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# Reduction of material swelling and recovery of titanium alloys in diamond cutting by magnetic field assistance

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## ABSTRACT

Ultra precision machining (UPM) is extensively used to fabricate high accuracy products. However, the problematic material swelling/recovery effect due to elastic recovery of materials in UPM remains unresolved. It causes ragged surface and extra engineering tolerance which are unadoptable in extremely precise components. In particular to high elastic recovery rate with low thermal conductivity materials like titanium alloys, swelling effect intensifies during machining. In this study, magnetic field was superimposed on titanium alloys during single point diamond cutting which aimed to minimize the material swelling effect on the machined surface using magnetic field influence. In the experiment, titanium alloys were located at the center of two permeant magnets with strength 0.02T and undergone diamond groove cutting. The experimental results showed the material swelling/recovery on the machined surface was significantly reduced in a presence of magnetic field in comparison to that of diamond cutting without magnetic assistance; the accuracy of depth of cut, width and radius of cutting groove in a magnetic field reached satisfactorily over 98 percent. The proposed machining technology solves the problem of material swelling/spingback of low thermal conductivity materials by a cost-efficient way which is needless of complicated equipment.

Keywords: magnetic field; diamond cutting; titanium alloys; material recovery; material swelling

## 1. Introduction

UPM is one of the most widespread nano-range level machining technology for producing medical and aerospace products in mirror grade surface finish with sub-micrometer form accuracy and nanometer range surface roughness. Extremely high cutting speed and small depth of cut are always involved in UPM; therefore, no bur is expected to form on the machined surface and the shape of cutting groove is anticipated as same as the tool radius ideally, however, the material swelling/ recovery caused the deviation from prefect case as illustrated in Figure 1. Heat generated at cutting process melts the material, the exertion force and pressure from the tool cause the melted materials flow laterally of moving tool, with the melted material at the tool bottom, they recover and expand on the cutting surface after solidification, consequently tool marks are left on machined surface. Especially for low thermal conductivity and elastic module alloys, huge amount of heat is trapped and cannot be dissipated effectively from the tool and surface interface which cause even large material recovery volume, they demonstrate notable swelling marks on machined surface thus.

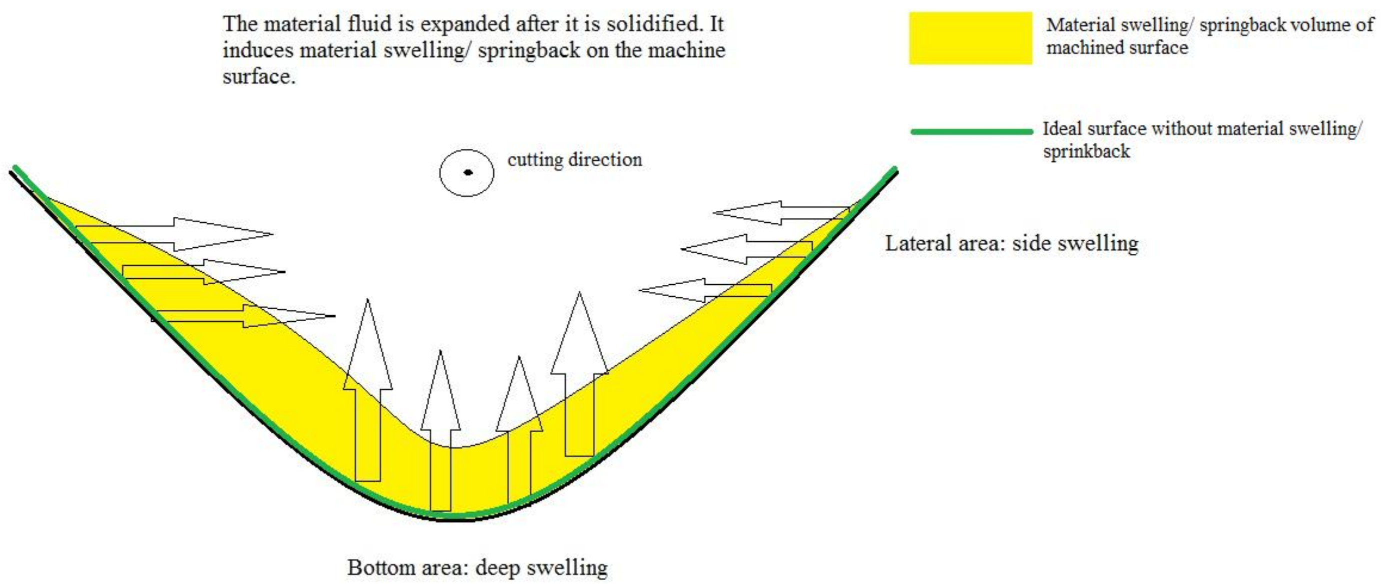



Figure 1. The illustration graph of material swelling/ recovery of machined surface

The problems of material swelling and recovery in single point diamond cutting are treated as natural response of materials properties, they are unavoidable and uncontrollable unless the materials are undergone change of chemical composition or change of cutting parameters in machining process. Those methods lead to large investigation time and cost and even change of machining strategy if the cutting parameters are adjusted to cause low material removal rate. Material swelling effect is considered as the dominant factors to worsen the surface roughness and form accuracy[1-4] in machining. Because of material swelling effect, the assigned cutting depth, width and radius are invariably difference from the designed values of the final machined products. The material swelling effect is reinforced especially for the materials with low elastic module and thermal conductivity such as titanium alloys.

Recently, researchers investigated the mechanism of swelling effect in order to reduce the negative effects induced *(5-8)*. However, these works only defined the existence of problematic recovery but provided no solution.

The researches of changing anisotropic and internal energy related to microstructure of materials by magnetic field have been got attention. Orientation ordering of grains of different materials including alloys and superconductors were obtained through alignment by magnetic field [5-8]. Kainuma further proposed that nearly perfect shape recovery of NiCoMnIn alloys with only 3% deformation behavior to a reverse transformation under applying magnetic field was achieved [9]. The recent researches successfully provided evidences that the magnetic energy offers advantages to alter the material properties. With proofing the orientation or the alignment structure inside the substances with positive magnetic sensitivity could be influenced by magnetic field. The further question would focus on the effect of the alignment and ordering using magnetic field on the material properties especially on thermal transference of low thermal conductivity materials.

In our proposed study, we add magnets and utilize a magnetic field to increase of thermal conductivity of titanium alloys during diamond cutting in UPM, we only employ extra two permanent magnets to give out results of reduction of material recovery with high form accuracy and low surface roughness of machined surface. Our works only require 0.02T magnetic field strength without any extra source to obtain the unprecedented findings.

# 2. Theory

## 2.1 Material swelling and recovery in diamond turning

In ultra-precision diamond cutting, material swelling/ recovery are known to be reasons for the spring back of machined surface and lead to tool marks on the machined surface which cause lowering of surface integrity. These two effects are dominant, especially when the depth of cut is extremely small. According to To et al.[10], material swellings are of two kinds: side swelling and deep swelling. Side swelling is the flowing of metal to the side of the tool when the cutting edge exerts high pressure and load on the machined materials; the side flow materials become viscous fluid under continuous cutting, the metal fluid stays at the two sides of the cutting edge and solidify when the temperature lowers, and consequently, they leave obvious tool marks thereby affecting the surface roughness. Similar to side swelling, deep swelling is the expansion of material volume at the bottom position of machined surface when the metal fluid is solidified after cutting.

### 2.2 Enhancement of thermal conductivity by magnetic moment alignment under magnetic influence

Different kinds of research works stated the thermal conductivity of nanofluid which containing ferroparticle/magnetite particles could be enhanced by a presence of magnetic flied [11-15]. Also, thermal conductivity of carbon nanotubes mixed or integrated with ferrometals or ferrofluid in the form of thin film, nanocomposite is well enlarged in a presence of magnetic field [16-18]. The basic principle and conclusion of the reason for the improvement of thermal conductivity using magnetic field of above literature is that, the ferroparticles of the nanofluid and carbon nanotubes are aligned with an application of external magnetic field. In the absence of an external magnetic field, some particles are position to each other because of the van der Waals forces and dipole–dipole interactions, which causing aggregations and the particles are randomly oriented and positioned [19-20]. In the presence of magnetic field, the magnetic dipolar energy is sufficient to come over the thermal energy, the ferroparticles inside or surrounding the nanofluid or carbon nanotube tend to align along with the direction of the external field as the positive value of magnetic susceptibility of ferroparticles.  The aligned particles or nanotubes act as linear chains which are highly conductive paths for the heat transfer and a fast heat transference along the path of fluid carrier is occurred [21-22].

The application of uplifting thermal conductivity from alignment of magnetite particles under influence of magnetic field could be extended to machining titanium alloys based on the same principle. According to the several source books of titanium alloys, the magnetic susceptibility of titanium alloys is 14.6ppm [23-

24], the positive value of magnetic susceptibility represents that the classification of magnetism of titanium alloys belongs to paramagnetic, their reaction tendencies toward magnetic field exist as long as the magnetic field is present, meaning that the magnetic moments of titanium alloys could be aligned in the presence of external magnetic field. Therefore, the machining process of titanium alloys is expected to take benefits from magnetic assistance, employing enhancement of thermal conductivity by aligning and forming chains of magnetic moment during liquid state of melted titanium alloys in cutting process for dissipating the cutting heat, the material swelling/ recovery consequently are reduced in the condition of less heat trapped inside the material in solidification.

In this paper, we reported a new application of using the properties of alignment of magnetic moment of titanium alloys under magnetic field, to solve the problem of high level recovery in machining titanium alloys due to low thermal conductivity of the materials. A single groove was cut onto titanium alloys' surface under magnetic field influence with a comparison test. The experimental results confirmed the above conclusion and the theory, they showed significant reduction of recovery and low surface roughness of machined surface by using magnetic field influence during diamond cutting in comparison to that in an absence of magnetic assistance.

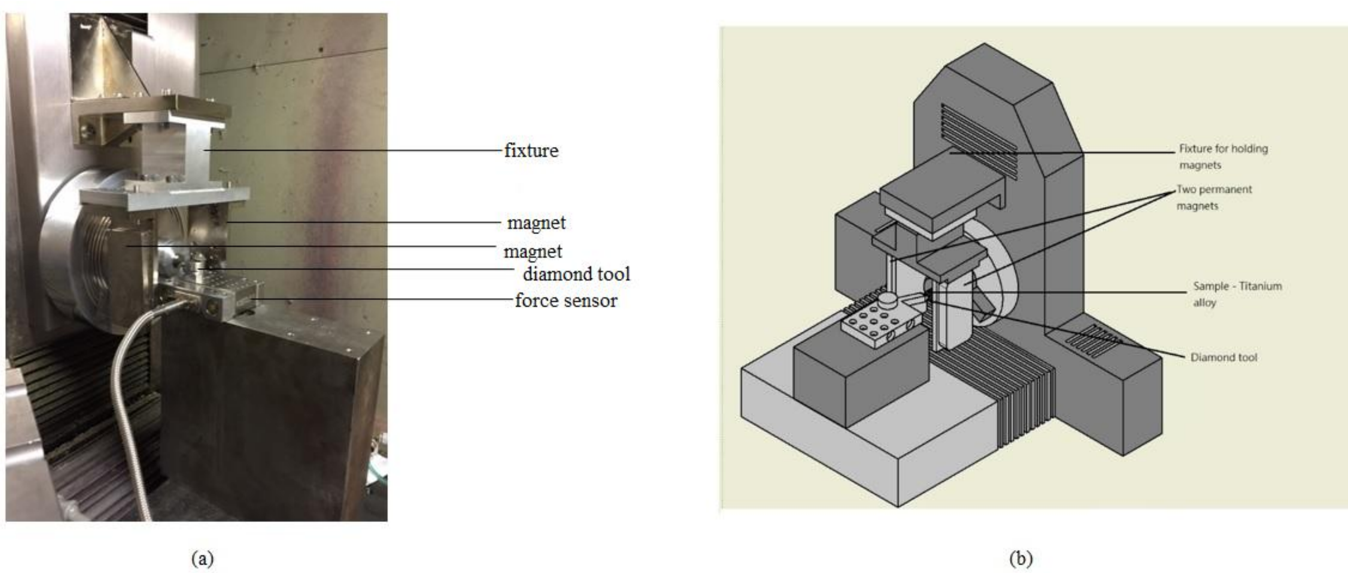
## 3. Materials and methods

### 3.1 Diamond cutting with magnetic assistance

Two phase titanium alloys, Ti6Al4V (TC4) were used as materials for the experiments. The composition of TC4 was listed in Table 1. A straight line was cut on the TC4s' surface using single point diamond tool with presence and absence of magnetic field. The cutting parameters and tool specification are: depth of cut: 3µm, feedrate: 200mm/min and single point diamond tool radius:1.514. The magnetic field was provided by two permanent magnets. The sample was placed at the center of two permanent magnets to expose the samples to the magnetic field where the magnetic field strength was 0.02T. The experimental setup is shown in Figures 2 (a-b). Moore Nanotech 350FG (4 axis Ultra-precision machine) was used as an equipment for diamond cutting. AFM Measurement System Park's XE-70 was used for observing bur formation. The surface roughness, cutting radius and depth of cut of samples were measured by Wyko NT8000 Optical Profiling System which is the optical profiler using non-contact measurement. The samples undergone diamond cutting in a presence and an absence of magnetic field are named MFS (magnetic field sample) and NMFS (non-magnetic field sample).

Table 1. The composition of titanium alloys used in the experiments

| | Element composition (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | V (Vanadium) | Al (Aluminium) | N (Nitrogen) | O (Oxygen) | H (Hydrogen) | C (Carbon) | Fe (Iron) |
| Titanium alloys (TC4) | 4 | 6 | 0.05 | 0.2 | 0.012 | 0.1 | 0.3 |

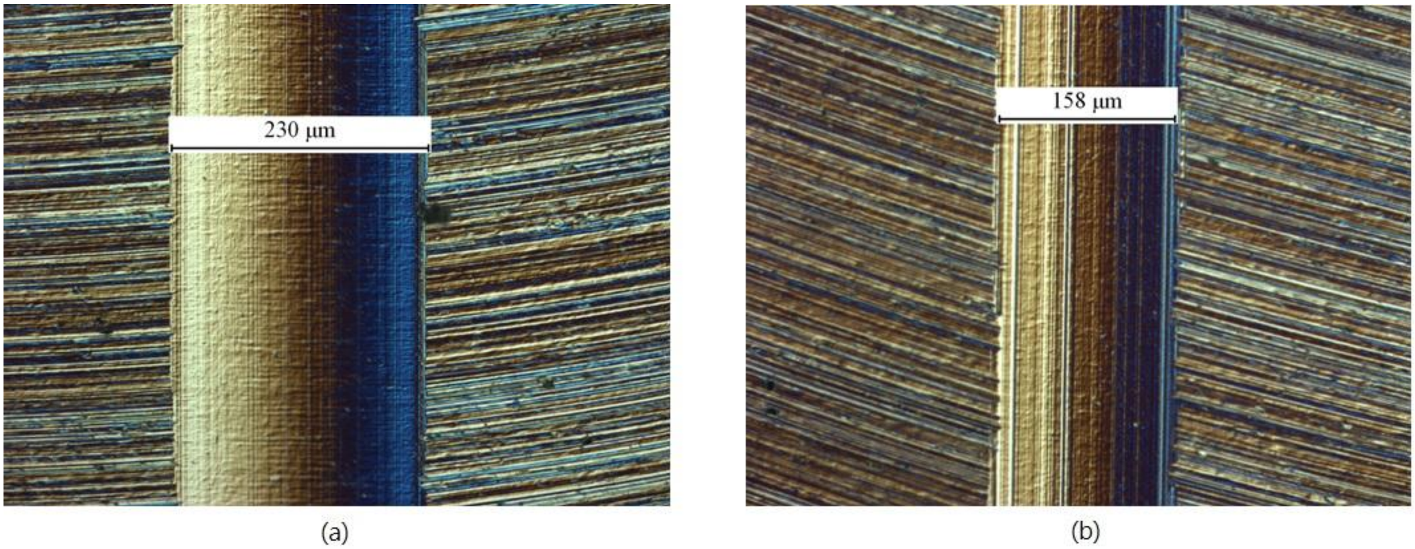



Figures 2. (a) Experimental setup (b) illustration graph of experimental setup

## 4. Result and Discussion

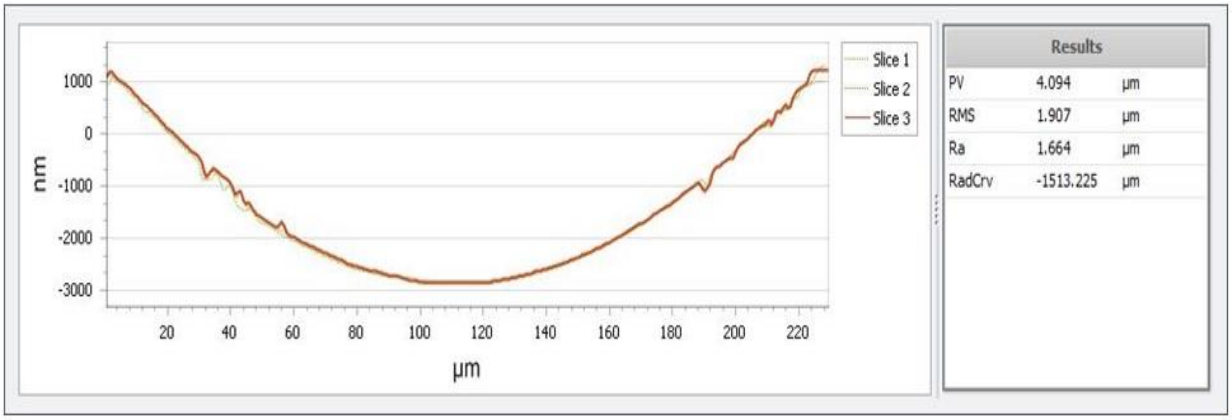
The spingback level during solidification of metal fluid was highly reduced due to transference of high amount of cutting heat by alignment of dipole moments of titanium alloys, forming a conductive path to dissipate the cutting heat to the surrounding. In the experiment, the magnetic field at 0.02T was added to the sample during diamond cutting to minimize material swelling surface. Referred to the results from the microscope Figures 3 (a-b), clear, obvious and straight swelling marks were exposed linearly on the bottom of cutting surface at the NMFS, in particular to the centre of the cutting surface, the swelling marks were the most apparent. It implied the swelling effect concentrated at the bottommost of cutting profile, the direction of material recovery was located at bottom area and the solidified material was expanded upward which is a kind of deep swelling as mentioned in previous section. On the other hand, the side swelling was appeared in the groove side, the side surfaces of the cutting groove showed raised and uneven, even some cracks were appeared on the side surface. it signified the bur formation and material recovery were localized and appeared at cutting edge sidelong. For the same cutting condition of MFS, it demonstrated smooth and unclear swelling marks, the bottom surface of cutting groove showed horizontal lamella vein surface texture with little vertical swelling marks suggesting smooth and small level of deep swelling. Also, the groove side showed straight and has nearly no crack in comparison to the NMFS showing reduction of side swelling under magnetic influence.

For the width of the cut groove, the MFS was 230μm while that of NMFS was 158μm; With the assigned cutting width 220μm, the cutting width error of MFS counted for only 4.5% which was smaller than that of NMFS 28.2%. The side swelling introduced the larger volume of material at the groove side and therefore the width of sample undergone normal diamond cutting become smaller than the assigned one. The side swelling of machined groove was highly supressed under magnetic influence which was reflected by the accuracy of groove width generated in a presence of magnetic field.

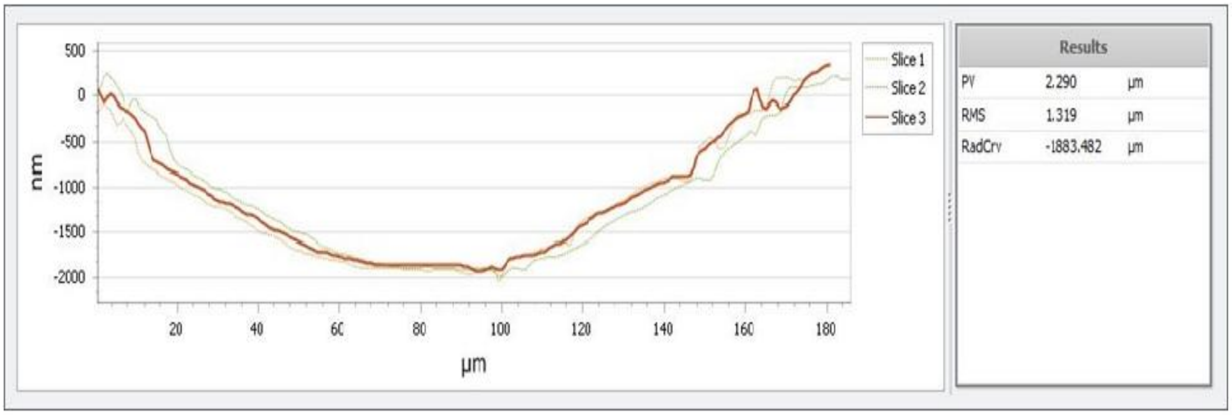



Figures 3. The micrographs of cutting groove of (a) MF sample, (b) NMF sample.

The cutting profiles of grooves of NMFS and MFS are shown in Figures 4 (a-b), the depth of cut and the radius of curvature of cutting profile of MFS were about 2.96µm and 1.513 (RadCrV in the Figures 4(a-b)) respectively which were near to the assigned depth of cut 3µm and diamond tool radius 1.514; the cutting edge of MFS showed smooth radius curve without wavy and vibration characteristics. Adversely, due to dominant of material recovery effect, the materials were expanded after cutting, ragged and crude profiles were displayed in the surface sides of NMF sample, the whole cutting profile of NMFS was even distorted to left which deviated largely from the tool shape; Moreover, its depth of cut and the radius of curvature of cutting profile were 1.9µm and 1.883 which indicated significance of deep swelling and largely strayed form from the assigned parameters.



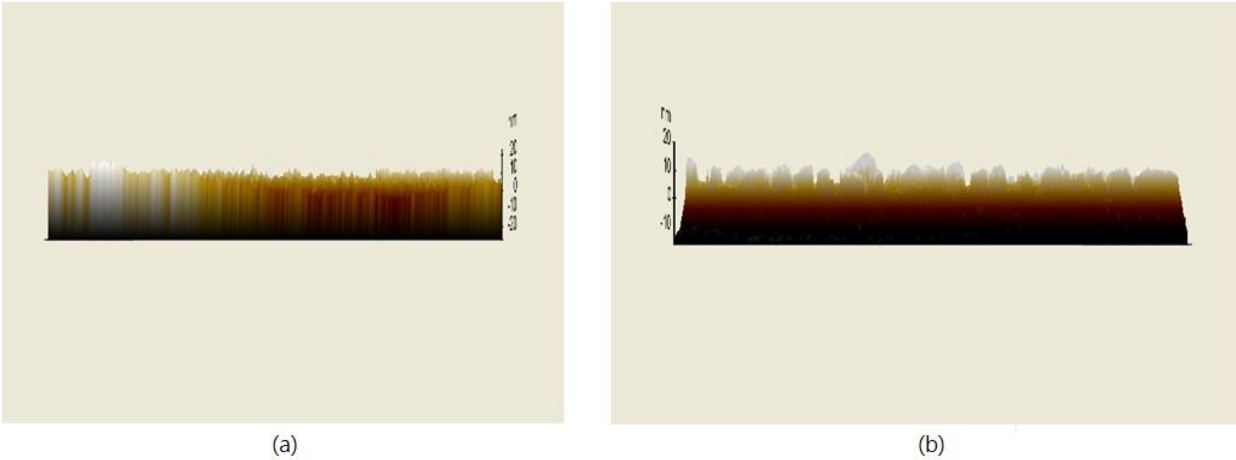

(a)




(b)

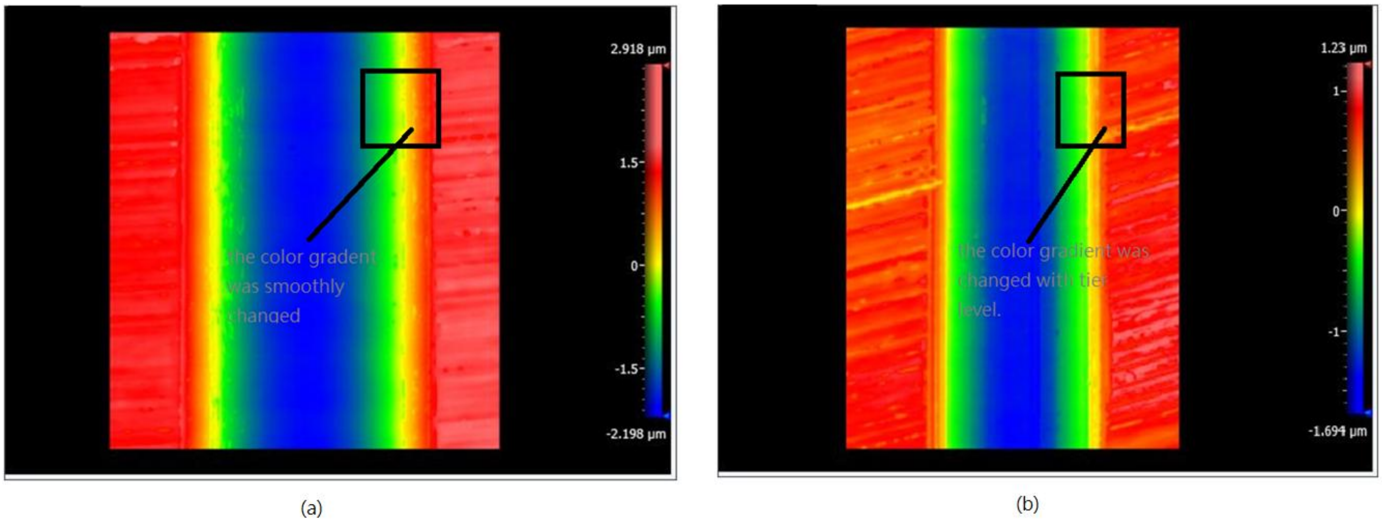
Figure 4. The cutting profiles of cutting grooves of (a)MFS (b) NMFS

The burs caused by side material swelling are analysed by Atomic-force microscopies (AFM) in Figures 5 (a-b) which they captured the pictures of area of groove side. The comparison of AFM between NMFS and MFS showed that less Poisson burs was formed for the latter. MFS illustrated a manifestly smaller bur size and shorter bur height in comparison to that of NMFS. The width of uplift materials at the groove side for NMFS was larger and the burs was showed separately with obvious crests.




Figures 5. AFMs of burs formation at the groove side of (a) MFS (b) NMFS

More supporting results for the enhancement of form accuracy and surface finishing of machined groove in a presence of magnetic field are shown in Figures 6-8. Figures 6 show  surface roughness of grooves in the plane view, MFS showed a relatively less radical color change of surface roughness than NMF sample at two groove sides, the gradual color change of surface roughness color at the groove sides suggested the small different for bur height and distance between every bur along the cutting side, it implied the minimization of side material swelling under magnetic field influence. In Figures 7, it shows the bottom surface roughness of MFS reached to 15nm, it was contrary to that of NMFS which the surface roughness was 36.58nm, the result is consistent to the previous discussion which stated the deep swelling was highly suppressed in a presence of magnetic field. Figures 8 show the histograms of both MFS and NMFS, X axis of histogram refers to the height of machined surface. histogram of MFS illustrated that over 1000 pixels was located at 0nm of x axis with less dispersion, in contrast to NMFS samples with only about 250 pixels was located at 0nm of x axis with highly scattered pattern. The higher concentration of pixel at 0nm for MFS in histogram indicated that higher proportion of measured data point for the surface height are relatively zero, it revealed that MFS consisted smooth surface with less wavy and the deep material swelling was restricted.




Figures 6. The plane views of surface roughness of (a) MFS(b) NMFS.

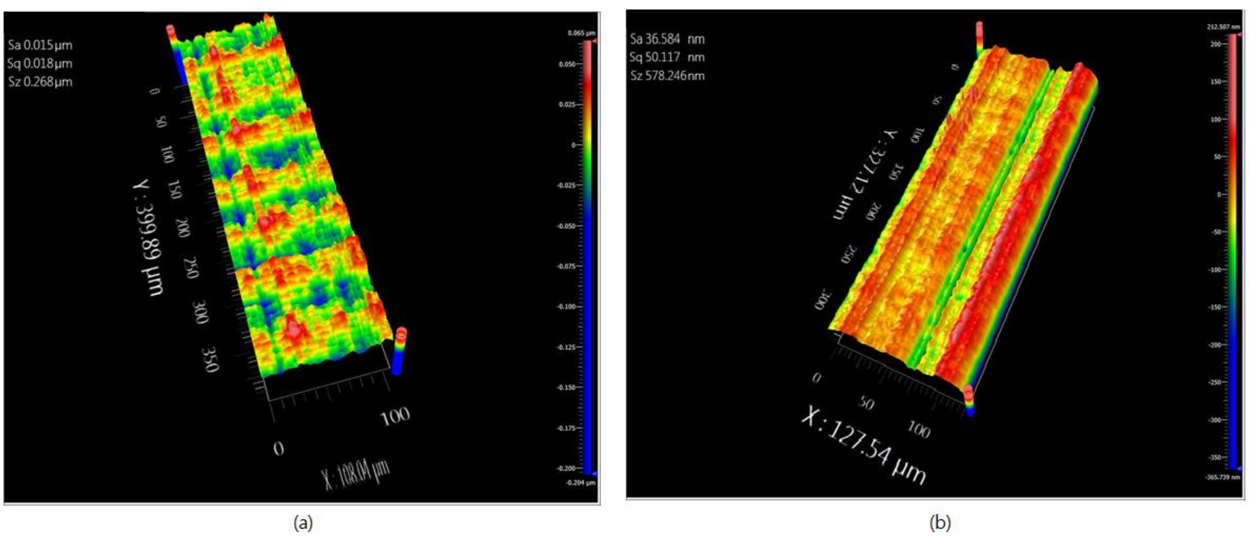
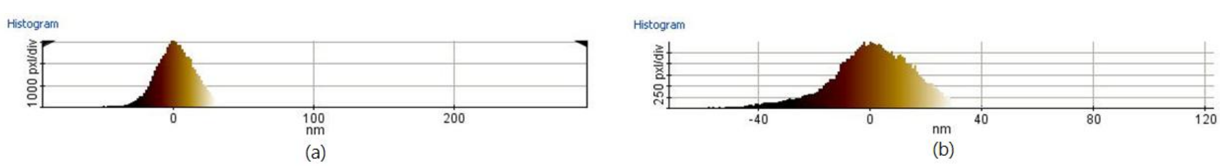



Figure 7. The surface roughness of bottom surface of (a) MFS -15nm (b)NMFS – 36.58nm




Figures 8. Histograms of bottom surface of (a) MFS (b) NMFS.

## 5. Conclusion

The accuracy of cutting width, depth of cut and cutting radius in term of absolute difference and percentage errors are summarized Table 2 and Table 3. In an absence of magnetic field, the depth of cut, cutting width and profile radius were 1.9μm,158μm and 1.883 respectively. While in a presence of magnetic field, the respective measurements improved to 2.96μm, 192μm and 1.513. Noting that the sample in an absence of magnetic field constituted almost 25-37 percent percentage errors between designed and actual results for all of the form accuracy indicators, while the magnetic field assistance achieved a under 4 percent for all of these.

Table 2. Designed machining parameter and experimental results of NMF and MF samples

| | Designed parameters (DP) | Experimental results (ER) of NMF | Experimental results of MF |
|---|---|---|---|
| Depth of Cut (μm) | 3 | 1.9 | 2.9 |
| Cutting Width (μm) | 220 | 158 | 230 |
| Cutting Radius | 1.514 | 1.883 | 1.513 |
| Bottom Surface Roughness(nm) | - | 36.58 | 15 |

Table 3. Absolute difference and relative percentage error between designed parameters and experimental results of MFS and NMFS

| | MF | | | NMF | | |
|---|---|---|---|---|---|---|
| | Depth of Cut | Cutting Width | Cutting Radius | Depth of Cut | Cutting Width | Cutting Radius |
| Absolute difference between designed parameters and experimental results | 0.1μm | 10μm | 0.001 | 1.1μm | 62μm | 0.369 |
| Percentage error (%) | 3.33 | 4.5 | 0.07 | 36.7 | 28.2 | 36.9 |

In our proposed study, we solve the problematic material swelling/ recovery which is unavoidably occurred in UPM. With reduction of material swelling/ recovery, titanium alloys take advantages of this machining technique by achieving excellent surface roughness and form accuracy. The application can be further extended to other medical alloys especially they have elastic behavior dominantly such as nickel titanium alloys as long as their magnetic susceptibility are positive. Furthermore, the proposed study did not utilize complicated pre-treatments and equipment, we simply employed extra two permanent magnets with only 0.02T magnetic field strength in the cutting process to solve the material swelling/ recovery problems. The small size of magnets enable them to be adjusted freely inside UPM machine which it overcomes the problem of inadequate space of UPM machines, the technique can contribute to high precision products in the current market in the future.

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## 1. Introduction

UPM is one of the most widespread nano-range level machining technologies for producing medical and aerospace products in mirror grade surface finish with sub-micrometer form accuracy and nanometer range surface roughness. Extremely high cutting speed and small depth of cut are always involved in UPM; therefore, no bur is expected to form on the machined surface and the shape of cutting groove is anticipated as same as the tool radius ideally. However, the material swelling/ recovery effect causes the deviation from the prefect case as illustrated in Figure 1. The heat generated melts materials during the cutting processes, the exertion force and pressure from the tool are sufficiently high to cause the plastic side flow of melted materials laterally, leaving the materials behind the cutting edge especially at the side and bottom location of cutting edge. When the materials recover during the solidification process, they are expanded and their volumes are enlarged, leaving tool marks on the machined surface. Especially for low thermal conductivity and elastic module alloys, a huge amount of heat is trapped and cannot be dissipated effectively from the tool and surface interface which further cause larger material recovery volume, they demonstrate notable swelling marks on the machined surface thus.

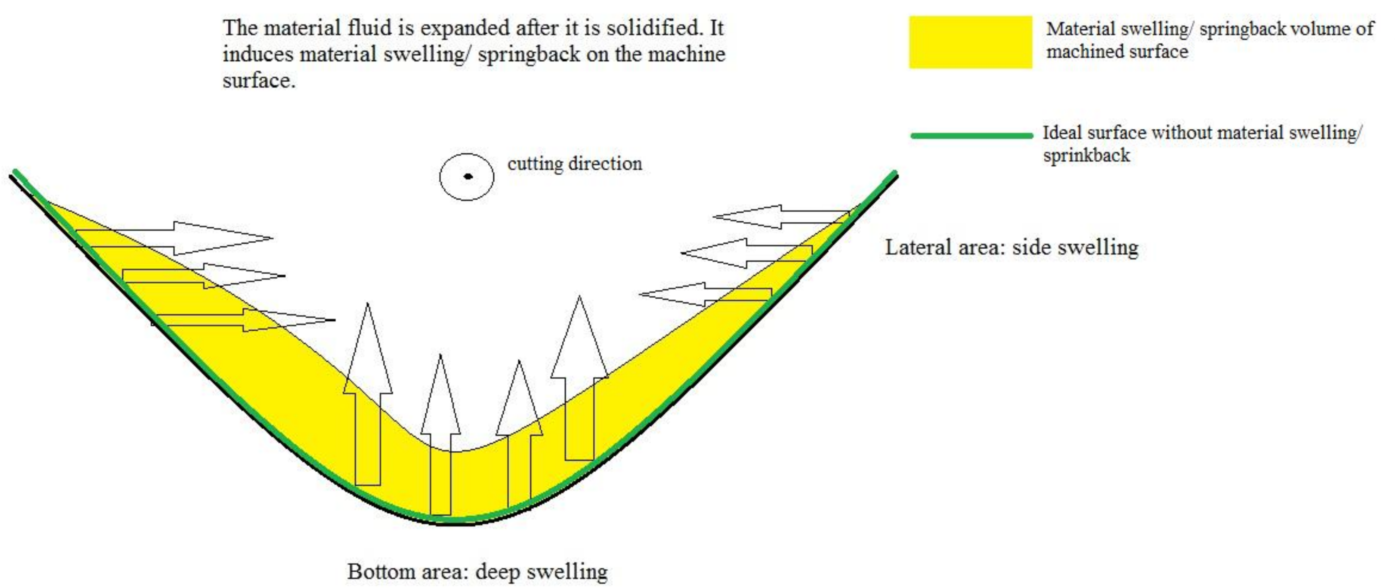



Figure 1. The illustration graph of material swelling/recovery of machined surface

The problems of material swelling and recovery in the single point diamond cutting are treated as the natural response of materials properties, they are unavoidable and uncontrollable unless the materials undergo a change of chemical composition or cutting parameters in machining processes. Those methods minimized the level of material swelling and enhanced the surface integrity, at the meantime, they generated several side effects including large investigation time, high machining cost and a change of machining strategy which may lower material removal rate; therefore, a better machining approach should be adopted to fill up the research gap which lowers the negative impacts from the material swelling without sacrificing the machining performance simultaneously. The material swelling effect is considered as the dominant factors to worsen the surface roughness and form accuracy [1-4] in machining processes. Because of the material swelling effect, the assigned machining parameters such as the cutting depth, width and radius are invariably different from the corresponding results displayed into the machined components, leading the variation between the designed and actual products. The material swelling effect is reinforced especially for the materials with low elastic module and thermal conductivity such as titanium alloys.

Recently, researchers investigated the mechanism of swelling effect in order to reduce its' negative impacts induced. However, these works only defined the existence of problematic recovery but provided no solution. On the other hand, there has been academic attention on how a magnetic field changes the isotropic and internal energy of material microstructures. The grain orientation and ordering of different materials including alloys and superconductors were obtained through the alignment under the magnetic field influence [5-8]. Kainuma et al. [9] further discovered that NiCoMnIn alloys displayed nearly perfect shape recovery by applying a magnetic field, showing only 3% deformation behavior during a reverse transformation. Existing empirical evidence has already showed that a magnetic field enables to alter material properties of particular materials with positive magnetic sensitivity to provide the aligned microstructure. The next question would be focused on the effect of the alignment using a magnetic field on the thermal transference of low thermal conductivity materials, which is the main reason for the high level of material swelling in machining titanium alloys

In our proposed study, a magnetic field was superimposed on titanium alloys to enhance the thermal conductivity of titanium alloys during the diamond cutting in UPM, we only employ two permanent magnets additionally to deliver the results of significant reduction of material recovery as well as high form accuracy and low surface roughness of machined groove. Our works only require 0.02T magnetic field intensity without utilizing an extra source to obtain the unprecedented findings.

## 2. Theory

### 2.1 Material swelling and recovery in diamond turning

In ultra-precision diamond cutting, the material swelling is known to be a reason for the springback of machined surface and leads tool marks on the machined surface, causing poor surface integrity and form accuracy. The material swelling effect is dominant especially when the depth of cut is extremely small. According to To et al. [10], the material swelling is classified as two types: side swelling and deep swelling. Side swelling is material side flow when the cutting edge exerts high pressure and load on the machined materials; the side flow materials become viscous fluid under continuous cutting, consequently, the metal fluid stays at the two sides of the cutting edge and solidifies with the temperature decrease, as a result, the solidified materials leave obvious tool marks thereby affecting surface roughness. Similar to side swelling, deep swelling is the expansion of material volume at the bottom position of machined surface after the metal fluid solidifies in a cutting process.

### 2.2 Enhancement of thermal conductivity by magnetic particle alignment under the magnetic influence

Researches stated the thermal conductivity of nanofluid and ferrofluid containing ferroparticles /magnetic particles could be enhanced in presence of magnetic flied [11-15]. Also, the thermal conductivity of nanocomposite with ferrometals or ferrofluid in the form of thin film was well enlarged in presence of magnetic field [16-18]. The basic principle and underlying reason for the improvement of thermal conductivity using a magnetic field of above literature are that, the ferroparticles inside nanofluid and nanocomposite are aligned under an application of external magnetic field. In absence of external magnetic field, ferroparticles join and attach each other because of the van der Waals forces and dipole–dipole interactions, causing aggregations and the particles are randomly oriented and positioned [19-20]. In presence of magnetic field, magnetic dipolar energy is sufficient to come over the thermal energy, the ferroparticles inside the nanofluid or nanocomposite tend to align along with the direction of the external field as the positive value of magnetic susceptibility of ferroparticles. The aligned magnetic particles act as linear chains which are highly conductive paths for transferring heat, promoting the fast heat transference along the paths of fluid carrier [21-22].

In absence of an external magnetic field, paramagnetic particles may attach to each other because of the van der Waals forces and dipole-dipole interactions. However, once a magnetic field presence, the dipole moments liked to align with an external applied magnetic field. The dipole-dipole interaction energy $U_d$ between the magnetic particles is termed as [23]:

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

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

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

which defines the effective attraction between two magnetic particles, where $k_B$ is Brownian constant and $T$ is the temperature respectively. In absence of magnetic field, the magnetic particles are oriented in random directions and follow with Brownian motion as L<1. When applying a magnetic field, the magnetic dipole interaction energy turns to be large enough, leading the magnetic particles start to align themselves 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 the magnetic field. The chain structures of magnetic particle enhance the thermal conductivity in the magnetic field [21], the aligned particles act as linear chains which are highly conductive paths for transferring heat. The lengths of the chains increase with increasing magnetic field [13], also, the amount of magnetic particles which have tendency to align in the direction of magnetic field remarkably increase with magnetic field intensity increase [24].

The application of uplifting thermal conductivity from the alignment of magnetic particles under the magnetic field influence could be extended to machining titanium alloys based on the same principle. According to the several source books of titanium alloys, the magnetic susceptibility of titanium alloys is 14.6ppm [25-26], the positive value of magnetic susceptibility represents that the classification of magnetism of titanium alloys belongs to paramagnetic, their reaction tendencies toward magnetic field exist as long as the magnetic field is presence, meaning that the magnetic moments of titanium alloys could be aligned in presence of external magnetic field. In the cutting process, titanium alloys melted under the high cutting temperature. Melted titanium alloys consisted of suspensive paramagnetic particles in a carrier fluid. With the same logic as mentioned magnetic particle characteristics, the machining process of titanium alloys is expected to take benefits from a magnetic assistance. In presence of magnetic field, the paramagnetic particles inside the melted titanium alloys would move with the direction of magnetic field. The migration of paramagnetic particle formed conductive paths and facilitated the thermal conductivity of titanium alloys in diamond cutting process in a magnetic field.

In this paper, we reported a new application of using the properties of paramagnetic particle alignment of titanium alloys under the magnetic field influence, to solve the high-level recovery in diamond cutting of titanium alloys due to the low thermal conductivity of materials. A single groove was cut on titanium alloys' surface in presence of magnetic field with a comparison test. The experimental results confirmed the above conclusion and the theory, they showed a significant reduction of recovery and low surface roughness of machined surface using a magnetic field during the diamond cutting process in comparison to that without a magnetic assistance.

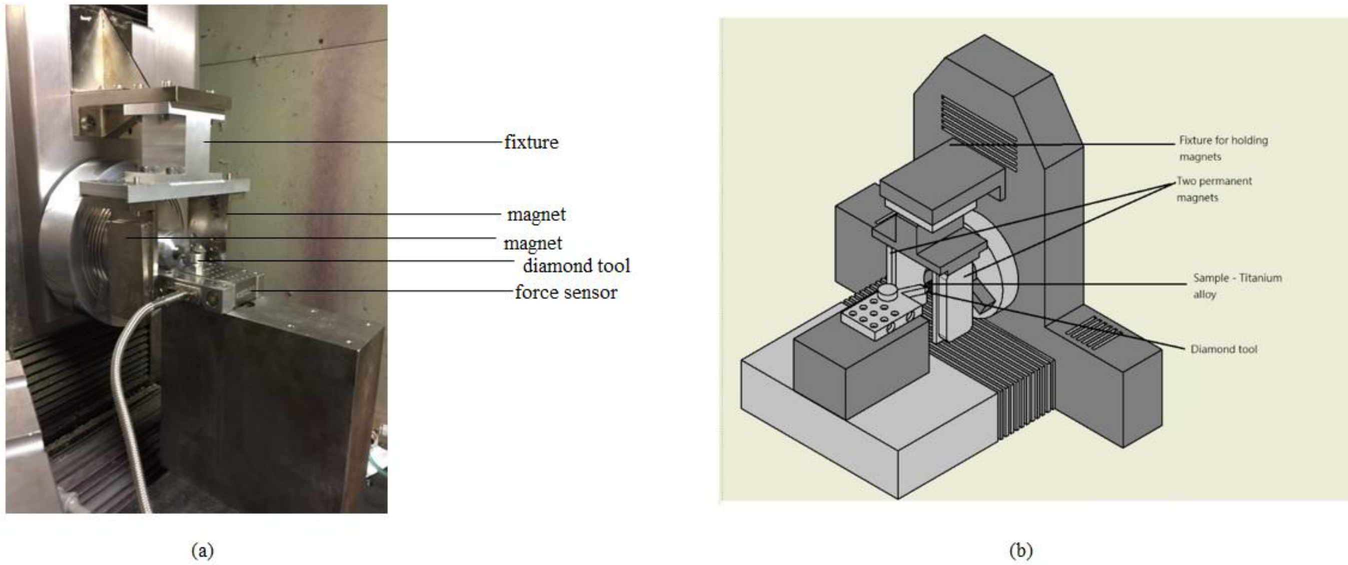
## 3. Materials and methods

### 3.1 Diamond cutting with magnetic assistance

Two phase titanium alloys, Ti6Al4V(TC4) were used as materials for the experiments. The composition of TC4 was listed in Table 1. A straight line was cut on the TC4s' surface using a single point diamond tool in presence and absence of magnetic field. The cutting parameters and tool specification were: depth of cut: 3μm, feedrate: 200mm/min and the tool radius:1.514. A magnetic field was provided by two permanent magnets. Titanium alloys were placed at the center of two permanent magnets to expose the samples to a magnetic field where the magnetic field intensity was 0.02T. The experimental setup is shown in Figures 2 (a-b). Moore Nanotech 350FG (4 axis Ultra-precision machine) was used as an equipment for the diamond cutting. AFM Measurement System Park's XE-70 was used for observing the bur formation. The surface roughness, cutting radius and depth of cut of samples were measured by Wyko NT8000 Optical Profiling System which is the optical profiler using non-contact measurement. The samples processed the diamond cutting test in presence and absence of magnetic field are named MFS (magnetic field sample) and NMFS (non-magnetic field sample) respectively.

Table 1. The composition of titanium alloys used in the experiments

| | Element composition (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | V (Vanadium) | Al (Aluminium) | N (Nitrogen) | O (Oxygen) | H (Hydrogen) | C (Carbon) | Fe (Iron) |
| Titanium alloys (TC4) | 4 | 6 | 0.05 | 0.2 | 0.012 | 0.1 | 0.3 |

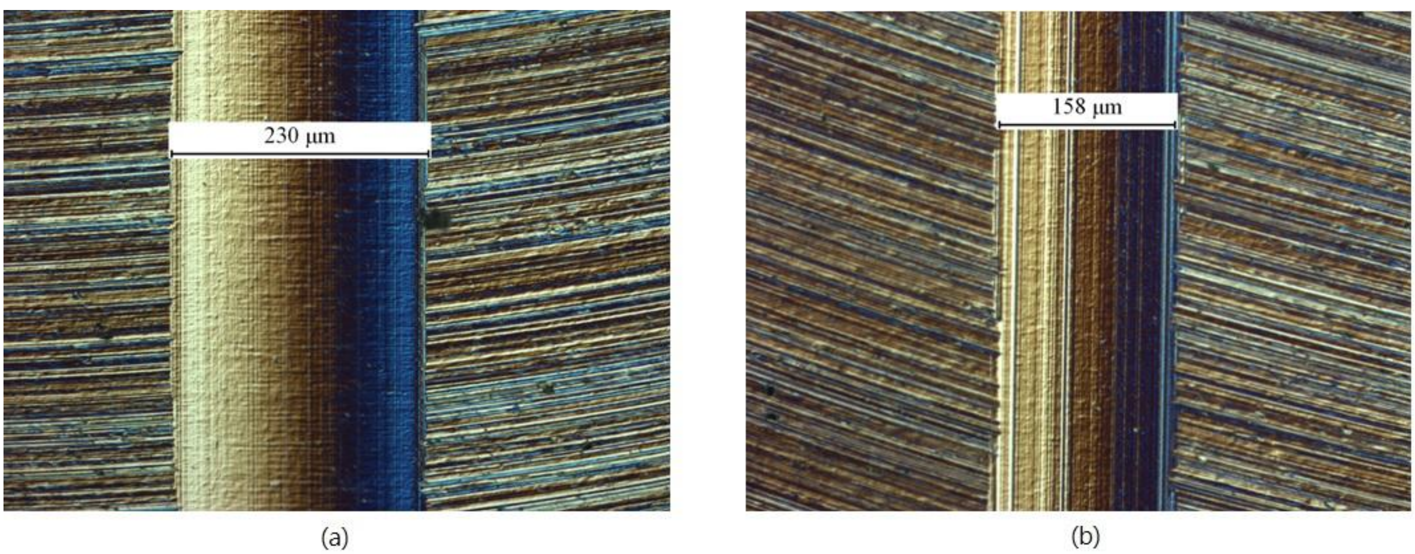



Figures 2. (a) Experimental setup (b) illustration graph of experimental setup

## 4. Results and Discussion

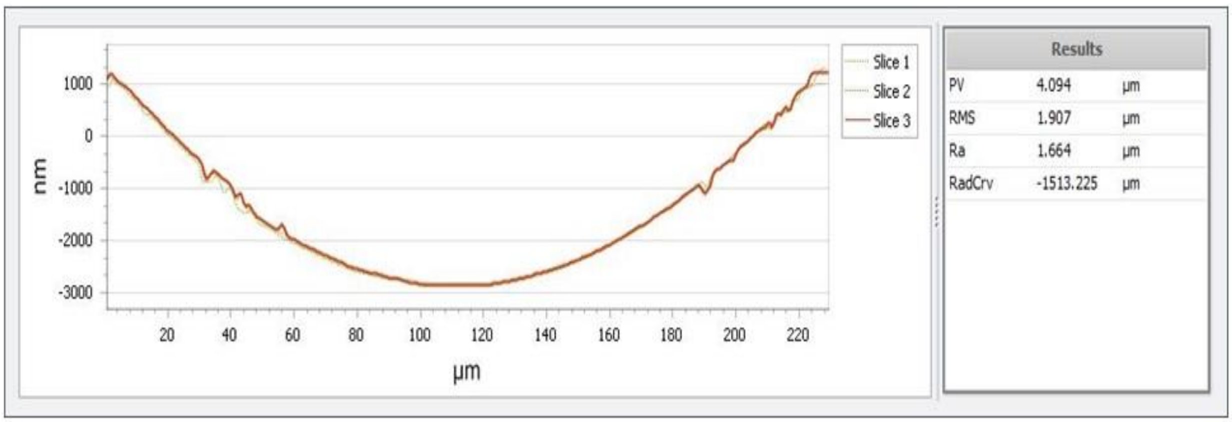
The spingback level during the solidification of metal fluid was highly reduced due to the effective transference of cutting heat by the alignments of paramagnetic particles of titanium alloys, forming conductive paths to dissipate the cutting heat to the surrounding. In the experiment, the magnetic field intensity 0.02T was added to the sample during the diamond cutting to minimize the material swelling effect on the machined surface. Figures 3 (a-b) show the micrographs of MFS and NMFS, clear, obvious and straight swelling marks were exposed linearly on the bottom of cutting surface at the NMFS, in particular to the centre of the cutting surface, the swelling marks were the most apparent. It implied the swelling effect concentrated at the bottommost of cutting profile, the direction of material recovery was located at bottom area and the solidified material was expanded upward which is a kind of deep swelling as mentioned in the previous section. On the other hand, the side swelling was appeared in the groove side, the side surfaces of the cutting groove showed raised and uneven, even some cracks were appeared on the groove edge. it signified the bur formation and material recovery were localized and appeared at cutting edge sidelong. For the same cutting condition of MFS, it demonstrated smooth and unclear swelling marks, the bottom surface of cutting groove showed horizontal lamella vein surface texture with a few vertical swelling marks suggesting smooth and small level of deep swelling. Also, the groove side showed straight and had nearly no crack in comparison to the NMFS showing reduction of side swelling under the magnetic field influence.

For the width of cut groove, the MFS was 230μm while that of NMFS was 158μm; With the assigned cutting width 220μm, the cutting width error of MFS counted for only 4.5% which was smaller than that of NMFS 28.2%. The side swelling introduced the larger volume of material at the groove side and therefore the groove width in NMFS became smaller than the assigned one. Side swelling of machined groove was highly suppressed under the magnetic influence which was reflected by the accuracy of groove width generated in presence of magnetic field.

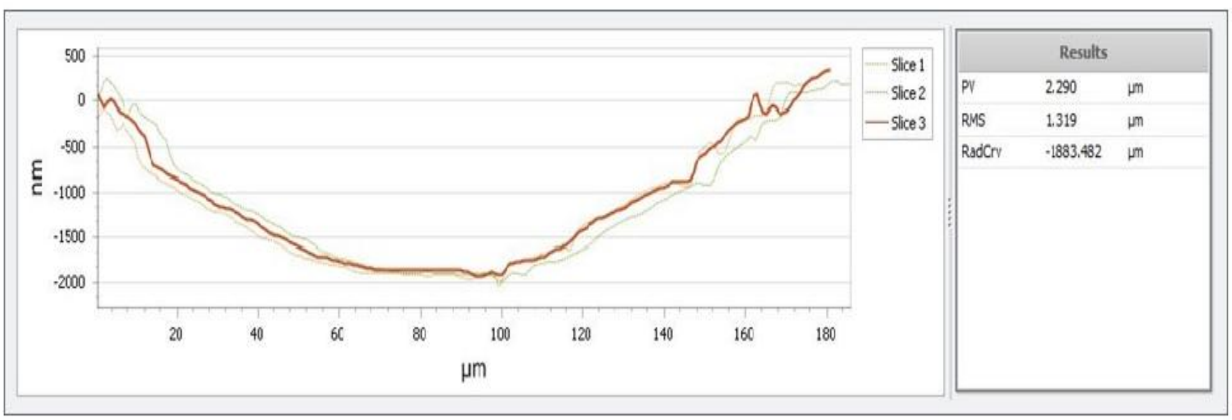



Figures 3. The micrographs of cutting groove of (a) MFS and (b) NMFS.

The groove profiles of NMFS and MFS are shown in Figures 4 (a-b), the depth of cut and radius of curvature of cutting profile of MFS were about 2.96μm and 1.513 (RadCrV in the Figures 4(a-b)) respectively which were near to the assigned depth of cut 3μm and the diamond tool radius 1.514; the cutting edge of MFS showed smooth radius curve without wavy and vibration characteristics. Adversely, due to the dominant of material swelling effect, the materials were expanded after a diamond cutting, ragged and crude profile was displayed in the surface of NMFS, the shape of cutting profile of NMFS was even distorted which deviated largely from the actual tool shape; Moreover, its depth of cut and the radius of curvature of cutting profile were 1.9μm and 1.883, indicating a significance of deep swelling on the machined surface, causing greatly stray from the assigned parameters.



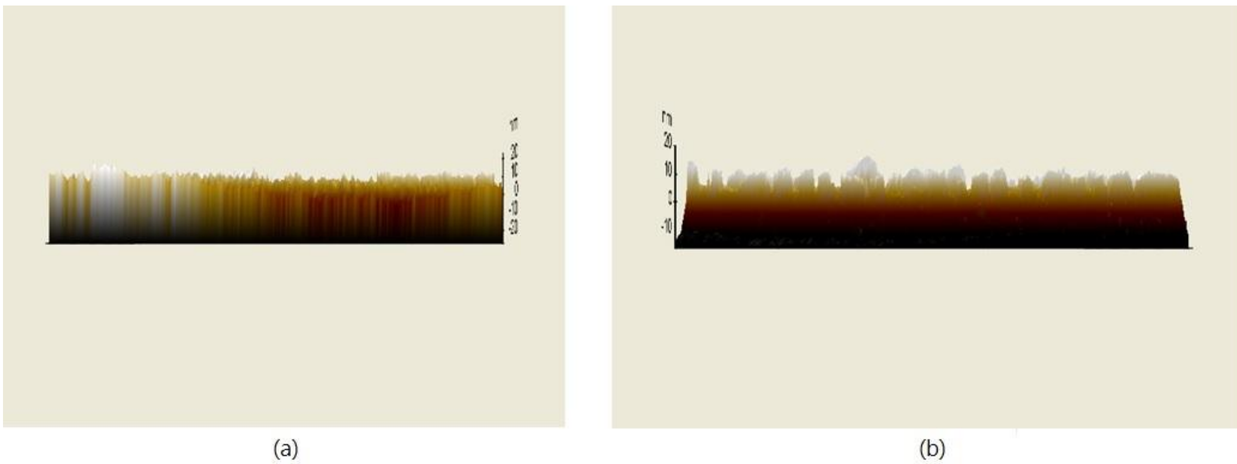

(a)




(b)

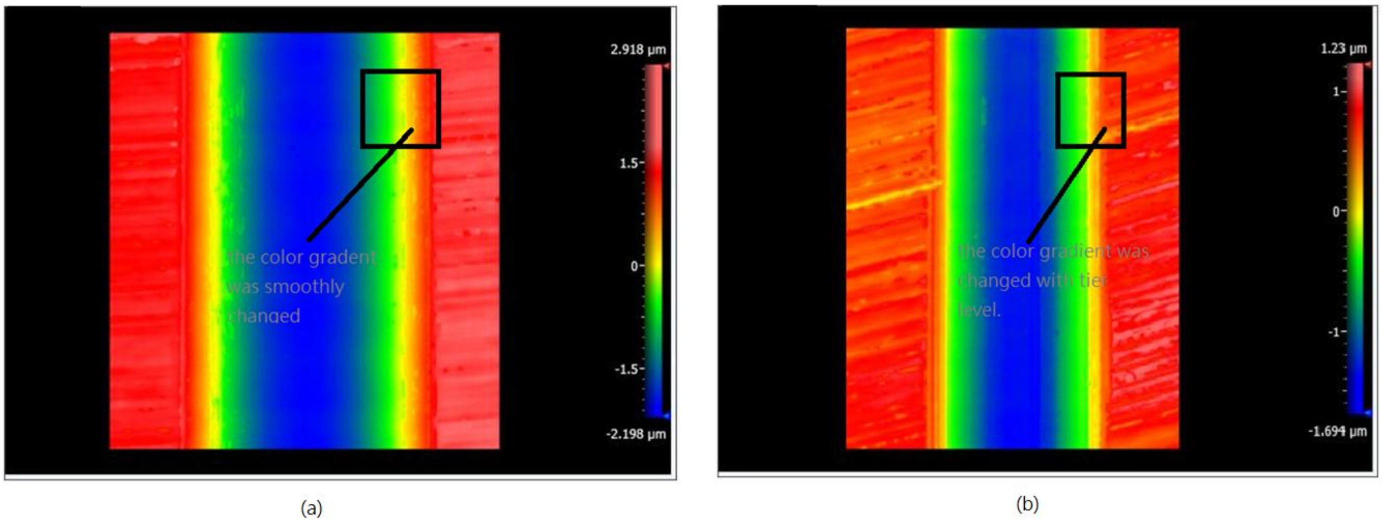
Figure 4. The cutting profiles of cutting grooves of (a)MFS and (b) NMFS

The burs caused by side material swelling are analysed by Atomic-force microscopies (AFM) as shown in Figures 5 (a-b), which they captured the figures of groove side area. The comparison of AFM between NMFS and MFS showed that less Poisson burs was formed for the latter. MFS illustrated a manifestly smaller bur size and shorter bur height in comparison to that of NMFS. The width of uplift materials at the groove side of NMFS was larger and the burs was showed separately with obvious crests.



Figures 5. AFMs of burs formation at the groove side of (a) MFS and (b) NMFS

More supporting results of the enhancement of form accuracy and surface finishing of machined groove in presence of magnetic field are shown in Figures 6-8. Figures 6 show the surface roughness of grooves in the plane view, MFS showed a relatively less radical color change of surface roughness at two groove sides than NMFS, which suggested the small different of bur height and distance between every bur along the cutting side, it implied the minimization of side material swelling under magnetic field influence. In Figures 7, it shows the bottom surface roughness of MFS which was only 15nm, it was contrary to that of NMFS which the surface roughness was 36.58nm, the result is consistent to the previous discussion, stating a significant suppression of deep swelling in presence of magnetic field. Figures 8 show the histograms of groove bottom surface of both MFS and NMFS, X axis of histogram refers to the height of machined surface. The histogram of MFS illustrated that over 1000 pixels was located at 0nm of x axis with less dispersion shape, it is in contrast to NMFS samples that only about 250 pixels was located at 0nm of x axis with highly scattered pattern. The higher concentration of pixel at 0nm for MFS in the histogram indicated that the higher proportion of measured data point for the surface height is relatively zero, revealing that MFS consisted smooth bottom surface and deep material swelling was highly restricted in a presence of magnetic field.




Figures 6. The plane views of surface roughness of (a) MFS and (b) NMFS.

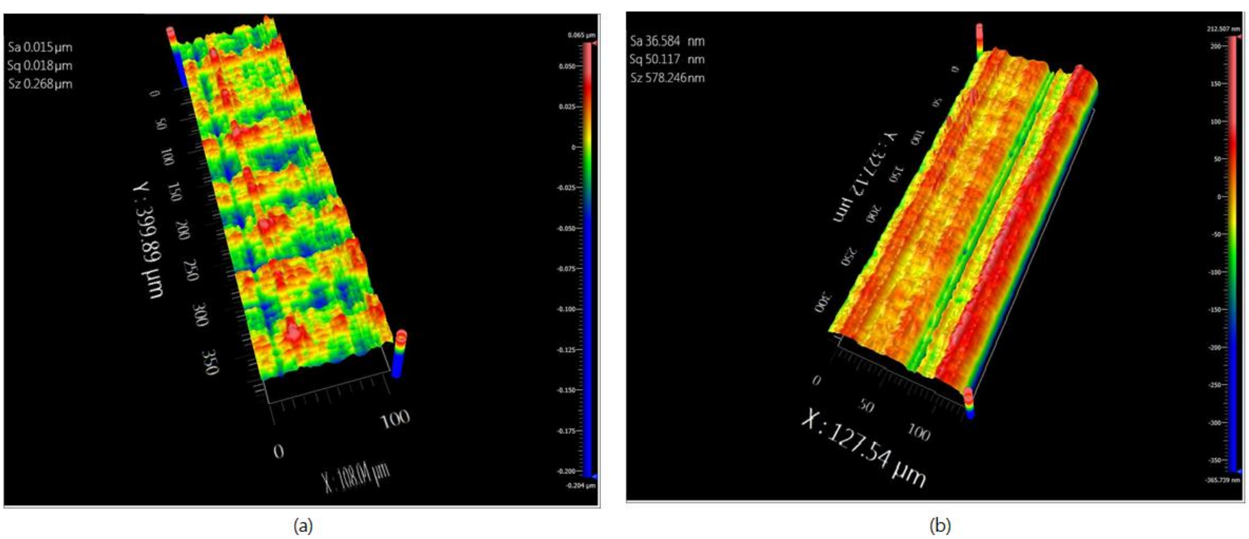
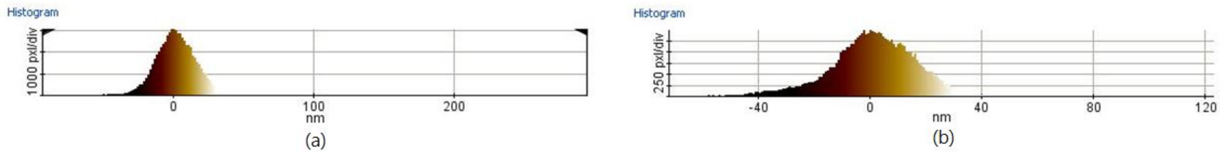



Figure 7. The surface roughness of bottom surface of (a) MFS -15nm and (b) NMFS – 36.58nm




Figures 8. The Histograms of bottom surface of (a) MFS and (b) NMFS.

## 5. Conclusion

In our proposed study, the problematic material swelling/ recovery, which is unavoidably occurred in UPM, was minimized using the magnetic field influence. UPM of titanium alloys take advantages of the proposed machining technique by achieving excellent surface roughness and form accuracy. The accuracy of cutting width, depth of cut and cutting radius of cutting groove were improved significantly under the magnetic field influence, their values in term of absolute difference and percentage errors are summarized in Table 2 and Table 3. In absence of magnetic field, the depth of cut, cutting width and profile radius were 1.9 μm, 158 μm and 1.883 respectively, while in presence of magnetic field, the respective measurements improved to 2.96µm, 192µm and 1.513. Noting that the sample in absence of magnetic field constituted almost 25-37 percent percentage errors between designed and actual results for all of the form accuracy indicators, while the magnetic field assistance achieved a under 4 percent for all of these.

The application can be further extended to other medical alloys as long as their magnetic susceptibility are positive. The potential alloys are nickel titanium alloys as they have elastic behavior dominantly. Furthermore, the proposed study does not utilize complicated pre-treatments and equipment, we simply employed extra two permanent magnets with only 0.02T magnetic field strength in the diamond cutting process to solve the material swelling/ recovery problems. The small size of magnets enable them to be adjusted freely inside UPM machine which it overcomes the problem of inadequate space of UPM machines, the technique can contribute to high precision products in the future.

Table 2. The designed machining parameters and experimental results of NMF and MF samples

| | Designed parameters (DP) | Experimental results (ER) | Experimental results of |
|---|---|---|---|

| | | of NMF | MF |
|---|---|---|---|
| Depth of Cut (μm) | 3 | 1.9 | 2.9 |
| Cutting Width (μm) | 220 | 158 | 230 |
| Cutting Radius | 1.514 | 1.883 | 1.513 |
| Bottom Surface Roughness(nm) | - | 36.58 | 15 |

Table 3. The absolute differences and relative percentage error between the designed parameters and experimental results of MFS and NMFS

| | MF | | | NMF | | |
|---|---|---|---|---|---|---|
| | Depth of Cut | Cutting Width | Cutting Radius | Depth of Cut | Cutting Width | Cutting Radius |
| Absolute differences between the designed parameters and experimental results | 0.1μm | 10μm | 0.001 | 1.1μm | 62μm | 0.369 |
| Percentage error (%) | 3.33 | 4.5 | 0.07 | 36.7 | 28.2 | 36.9 |

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