firstly demonstrated. The experimental results showed the long and continuous chip formation, the reduction of cutting force variation and adhesive tool wear which all are favorable to the machining performances of titanium alloys in SPDT. Under the influence of eddy current damping effect, the machining vibration as well as tool vibration is highly suppressed, thus the tool life is lengthened. The tool life of NMFS tool was 79.4min in SPDT of titanium alloy, which was lower than that of MFS tool. The application of an eddy current damping in SPDT successfully suppresses the machining vibration and enhances the machinability of titanium alloys. The effectiveness of an eddy damping current effect directly affects the machinability change of titanium alloys during SPDT, the proper magnetic field should be applied in order to provide an adaptive damping force to suppress the turning vibration. The optimum magnetic field intensity in the presented experiments was 0.02T; Combining the optimum magnetic field intensity 0.02T with the machining parameters: feedrate: 8mm/min, depth of cut: 4μm, spindle speed 1500rpm, the best machining performance displayed. In case of altering machining parameters for the particular application, the magnetic field intensity needs to be adjusted with the machining parameters in order to deliver the proper degree of an eddy current damping effect; this issue relates to the optimization processes and will be the focus in the later research.

Because of the domination of eddy current damping effect in SPDT, the machining performance of SPDT is uplifted. Generally, higher magnetic field intensity improves the machining performance of SPDT in comparison to an absence of magnetic field, as shown in the revised manuscript. However, the optimum magnetic field intensity in SPDT may not be obtained at the relatively high magnetic field because of the induced eddy current, the optimum magnetic field intensity may be obtained at the middle value of adaptive range.

The proper magnetic field intensity was critical to provide an adaptive damping effect to suppress the turning vibration in SPDT of titanium alloys. If the values of depth of cut and feedrate in SPDT of titanium alloys increase, the cutting force as well as the vibration force will increase, in these cases, a higher eddy current damping force should be generated in order to suppress the higher vibration force, accordingly, the optimum magnetic field intensity will increase generally.

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