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Tool life enhancement in dry diamond turning of titanium alloys using an eddy current damping and a magnetic field for sustainable manufacturing

Abstract

Titanium alloys are widely applied in the aerospace, automobile, and biomedical industries for manufacturing precise components because of their excellent material properties. However, titanium alloys are regarded as difficult to cut materials due to their low thermal conductivity, the resulting serious tool wear and poor surface integrity inevitably lead to high machining cost and energy consumption. On the other hand, uses of fluid lubricant in machining processes of titanium alloys are sizable in order to provide an effective cooling media to dissipate high cutting heat generated in machining. Although the use of lubricant has been discouraged because of the drew damages to the environment and health, dry machining of titanium alloys is not practical currently as high friction force and cutting temperature induced from the dry machining environment which further accelerate and worsen tool life. Therefore, the environmental concerns cover a feasibility of dry machining of titanium alloys; In this study, a novel machining technology, a magnetic field was applied in dry single point diamond turning (SPDT) of titanium alloys to enhance diamond tool life, which aims to overcome the machining difficulties of dry machining. An eddy current damping effect reduces the machining vibration of rotating workpiece and a magnetic field enhances the thermal conductivity of tool/workpiece interface in SPDT, which help to relieve the problematic sources of tool damage in dry machining process. Under the influence of magnetic field, experimental results showed an improvement of surface integrity of machined surface, reductions of adhesive wear, flank wear and built up edge of tool as well as the machining vibration in dry SPDT. The proposed machining technology minimizes the environmental damage of wet machining, uplifting tool life and surface quality of machined components simultaneously, it offers a feasibility of environmental friendly dry SPDT of titanium alloys in practical applications, providing sustainable manufacturing for high precise products.

Keywords: Dry diamond turning; Eddy current damping; Tool wear; Magnetic field; Surface integrity; Titanium alloys

1. Introduction

Titanium alloys are widely applied in different industries because of their superior material properties such as high strength to weight ratio and corrosion resistance (Rack and Qazi, 2006). Titanium alloys are currently one of the most widely used materials for biomedical applications (Niinomi, 2003). The applications of titanium alloys in medical include surgical and dental devices (Liu et al., 2004). However, titanium alloys are low thermal conductivity and hold a high level of sustainability in work hardening at the elevated temperature, which cause them difficult to machine especially in SPDT of ultra-precision machining (UPM). High turning temperature is generated and trapped at the tool/workpiece interface during SPDT of titanium alloys, causing adhesive tool wear and short diamond tool life.

Diamond tool life of difficult to cut materials in SPDT was reported to be short and problematic (Zhang et al. 2016). Fang et al. (2003) indicated that flank wear in SPDT of optical glasses reached to 70μm after a cutting distance of 4km. Jia and Zhou (2012) discovered diamond tool wear started quickly after a relatively short cutting distance of 50m in machining glass soda lime. For diamond cutting of silicon carbide, Yan et al. (2003) stated that diamond tool wear occurred after a cutting distance of 1km in SPDT of single crystal silicon. In contrast to the difficult to cut materials, diamond tool life of easy to cut materials such as aluminum alloys and copper was demonstrated to be longer; tool wear occurred at the cutting distances over thousand km (Zhang et al. 2016). Therefore, diamond tool life is highly depended on the machined materials. For the difficult to cut materials especially titanium alloys, diamond tool life is expected to be short.

As the machining difficulties exist, there have been many literature concerns on resolving tool wear in machining difficult to cut materials in order to minimize the elicited impacts to the environment. Sarikaya et al. (2016) reported serious tool wear happened during machining of a difficult to cut material Haynes 25 superalloys, they used Minimum Quantity Lubrication approach together with the statistical analysis to reduce tool wear as well as the amount of cutting fluids used in the cutting process, the amount of cutting oil unitized in the cutting process was successfully reduced while the machinability of Haynes 25 superalloys was enhanced. Wang et al. (2017) employed ecofriendly method, oil on the water, to reduce tool wear and the environmental pollution in machining of difficult to cut material - compacted graphite cast iron. Fan et al. (2015) investigated the tool wear mechanism of Nickel-based alloy Inconel 718 which is a difficult to cut material, they compared different lubrication conditions, they discovered that water vapor plus air lubrication condition would increase the chemical rate and growth rate of oxide films, they offered better lubrication effect at the tool/chip interface and thus reduced tool wear. Zhang et al. (2012) proposed dry cutting and minimum quantity cooling lubrication cutting of Inconel 718 with biodegradable vegetable oil. They suggested that minimum quantity cooling lubrication cutting with biodegradable vegetable oil enabled to enhance the machinability of Inconel 718 in term of tool life and cutting force, the outcomes fulfilled an increasing demand of cleaner manufacturing of Inconel 718. Researches demonstrated various environmental friendly methods to resolve the problematic tool wear and the environmental impacts of lubricant use in machining processes of different difficult to cut materials. In the presented study, an environment friendly machining technology was proposed to machine difficult to cut titanium alloys in dry machining condition, which aims to contribute to lower the environmental impacts brought from SPDT.

Dry machining is one of the important machining technologies to minimize the damage and waste induced from machining processes. However, due to an absence of lubricant or coolant, dry machining generates a high amount of heat energy and friction force in machining processes which accelerate tool failure and cause poor surface integrity of machined component. Integrating the subsequences of low thermal conductivity of titanium alloys with high cutting heat generated in dry machining, dry SPDT of titanium alloys is almost infeasible as it further worsens diamond tool life and deteriorates the surface integrity, making rejections of final products from the industries. Machining processes containing cooling lubricants generally show better machining performances than dry machining. Devillez et al. (2011) proposed that dry machining with suitable coated tool enabled to provide an acceptable level of surface quality which was similar to that obtained in wet machining at optimal cutting speed value. Sreejith and Ngoi (2000) presented that dry machining of common metals usually required lubricants for dissipating cutting heat and therefore dry machining should be modified to fulfil both environmental issue and product quality. High cutting temperature at the tool/workpiece interface is dissipated and taken away from a workpiece by the flow of lubricants, adhesive wear is significantly reduced because of the heat reduction at the cutting edge, preventing tool failure. However, drawbacks remain valid for wet machining; lubricants and material particles pollute water sources and those contaminated sources damage the environment in disposal processes (Davoodi and Tazehkandi, 2014).

Previous literature indicated that titanium alloys melts under the condition of high cutting heat, melted titanium alloys weld on the cutting edge and thus adhesive wear occurs. Zoya and Krishnamurthy (2000) reported that there was strong adhesion between the tool and workpiece in machining of titanium alloys, it caused a high degree of adhesive tool wear. Wang et al. (2005) observed adhesive tool wear happened in milling of titanium alloys especially at tool flank face. Due to the machining difficulties of titanium alloys and the resulting tool wear in dry SPDT, few researches have showed successive implementations of dry SPDT of titanium alloys, as well as proposing measures to reduce diamond tool wear in dry SPDT of such low thermal conductivity alloys. Moreover, the demand of high precise components has remarkably increased, the corresponding machining impacts to the environment unavoidably increase at the same time, therefore, for sustainable manufacturing, an effective dry SPDT is urged to adopt which enables to benefit both the environment and quality of precise products. In this study, a novel machining technology, an eddy current eddy damping effect and a magnetic field effect were employed into dry SPDT of titanium alloys to reduce tool wear in the dry machining environment. A rotating titanium alloy was placed in between of two magnets in order to suffer from an eddy current damping effect and a magnetic field effect during experiments. The resulting tool wear in dry SPDT of titanium alloys was significantly reduced under the influences of eddy current damping effect and magnetic field. Moreover, the proposed machining technology only employed extra two magnets which are low cost, environmental friendly and endorsable; the proposed machining technology seeks to contribute to provide a feasibility of dry SPDT of titanium alloys in practical applications for sustainable manufacturing.

2. Theory

2.1 Reduction of turning vibration using an eddy current damping effect

When a conductive metal suffers from a magnetic field and rotates in between of the magnetic field, eddy current is generated inside the moving conductor due to the varying static magnetic field. Eddy current further generates its own magnetic field with the direction against the external magnetic field. The kinetic energy of vibration motion in the mechanical system will be dissipated in the form of heat to heat up the conductor. Sodano and Bae (2004) reviewed the mechanism of eddy current damping generation and suggested that the processes of creating eddy current and dissipating the vibration energy suppressed the vibration in structures. Sodano et al. (2006) established the theoretical model of eddy current damping system, they proved that it was effective to suppress the transverse beam vibration. Bae et al. (2005) made comparisons between experimental and theoretical model of eddy current damper using an eddy current damping effect, showing the successful vibration suppression of moving system. Actually, an eddy current damping effect has been applied to many practical uses, showing the positive outcomes of mechanical vibration reduction and uplifting the operational performance of particular device. Liu et al. (2011) examined the working principles of eddy current retarder using an eddy current damping effect and applied to the automobile brake. Jou et al. (2006) applied the principle of eddy current damping effect to develop an upright magnetic braking system, which enhanced the safety performance of elevator.

Applying the same theory of eddy current damping effect to this study, titanium alloys were rotated in between of two permanent magnets and influenced by an eddy current damping effect. The overall turning vibration as well as the tool vibration was then suppressed by transferring the kinetic energy of vibration into heat energy, thus tool wear was reduced and the surface integrity of machined titanium alloys was improved.

2.2 Enhancement of thermal conductivity of titanium alloys under a magnetic field influence

Literature indicated that the thermal conductivity of ferrometals/ferrofluid was enhanced under a magnetic field influence. Summarized reasons of literature are, the ferroparticles inside ferrometals/ferrofluid are aligned in the presence of external magnetic field. In the absence of magnetic field, the ferroparticles are randomly orientated because of van der Waals force and dipole-dipole interactions. Once an external magnetic field exists, the ferroparticles tend to align along with the direction of physical field as the positive value of magnetic susceptibility of ferroparticles. Aligned ferroparticles then become continuous chains which are highly conductive, serving as the paths for quick heat transfer and dissipation. Gavili et al. (2012) demonstrated the experimental results that the thermal conductivity of ferrofluid was enhanced more than 200% in the presence of magnetic field. Ghofraniet et al. (2013) showed the convective heat transfer rate of ferrofluid increased in the presence of alternating magnetic field because of intensifying the magnetic particle migration inside the ferrofluid. Lajvardi et al. (2010) made the same conclusion that the heat transfer performance of ferrofluid containing Fe_3O_4 magnetic particles was facilitated in the presence of magnetic field. The information of increase in thermal conductivity by a magnetic field could be revealed theoretically. In the absence of external magnetic field, magnetic particles may attach to each other because of van der Waals forces and dipole-dipole interactions. However, once a magnetic field presence, the dipole moments like to align with an external applied magnetic field. The dipole-dipole interaction energy U_d between the magnetic particles is termed as:

$$U_d(ij) = -\frac{3(m_i \cdot r_{ij})(m_j \cdot r_{ij})}{{r_{ij}}^5} - \frac{(m_j \cdot m_i)}{{r_{ij}}^3}, \quad r_{ij} = r_i - r_j \quad (1)$$

where r is the distance between the magnetic particles i and j, m is the mass of magnetic particle, i and j denotes to the i-th and j-th magnetic particles. The coupling constant is equal to

$$L = U_d(ij) / k_B T \quad (2)$$

which defines an effective attraction between two magnetic particles, where k_B is Brownian constant and T is the temperature respectively. In the absence of magnetic field, the magnetic particles are oriented in random directions and follow with Brownian motion as L is in smaller value. When applying a magnetic field, the magnetic dipole interaction energy turns to be large enough and the value of L increases, leading the initiation of magnetic particle alignments parallel to the direction of magnetic field. As the magnetic field increases, the magnetic particles begin to group as short chains along the direction of magnetic field, the chain structures of magnetic particle enhance the thermal conductivity of materials, the aligned particles act as linear chains which are highly conductive paths for transferring heat and the fast heat transfer along the conductive paths occurs. Philip et al. (2007) reported that an increase in thermal conductivity of ferrofluid was contributed by the chain like structure of magnetic particles inside the ferrofluid. Philip et al. (2008) observed the aggregations of linear chain nanomagnetic particles offered conductive paths for transferring heat, providing an enhancement of thermal conductivity of nanofluid.

As the magnetic susceptibility of titanium alloys is 14.6ppm which is a positive value, titanium alloys enable to react toward a magnetic field as long as an existence of magnetic field. Titanium alloys' particles could be aligned in the presence of magnetic field. The aligned particles act as linear chains which are highly conductive paths for transferring heat. Yip and To (2017) investigated an application of magnetic field into single point diamond cutting of titanium alloys, as the thermal conductivity of titanium alloys increased, the experimental results showed that the machined titanium alloys in the presence of magnetic field displayed increases in accuracy of cutting width, depth of cut and cutting radius, their absolute errors between assigned machining parameters were below 2%.

Applying the same theory into this study, Titanium alloys' particles inside melted titanium alloys generated in dry SPDT were enabled to form conductive chains for heat dissipation. When titanium alloys were exposed to a magnetic field in dry SPDT, the trapped heat was efficiently dissipated by the conductive chains, tool wear especially adhesive wear can be minimized because of the cutting heat reduction, consequently eliminating the weakened mechanical properties of diamond tool by adhered materials at high cutting temperature.

3. Experimental setup

Two phrase titanium alloys, Ti6Al4V(TC4) were used as materials for the experiments. Ti6Al4V have 6% aluminum, 4% of beta phrase stabilizer vanadium, 0.25% of iron, 0.2% of oxygen and remaining parts of titanium. Titanium alloys were in rod shapes with the length 40mm and diameter 16mm. Two samples underwent dry SPDT without lubricants. One sample processed dry SPDT in the absence of magnetic field, named as dry non-magnetic field sample (DNMFS), while another sample processed dry SPDT in the presence of magnetic field, named dry magnetic field sample (DMFS). A self-developed fixture was used for holding two permanent magnets in the ultra-precision turning machine, DMFS was turned in between of two magnets in order to suffer from an eddy current damping effect during dry SPDT. In dry SPDT, single point diamond cutting tool was used and is made of single crystal diamond which offers high accuracy fabrication of workpiece. The grain size of single point diamond tool would not be varied throughout the whole experiment as the single crystal natural of used diamond tool. The radius and height of diamond tool were 1.468mm and 10.172mm respectively.

The force sensor Kistler 9256C was used to measure the cutting force which would be transferred to Fast Fourier transform (FFT) analysis. Moore Nanotech 350FG (4 axis Ultra-precision machine) was used as the equipment for diamond turning. Surface roughness of machined samples was measured by Wyko NT8000 Optical Profiling System. The experimental setup is shown in Figure 1. The turning parameters for both DNMFS and DMFS were set as spindle speed: 1500rpm; feedrate: 8mm/min; depth of cut: 5µm. For the extremely small turning parameters (depth of cut and feedrate) used in dry SPDT, small vibration force would be generated in dry SPDT, therefore, a relatively small magnetic field intensity 0.02T was chosen as the valuable parameter to provide an adaptive eddy current damping effect for suppressing the turning vibration. The tool wear condition of titanium alloys in dry SPDT became significant at a cutting distance of 75m in the pilot experiments under the same machining condition. Therefore, in this experiment, the tool conditions at the cutting distances 75m,150m, 225m and 300m were chosen and observed under SEM. At each cutting distance, tool wear of both samples was evaluated by the observations of rake and flank faces. Flank and rake faces of both tools were cleaned by hydroflouridic acid before taking SEM so that the resulting tool wear was accurate without a distortion.

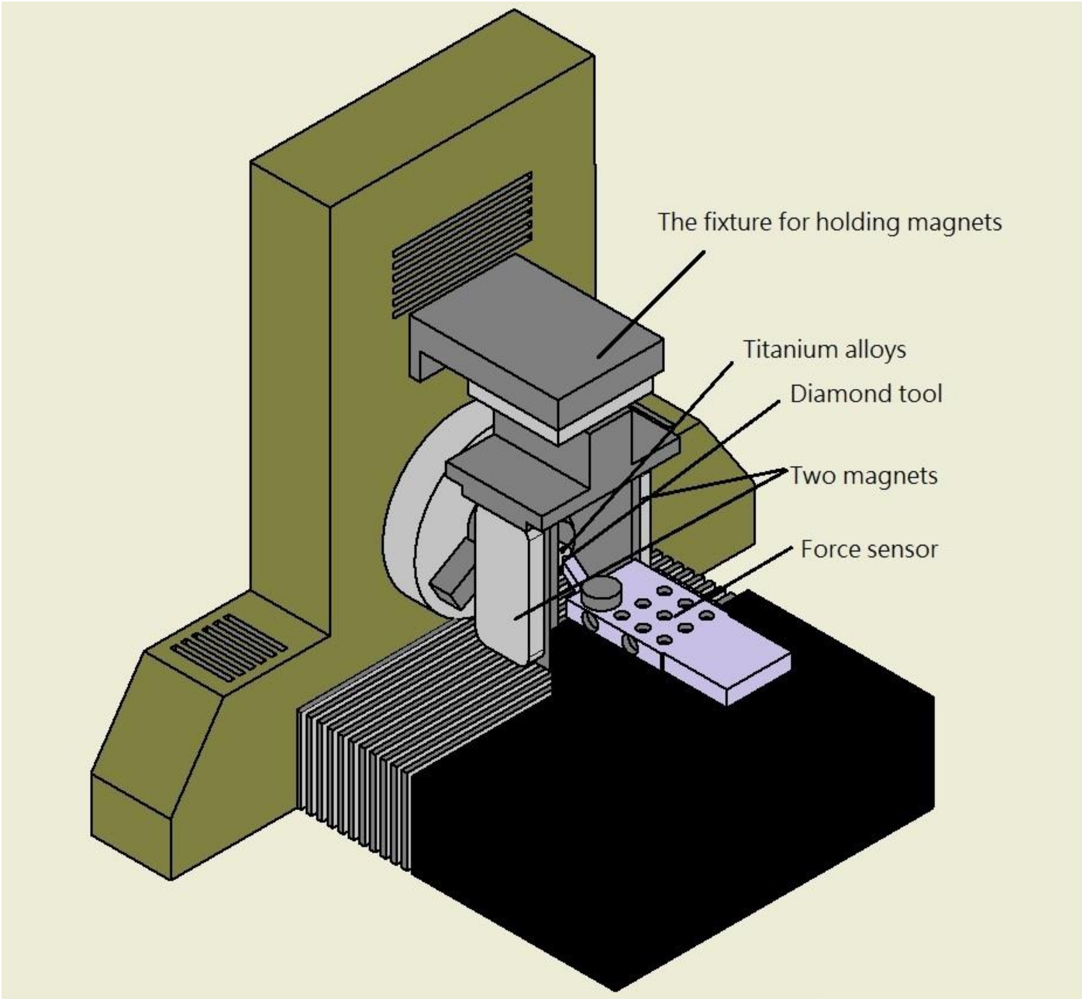


Figure 1. The experiment setup of proposed magnetic assisted diamond turning

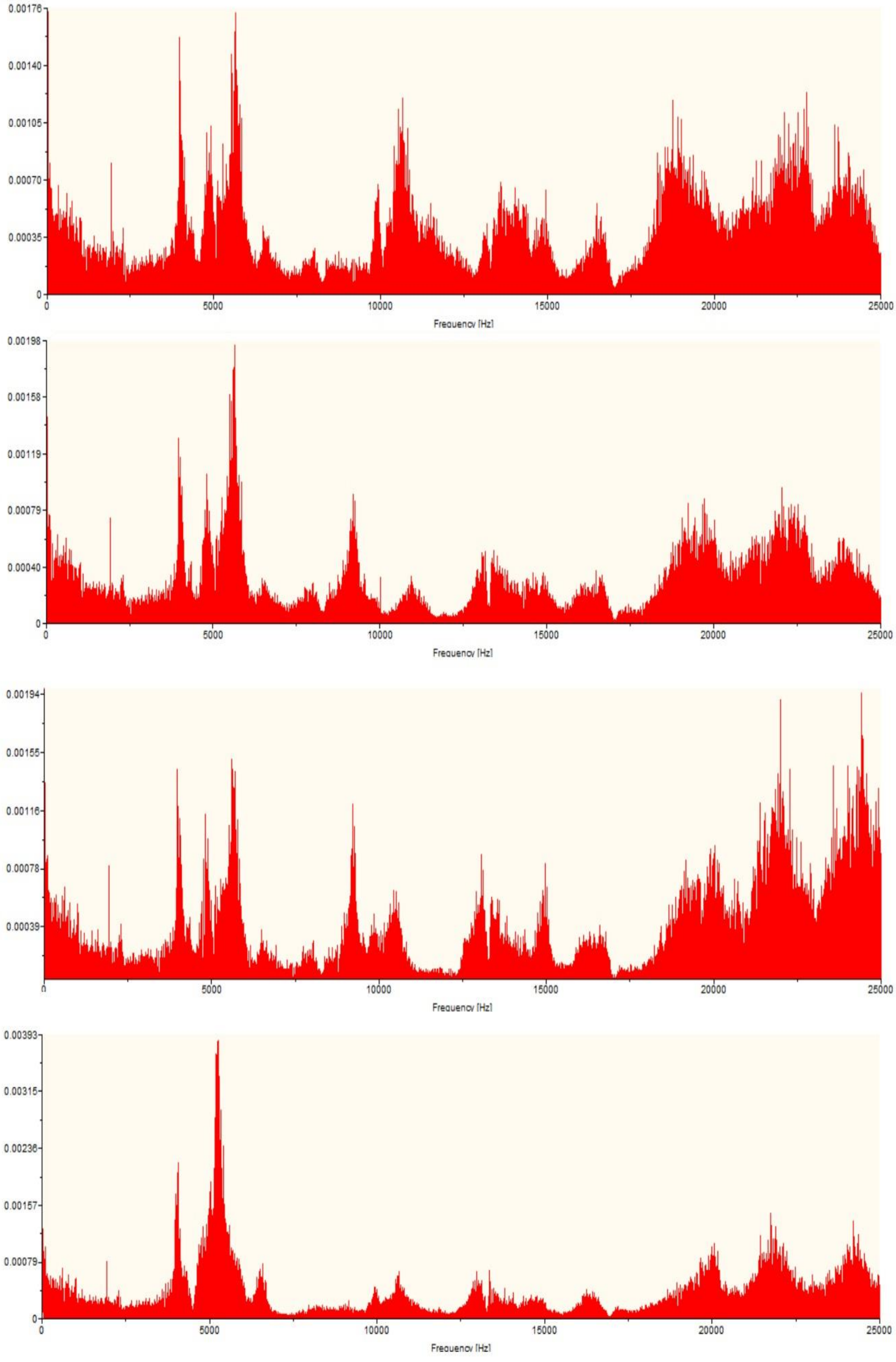
4. Results and discussion

4.1 Validation of turning vibration suppression an eddy current damping effect

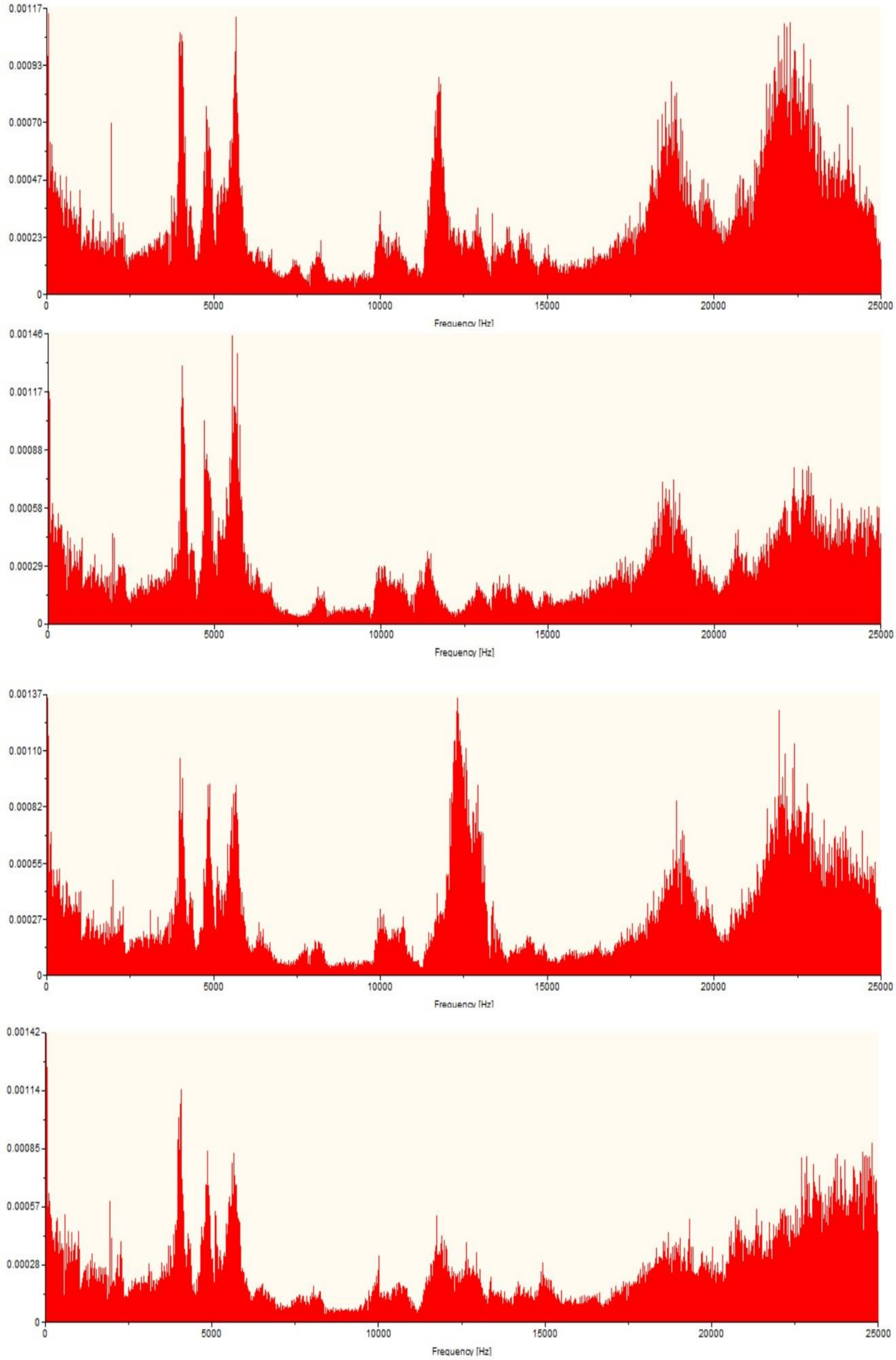
The machining vibration of turning system generated in SPDT was examined through Fast Fourier transform (FFT) of cutting force parallel to the feed direction as shown in Figures 2 and 3. The vibration amplitudes of turning system could be reflected into FFT which Fourier analysis converts the cutting force signal from time domain to frequency domain. The sample frequency of FFT is 50KHz. The y axis of the graph represents the amplitude of vibration force while x axis represents the corresponding frequency. Under an eddy current damping effect, the kinetic energy of vibration motion in the turning system would be converted to heat energy to heat up titanium alloys, which minimized the amplitudes of turning vibration. Therefore, the vibration amplitudes in dry SPDT of titanium alloys are expected to be lower for DMFS.

Comparing between the peak amplitudes of both samples in the relative frequency of FFT shown in Figures 2 and 3, at all cutting distances (75m - 300m), all peak amplitudes of DMFS in FFT were lower than that of DNMFS in the relative frequency, the above provided the solid evidence that the overall turning vibration was suppressed by an eddy current damping effect.

Generally, a significance of tool wear increases with cutting distance increase, therefore, to evaluate the turning vibration contributed by diamond tool wear in the experiments, FFT generated at the larger cutting distance of both samples under the same machining condition was compared. As shown in Figures 2 and 3, the difference of vibration amplitudes between two samples increased with the cutting distance increase; especially at the last cutting distance 300m, the maximum peak amplitude in FFT of DMFS was noteworthily smaller than that of DNMFS, the maximum peak amplitude of DMFS was only 0.00142N while that of DNMFS was 0.0039N, which the maximum peak amplitude of DNMFS was at least 2.76 times of DMFS, it showed the turning vibration at the longer cutting time was significantly reduced under an eddy current damping effect, which possibly caused by the reduction of tool wear. Moreover, previous literature reported that tool wear would produce the tool vibration in high frequency. Kopač and Šali (2001) reported that tool flank wear increased the vibration amplitudes in a relatively high frequency range. Toh (2004) suggested that tool wear could be characterized by high frequency in frequency spectrum analysis. Referring to FFT of both samples at all cutting distances, the vibration amplitudes located at a relatively high frequency were lower for DMFS in comparison to DNMFS, which explained that tool wear was remarkably reduced in dry SPDT with an assistance of eddy current damping effect.



Figures 2. FFT of feed force generated in DNMFS at the cutting distances (a) 75m, (b) 150m, (c) 225m, (d) 300m



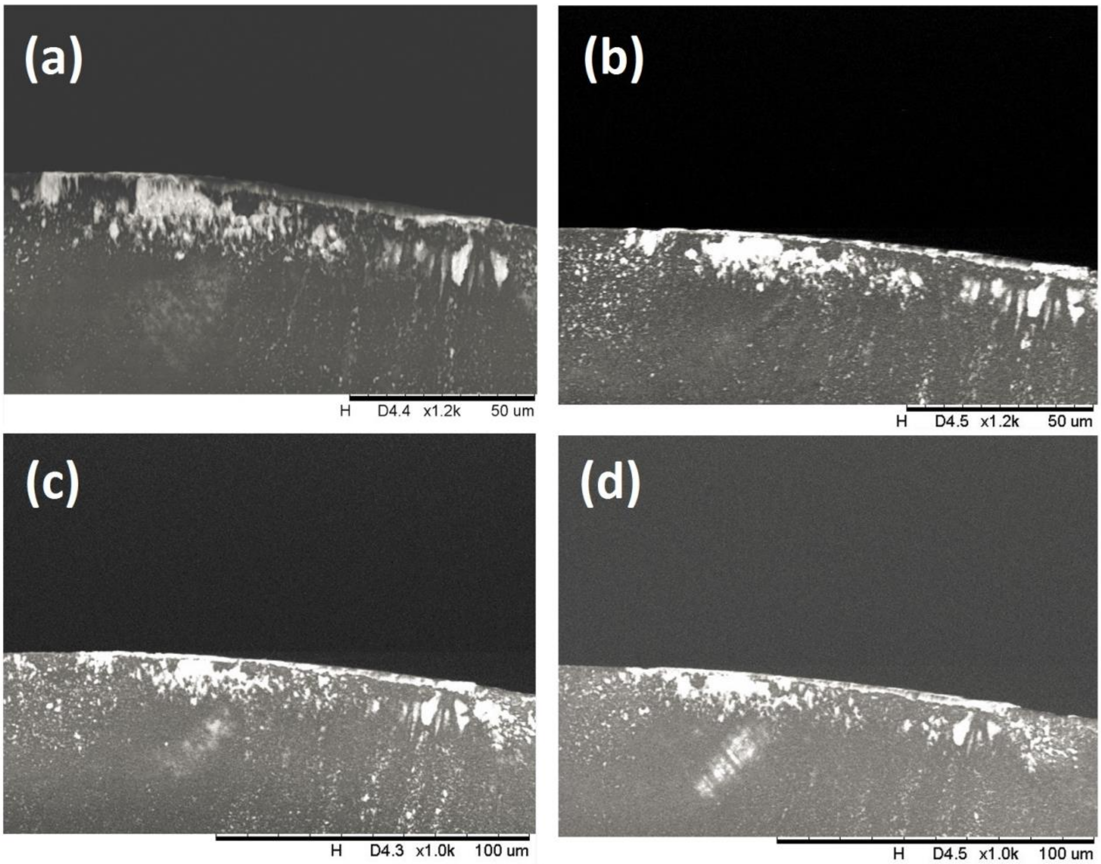
Figures 3. FFT of feed force generated in DMFS at the cutting distances (a)75m, (b)150m, (c)225m, (d)300m

4.1 Analysis on rake wear

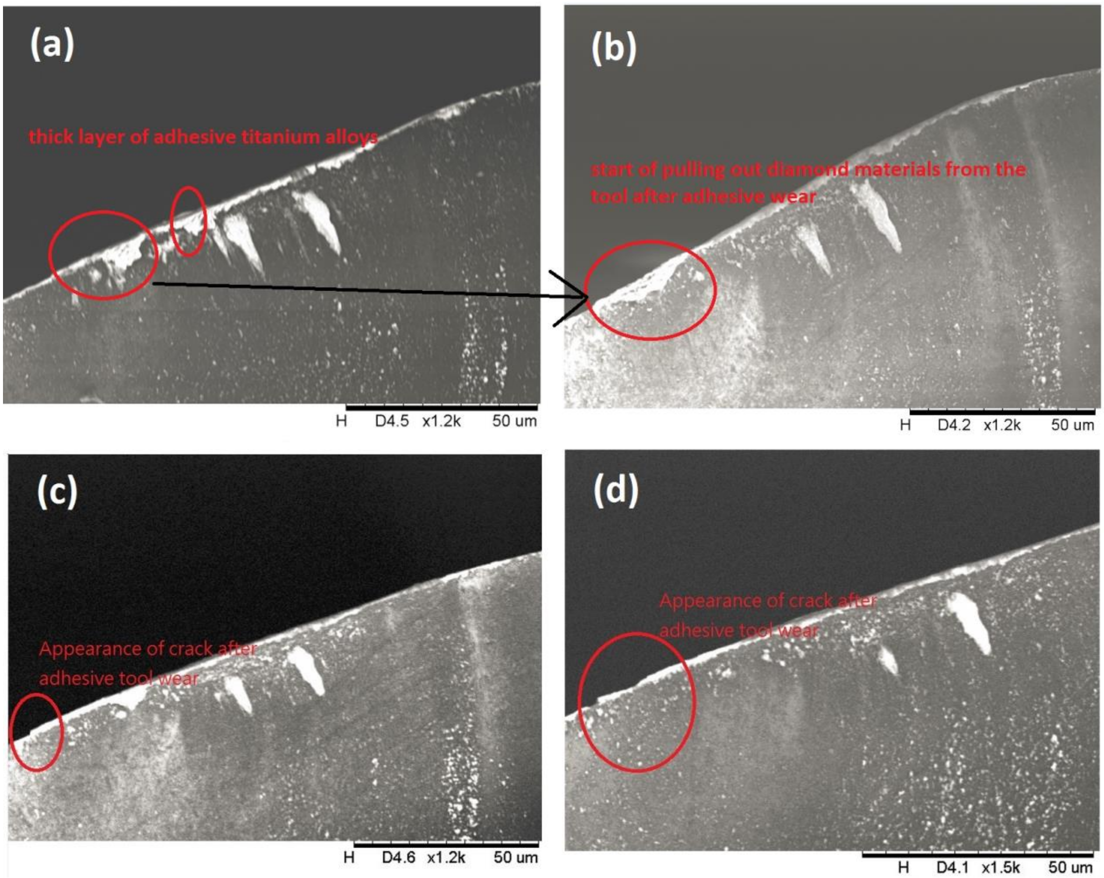
Actually, titanium alloys are classified as difficult to cut materials and proven to be low machinability due to their low thermal conductivity, which restricts the dissipation of cutting heat from the tool/workpiece interface (Bordin et al., 2015); as a result, there is strong adhesion between the tool and workpiece materials, which affects the tool adversely. In comparison to other materials, cutting temperature in machining titanium alloys is comparatively high (Ezugwu et al., 2003), Li et al. (2017) reported that the cutting temperature of titanium alloys achieved over 1000K under the particular machining condition. Under turning at an extremely high cutting temperature, chips melt and stay contacts with the rake and flank faces of diamond tool, resulting serious adhesive wear. Adhesive wear was reported to be the dominant wear mechanism in machining of titanium alloys. Rahim and Sadahara (2011) conducted experiments and observed that adhesion was the dominant tool wear mechanism at all coolant–lubricant conditions in high speed drilling of Ti6Al4V. Da Silva et al. (2013) reported the same that there was strong adhesion tendency between titanium alloys and the tool in machining of titanium alloys with PCD tool. On the other hand, adhesive tool wear mainly happened on tool rake face (Dearnley and Grearson, 1986). Therefore, adhesive wear on the rake face of diamond tool would be observed in detail in this study. Figures 4 and Figures 5 show SEMs of rake faces of tools in dry SPDT. As shown in Figure 4(a) and Figure 5(a), at the first cutting distance 75m, the melted titanium alloys generated in dry SPDT had already been attached to the cutting edge of DNMFS tool. In the case of low thermal conductivity materials in dry machining condition, extremely high cutting heat was generated and localized at the cutting edge, titanium alloys melted and welded on the tool edge consequently. The shiny melted titanium alloys were formed as a layer on the diamond tool tip of DNMFS tool, showing an occurrence of chipping on the tool edge and adhesive tool wear. Actually, chipping originally happens before adhesive wear and normally at the beginning of cutting, which is induced by high cutting temperature (Kikuchi, 2009), Dhar et al. (2006) reported that chipping was the common drawback in dry machining. In contrast to DMFS tool, fewer shinny titanium alloys were attached on the tool edge, only flaked fragments of titanium alloys were adhered on the cutting edge of DMFS tool in comparison to DNMFS tool. The underlying reason for the reduction of titanium alloys adhesion of DMFS tool is that, the thermal conductivity of titanium alloys is enhanced under the influence of magnetic field, due to the quicker heat transfer, cutting heat trapped at the tool/workpiece interface could be dissipated sufficiently, the tool/workpiece interface was suffered from lesser heat. With the tool vibration reduction benefited from an eddy current damping effect, the tool motion would be continuous and smooth with little vibration, thus the melted titanium alloys could be flowed from the tool/workpiece interface by the aerodynamic force generated from the rotating workpiece/fixture, as a result, the chips did not adhere on the tool edge and adhesive tool wear was reduced under a magnetic field influence. The significance of adhesive tool wear of DNMFS tool became serious at the cutting distance 150m. At the cutting distances 150m, due to the low thermal conductivity of materials and high turning vibration, titanium alloys melted and welted to the cutting edge continuously which the tool wear mechanism was as same as previous cutting distance 75m, the newly melted titanium alloys welded on the top of the adhered titanium alloys generated before, the accumulative welded materials increased the volume of adhesive titanium alloys and hence enlarged adhesive tool wear, a larger volume and thicker layer of titanium alloys displayed at DNMFS tool as shown in Figure 5(b). For DMFS tool at the same cutting distance, due to the fast heat transfer effect and tool vibration reduction conveyed by a magnetic field, friction and cutting heat at the tool/workpiece interface decreased, hence, adhesive tool wear just began, a thin adhesive titanium alloys layer was observed on the cutting edge, in comparison to DNMFS tool at the same cutting distance, the volume of adhered material at DMFS tool was much smaller.

At the cutting distance 225m, for DNMFS tool, as the physical strength of diamond tool was degraded by the welded materials at the cutting edge, therefore, due to the continuously inserted load at the cutting edge, the diamond materials were pulled off in the subsequent turning processes and DNMFS tool appeared cracking, the cutting edge of DNMFS tool displayed a crack as shown in Figure 5(c), the location of crack was previously the location of adhesive area at the cutting distance 150m. Actually, as reported by Gómez-Parra et al. (2013), when tool materials at the cutting edge are removed under continuous cutting process, the removal process involves the abrasion process due to friction generated between the material particles and tool rake face. When the cutting edge persists in continuous abrasion process, the worn tool appears cracks and the loss of tool geometry finally. The overall process of tool wear in machining titanium alloys is adhesive wear following with abrasion process. In comparison to DMFS tool shown in Figure 4(c), thanks to an increase of thermal conductivity by a magnetic field, only a small amount of titanium alloy was welded on the cutting edge accumulatively, adhesive tool wear became only slightly significant than that at the cutting distance 150m; with the reduction of turning vibration by an eddy current damping effect, abrasion between diamond tool and the workpiece particles decreased, therefore, there was no observation of crack and an enlargement of adhesive layer on the cutting edge of DMFS tool. At the final cutting distance 300m, for DNMFS tool, a higher amount of tool materials was drawing out, one more crack displayed, the number of crack increased to two as shown in Figure 5(d), the area of defect is magnified in Figure 6 for showing the cracks clearly. In contrast to DMFS tool, the area of adhesive titanium alloys on the cutting edge of DMFS tool slowly increased and not intensified dramatically as cutting heat was dissipated from the cutting zone effectively, there was no obvious difference of rake wear between the cutting distance 225m and 300m for DMFS tool.

In conclude, due to the thermal conductivity enhancement of titanium alloys and the turning vibration reduction by a magnetic field, lesser heat was trapped at the tool/workpiece and a high amount of heat was dissipated to outside, leading fewer volumes of melted and welded titanium alloys at the cutting edge and thus minimized adhesive tool wear. In addition, an eddy current damping effect suppressed the turning vibration as well as the tool vibration, the tool shift, friction force and friction heat at tool/workpiece interface were highly reduced, minimizing abrasion processes at the tool/workpiece interface, all the above were favor to the diamond tool condition.



Figures 4. SEMs of rake face of DMFS tool at the cutting distances (a) 75m, (b) 150m, (c) 225m and (d) 300m



Figures 5. SEMs of rake face of DNMFS tool at the cutting distances (a) 75m, (b) 150m, (c) 225m and (d) 300m

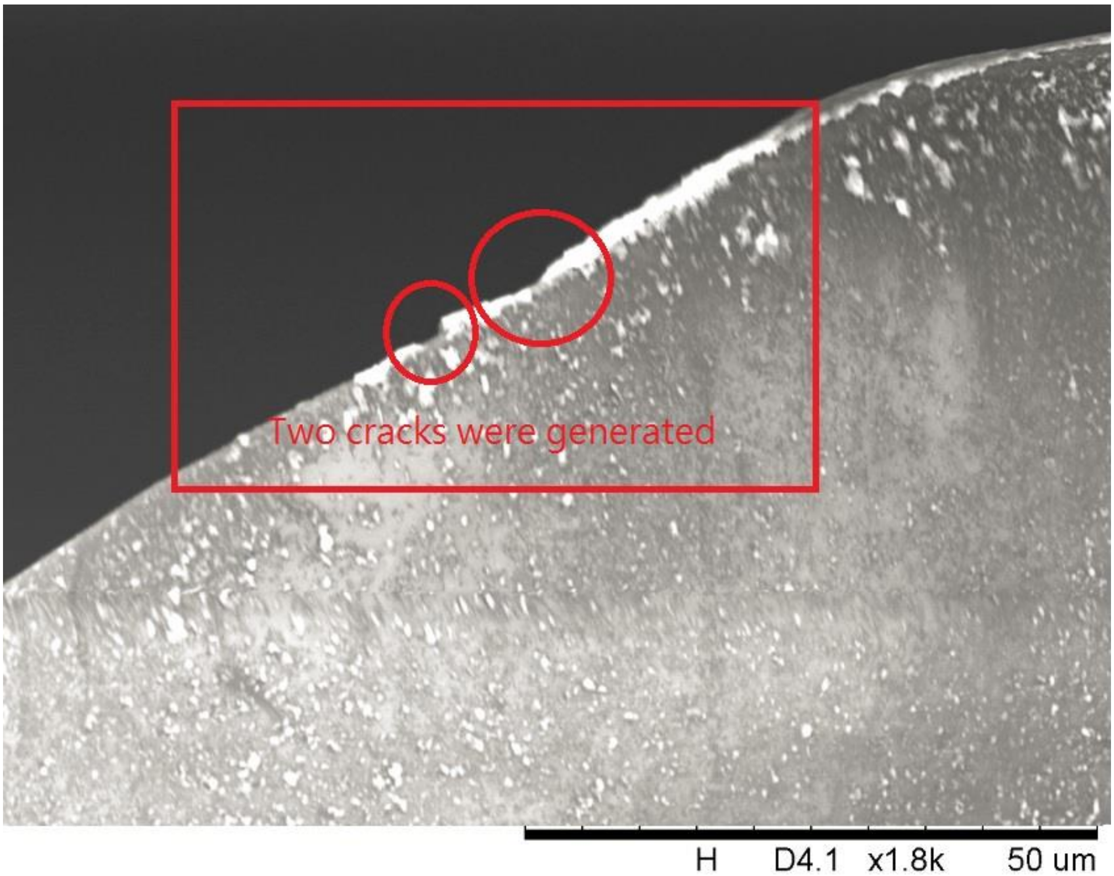


Figure 6. The closer view of defected area of cutting edge in Figure 3(d)

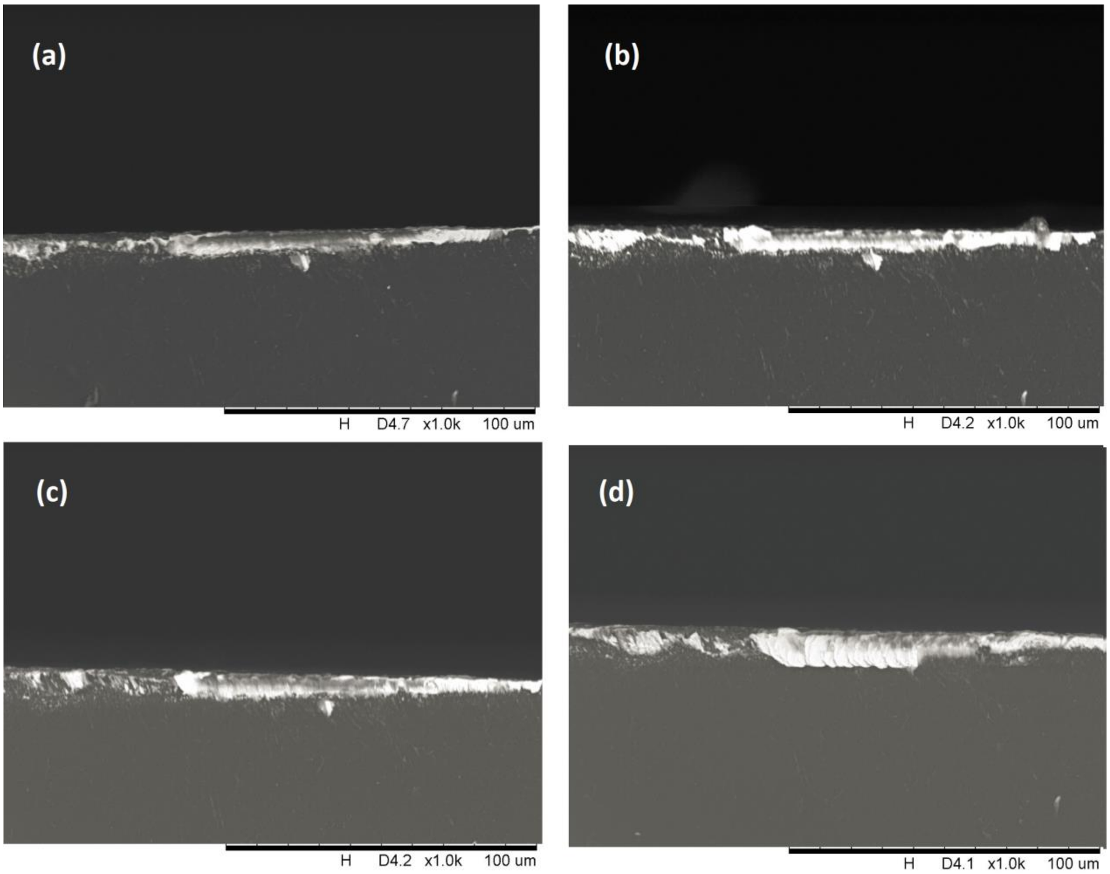
4.2 Analysis on flank wear and built up edge

Flank wear of both DNMFS and DMFS tools was examined. SEMs of flank faces of both tools are shown in Figures 7 and Figures 8. An incomplete removal of chip causes adhesion of chips on the rake face, giving rise to built-up edge. In addition, a rapid increase in cutting temperature in dry machining environment significantly reduces the strength of diamond tool and promotes the growth of built-up edge, which attributes to the plastic deformation of cutting edge. As high cutting heat remained at the removal chips causes built up edge formation, built up edge formation is one of the indicators for evaluating the performance of magnetic field on transferring heat in dry SPDT. At the beginning cutting distance 75m, built up edge was discovered at the cutting edge of DNMFS tool as shown in Figure 8(a). When the diamond tool edge moved along on the machined surface without lubricants, extremely high temperature remained in the removal chips, causing chip adhesion on the tool rake surface, forming as built up edge at the flank face of DNMFS tool. In the contrast to DMFS tool, as the enhancement of thermal conductivity of titanium alloys in the presence of magnetic field, the chips were sheared away efficiently from the workpiece without sticking to the rake face, consequently built-up edge was minimized; refer to Figure 7(a), there was no observation of built up edge on the flank surface of DMFS tool under the influence of magnetic field. At the cutting distances 150m and 225m, for DNMFS tool, adhesive wear developed quickly, a larger volume of titanium alloy was welded on the rake face which covered the whole cutting edge, an utilization of this degraded tool edge would lead to an unacceptable surface quality of machined surface. In the continuous turning process, the thickness of adhered materials successively increased, the newly melted titanium alloys plastically attached along the tool flank face, built up edge turned to become built up edge layer on the tool edge which displayed on the flank face of DNMFS tool as Figure 8(b) and 8(c). For the flank face of DMFS tool at the same cutting distance, the worn area in the tool edge was similar to that generated at the previous cutting distance 75m; only few growths of welded titanium alloys were on the tool edge but no built-up edge was found, implying a lower amount of cutting heat at the tool/workpiece interface, which reduced the volume of melted titanium alloys and caused a relatively low growth rate of titanium alloy adhesive layer. At the final cutting distance 300m, for DNMFS tool, as the cutting process was carried out for a longer time, built-up layer was continuously formed because the newly melted titanium alloys constantly welded on the tool edge. Because of this, the features of this built up layer was very similar to that at the cutting distances 150m - 225m. For DMFS tool at the cutting distance 300m, under the influence of quick heat conduction by a magnetic field and the turning vibration reduction, fewer titanium alloys melted and were attached to the tool edge. Therefore, although the volume of adhesive titanium alloys increased, the adhesive materials only covered to the diamond tool edge partly, a part of tool edge was still uncovered with titanium alloys, it acted as a smooth diamond edge which enabled to contribute to an effective cutting for the further turning process, lengthening the utilization time of diamond tool for sustainable manufacturing.

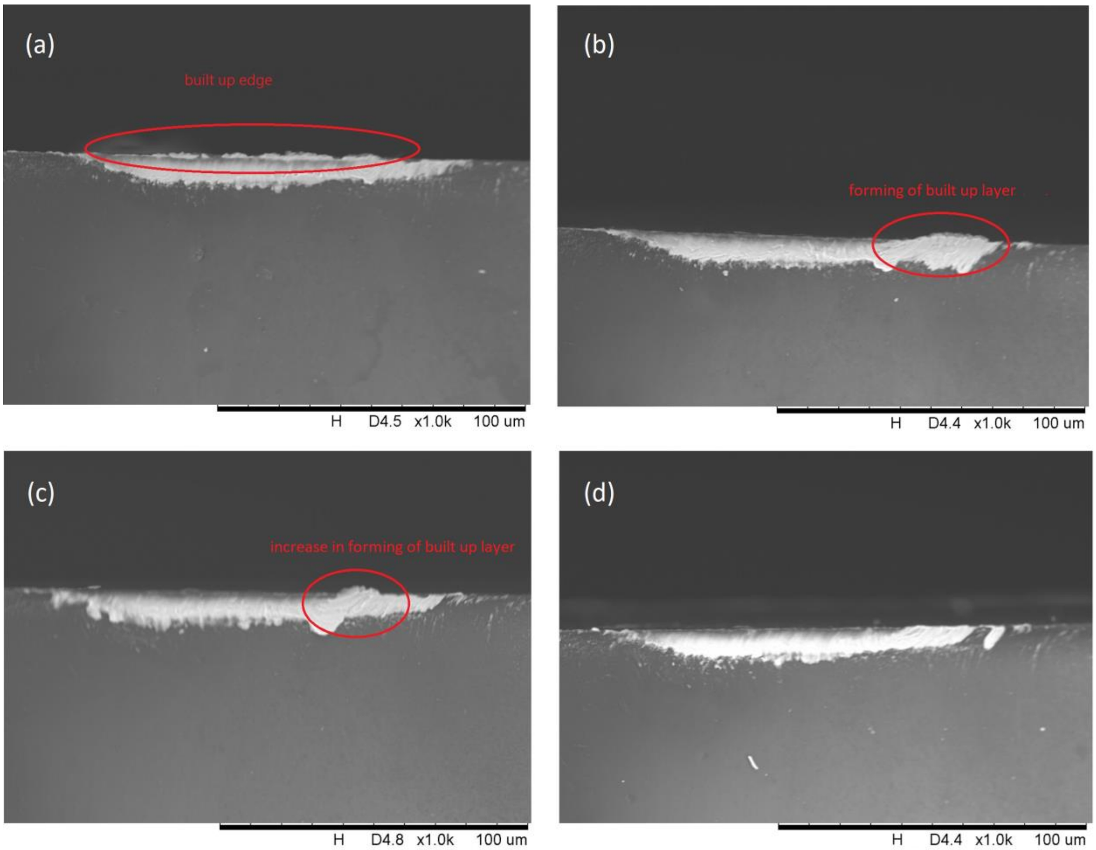
To conclude, as high cutting temperature and friction force in dry machining environment, built up edge started to form on the rake face of DNMFS tool at the beginning cutting distance 75m. the volume of adhesive materials was enlarged and attached to the tool edge in the continuous turning. In the further cutting distance, built up edge was accumulated, the accumulative built up edge generated built up layer which fully covered the tool edge. For DMFS tool, under the influence of a magnetic field, there was no built up edge on the rake face at the beginning distance, only few adhesive titanium alloys were found at the cutting edge, and the volume of adhesive titanium alloys increased in a slow rate with cutting distance increase. Even at the final cutting distance 300m, the tool edge was not covered fully by titanium alloys, there remained the fresh diamond tool edge which could contribute to the further turning process. The significances of flank wear and built up edge of DMFS tool were obviously lower than DNMFS.

A common way of presenting flank wear is by the parameter VB, which is denoted as the maximum width of wear mark on the flank face. Figure 9 and Table 1 show the maximum flank wear width of DNMFS and DMFS tools, as the cutting depth in dry SPDT was 5μm, so the maximum flank wear width was accordingly small and in micron range. Comparing VB between DNMFS and DMFS tools, VB of DNMFS tool was remarkably larger than DMFS tool at the whole cutting distances 75m - 300m, particular to the longer cutting distance 300m, VB of DNMFS tool was even larger than that of DMFS about 123%. The above fully proved that flank wear of DMFS tool was successfully reduced by a magnetic field assistance.

Also, the slope of maximum flank wear width against the accumulative cutting distance was larger for DNMFS tool, it showed that the adhesive rate of titanium alloys in the presence of magnetic field was smaller than that in the absence of magnetic field, possibly caused by the decrease of cutting heat as well as the friction force. Increasing the cutting distance from 150m to 225m, DNMFS tool showed a dramatic increase of maximum flank wear width, this was the signal that associated with the change in tool wear condition, integrating the information of Figures 5(b-d), the causes of dramatic increase of VB would be due to the cracks on DNMFS tool. For DMFS tool, as an effective heat transfer and a reduction of tool vibration, the maximum flank wear width displayed a steady growth with the accumulative cutting distance, the maximum flank wear width did not show a rapid increase throughout the whole cutting distances; it revealed the stable growth of adhesive materials on the tool edge without generating an obvious defect which was consistent with the results shown in Figure 4(a-d).



Figures 7. SEMs of flank face of DMFS tool at cutting distances (a) 75m, (b) 150m, (c) 225m and (d) 300m



Figures 8. SEMs of flank face of DNMFS tool at cutting distances (a) 75m, (b) 150m, (c) 225m and (d) 300m

Table 1. The maximum flank wear width VB of DNMFS and DMFS tools at different cutting distances

Cutting distance(m)	Maximum flank wear width VB (μm)	
	DMFS	DNMFS
75	5.16	11.2
150	5.46	12.4
225	6.5	15.5
300	8.6	19.2

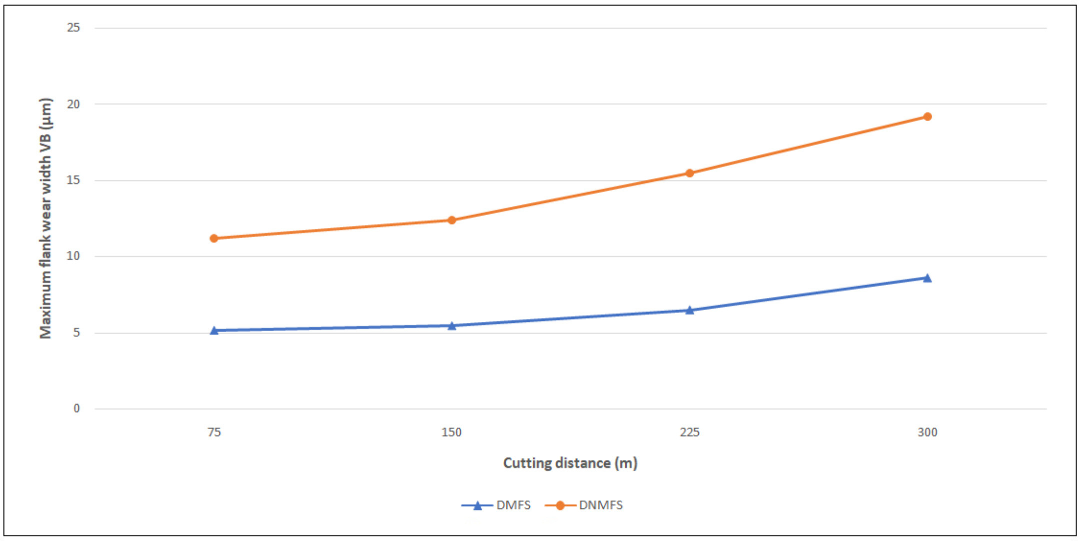
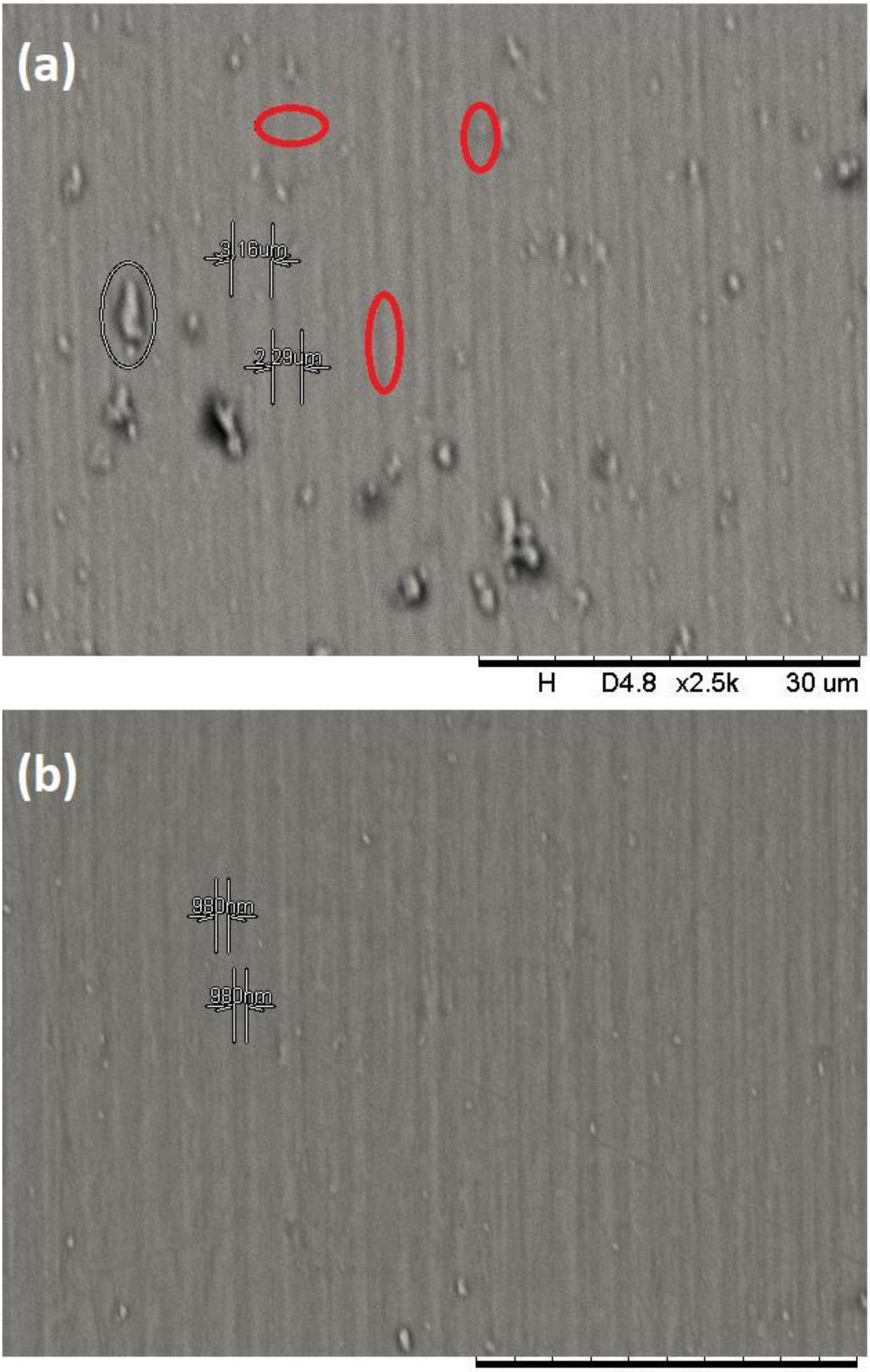


Figure 9. The maximum flank wear width of DNMFS and DMFS tools at different cutting distances

4.3 Surface analysis

Jawahir et al. (2011) presented an advanced study about the significant impacts of tool wear on the surface integrity of machined surface, therefore, the machined surface by DNMFS and DMFS tools was measured and is shown in Figures 10. Refer to Figure 10(a), there were many uncut materials left on the machined surface of DNMFS. Uncut materials were randomly distributed on the machined surface and ragged above the average height of machined surface, leading poorer surface finishing. In comparison to the machined surface of DMFS as shown in Figure 10(b), the machined surface displayed nearly none of uncut material which was far fewer than that of DNMFS, and the size of uncut materials was exceptionally small in contrast to that of DNMFS. Theoretically, the uncut materials on the turned surface are mainly due to the phase shift of tool vibration induced from high cutting temperature and friction force in machining processes, which is believed to intensify in the dry machining environment. The geometric illustration of generation of uncut materials and corresponding tool marks is shown in Figure 11. For an ideal turned profile, the diamond tool radius should be sufficiently large to generate continuous tool marks which offer small surface roughness without uncut materials. However, in the dry machining environment, high cutting temperature and friction force are resulted always and induce a high level of tool vibration. For DNMFS generated in dry SPDT, diamond tool continuously shifted backward and forward due to the tool vibration. As a result, the end of two adjacent tool marks was not connected continuously, causing separations or overlaps of two adjacent tool marks. The overlapping adjacent tool marks provided excessive cuts of materials which caused the machined area below the average surface height, which was indicated by the concave surface on the machined surface (the red circles in Figure 10(a)), while the separations of adjacent tool marks induced the ragged materials on the machined surface which were notified as the uncut materials on the machined surface (white circles in the Figure 10(a)). They contributed to poor surface finishing of machined surface of DNMFS. In addition, the widths of tool mark of DNMFS were about 2.29μm - 3.16μm while that of DMFS was about 980nm. The widths of tool mark generated in DMFS were reduced by 57.2% - 68.99% in comparison to that of DNMFS. The better performance of surface integrity of DMFS proved an effectiveness of suppression tool vibration using an eddy current damping effect in dry SPDT, achieving a reduction of tool wear and an improvement of surface integrity simultaneously.



Figures 10. SEMs of turned surface of (a) DNMFS and (b) DMFS.

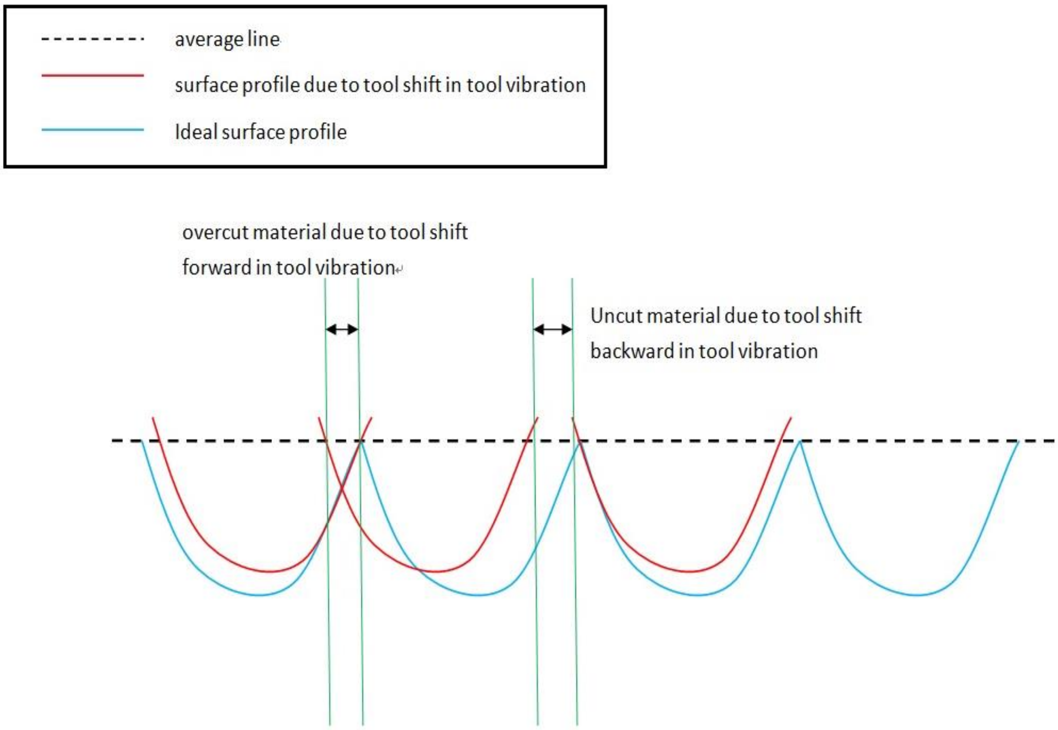


Figure 11. The illustration graph of tool shift induced by tool tip vibration in dry SPDT.

5. Conclusions

Dry machining effectively minimizes the damages of lubricant uses in machining process, it is environmentally advisable and necessary for manufacturing sectors especially for those which are producing precise products. However, the consequences of deteriorated tool life and product quality induced from dry machining remain unsolved which limit an implementation of dry machining practically. Therefore, the current machining technology should be evaluated in order to fill this technology gap. In this study, a novel machining technology was introduced, a magnetic field was firstly applied to dry SPDT of titanium alloys to reduce diamond tool wear and uplift the surface integrity of machined surface without using lubricants, exploring the feasibility of dry SPDT for sustainable manufacturing. Normally, diamond tool wear was found to be much serious in dry machining of titanium alloys because of low thermal conductivity of materials and high cutting temperature generated in the dry machining environment. Through the experimental results, diamond tool in dry SPDT in the presence of magnetic field showed lower degrees of adhesive wear, built up edge, cracking and ragged/concave machined surface in comparison to that in the absence of magnetic field. The machining difficulties in term of serious tool wear and poor surface integrity in dry SPDT of titanium alloys are minimized using a magnetic field and an eddy current damping effects, allowing the feasibility of dry SPDT of titanium alloys in practical uses. Without employing complicated equipment, the proposed machining technology reduces the negative environmental impacts resulted from dry SPDT, simultaneously, the machined components of titanium alloys show better surface integrity. The proposed machining technology only employed extra two magnets which are low cost and attainable; the proposed machining technology contributes to provide a feasibility of dry SPDT of titanium alloys in practical applications for sustainable manufacturing. The principle and the consequences of proposed machining technology on diamond tool wear are summarized step by step in Figure 12. To conclude, few points below should be noted:

1. A rotating titanium alloys was placed in between of two permanent magnets in the experiments, the vibration amplitudes in dry SPDT were lowered under the influence of eddy current damping effect at all cutting distances, it proved the machining vibration was highly reduced using an eddy current damping effect.
2. Adhesive tool wear is the dominant wear mechanism in dry SPDT of titanium alloys. Adhesive wear of diamond tool was overall minimized in the presence of magnetic field, no crack or built up layer was observed on DMFS tool.
3. The maximum flank wear width of DNMFS tool was remarkably larger than DMFS tool at the entire turning process, particular at the longer cutting distance 300m, the maximum flank wear width of DNMFS tool was even larger than that of DMFS about 123%. The maximum flank wear width of diamond tool was largely reduced under the influence of magnetic field.
4. The machined surface generated in the absence of magnetic field displayed many uncut materials and concave area which were induced by tool vibration. In comparison to the machined surface influenced by an eddy current damping effect, as a suppression of tool vibration, the amount of uncut materials and concave area showed fewer on the machined surface also, the widths of tool marks on the machined surface were much small. The surface integrity of machined titanium alloys in dry SPDT was highly enhanced in the presence of magnetic field.
5. Environmental issues of SPDT of difficult to cut materials for manufacturing precise components are highly related to lubricant uses. On the other hand, lubricant uses give rise to pollution problems related to waste disposal. Therefore,

dry machining is urged to adopt to minimize the environmental damage of wet machining. This paper proposed a novel machining technology in this direction.

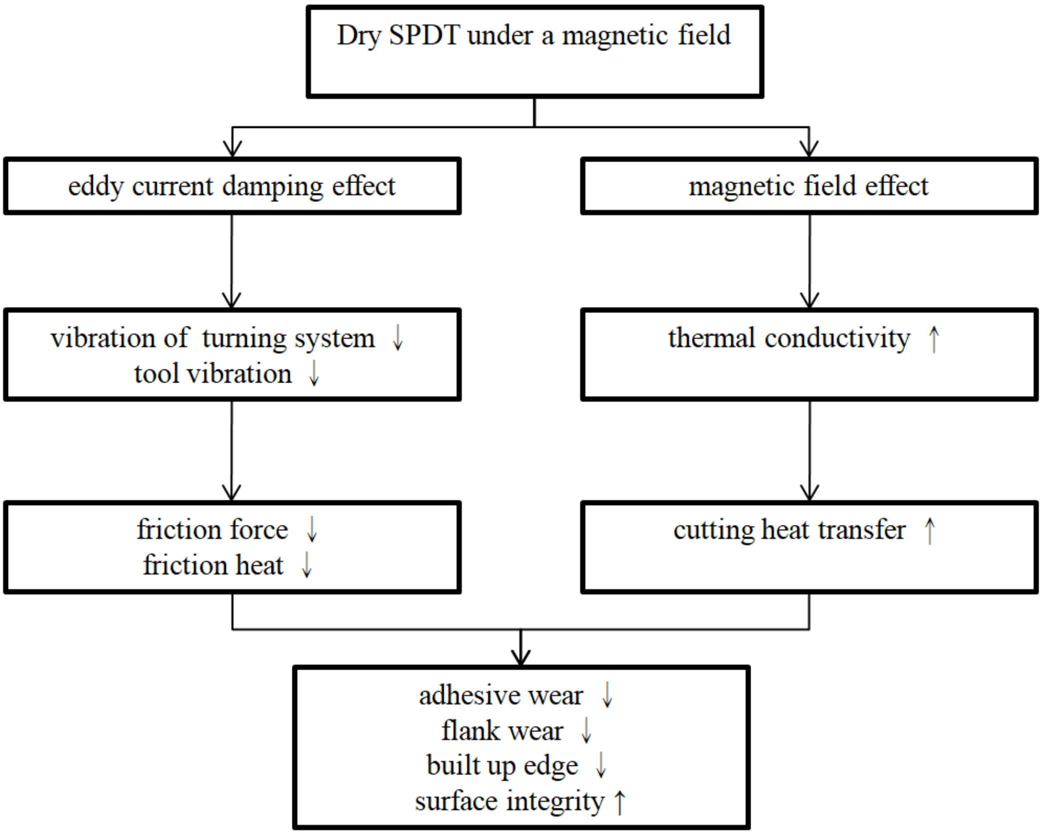


Figure 12. The principle and the consequences of proposed machining technology on diamond tool wear and surface integrity

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