https://doi.org/10.1016/j.jmatprotec.2021.117429

Theoretical and experimental investigations of magnetic field assisted ultra-precision machining of titanium alloys

Ahmed K. Khalil[a,b], **W.S. Yip**[a], **S.To**[a,*]

[a] State Key Laboratory in Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China

[b] Production Engineering Department, Faculty of Engineering, Helwan University, Helwan, Cairo, Egypt

*Corresponding email: sandy.to@polyu.edu.hk (S. To)

Abstract

Although titanium (Ti) alloys possess unique properties that allow them to compete with many other materials in advanced industries such as aerospace, marine and biomedical, they have poor machining performances. The primary objective of this study is to investigate the distribution of magnetic field intensity at the cutting environment in single-point diamond turning (SPDT) of Ti–6Al–4V alloy and its influence on the machining performances, with the goal of achieving the desired machining conditions of magnetic field assisted ultra-precision machining, especially magnetic field intensity and the corresponding machining parameters, and to enhance the machinability of Ti–6Al–4V alloy. In this study, magnetic field-assisted machining (MFAM) system was designed and coupled with ultra-precision machining (UPM) using single-point diamond turning for increasing the machinability and improving the surface quality of Ti6Al4V alloy machined parts. The finite element method (FEM) was developed to demonstrate the influences of the generated magnetic field on the machining processes. The Experimental results showed the capability of magnetic field assistance to enhance the machining performance of Ti–6Al–4V alloy. These findings provided strong evidence that a magnetic field has the ability to extend cutting tool life, additionally, MFAM achieved the lowest value of surface roughness, representing a 33 percent improvement in surface roughness. This research contributes to the support of the optimum MFAM by FEM and the achievement

of high-quality machined Ti alloys in UPM for similar research works, as demonstrated by the experimental results.

Keywords: Magnetic field; Ultra-precision machining; Titanium alloys; Surface integrity; Single point diamond turning

1. Introduction

Titanium Alloys (Ti6Al4V) have special advantages like considerable wear resistance and are not reactive to the human body. Based on these properties, the utilizing of these materials could add a significant contribution to the biomedical industries. They possess excellent mechanical properties among which a high strength-to-weight ratio, heat resistance and extraordinary corrosion resistance, which makes them suitable for use in the aerospace, marine, power generation, and offshore industries (Maurotto et al. 2013). However, titanium alloys are classed as hard materials because of their low thermal conductivity at elevated temperature which causes negative effects on the machinability of the materials. Poor thermal conductivity of titanium alloys decreases the heat transfer outside the cutting area during machining. Hence the dissipation of the generated heat from the cutting zone is low. The existence of localized heat at the cutting tool/workpiece interface decreases the tool life and leads to tool wear, which subsequently worsens the surface finish and surface integrity of the workpiece (Arrazola et al. 2009). Low surface integrity results mostly from machining hard-to-cut materials, which also affects the performance of the cutting process; hence the need to develop ways to maintain high surface integrity when cutting hard materials (Mir et al. 2016).

Many researchers focused on studying the cutting parameters and their effects on the cutting process, Hou et al. (2018)implemented a multi-step cutting technique on Ti6Al4V alloy and studied the effects of the cutting parameters on the surface quality, they obtained the optimal cutting conditions for achieving high surface quality in both rough and semi-finishing processes. Ruibin and Wu (2016) investigated the best fit of cutting parameters and concluded that a low feed rate and small cutting depth with a relatively high cutting speed should be implemented to obtain the highest cutting performance of titanium alloys in single point diamond turning (SPDT). Liang and Liu (2017) provided experimental data by studying the effect of tool flank wear on the surface quality of Ti6Al4V during orthogonal cutting experiments. However, the study of the cutting parameters and their impacts on the surface quality is complicated and is related to several factors, especially the cutting tool condition, cutting forces, and chip formation mechanisms. The factors involved in the cutting process of Ti6Al4V are complicated, interconnected, and not independent so that it is difficult to study an influence from a single factor (Yip et al. 2020). One of the reasons leading to low surface integrity is the localized heat-induced between the workpiece and the cutting tool interface, which leads to generating excessive heat in the cutting zone. To solve this problem, some researchers applied various lubricant techniques such as minimum quantity lubricant (QIN et al. 2012). Others applied cryogenic coolant (Bermingham et al. 2011). Water vapor or flood cooling, as well as high-pressure cooling, was also applied, which reduced the cutting temperature and surface roughness.

However, all these techniques pose potential hazards to the environment and the operator. Several studies implemented new cutting tools made of advanced material, which relatively improved the machining process (Yoshiak et al. 2015). Da Silva et al. (2016) demonstrated the use of different cutting tool materials such as carbides tool, ceramics boron nitride (CBN) and polycrystalline diamond (PCD) tools and proved the effectiveness of PCD over carbide and CBN tools, still encounter difficulties when cutting materials like titanium alloys, especially when machining at high cutting speeds, due to the occurrence of tool wear leading to low surface integrity. The literature works reveal that many methods have been applied to improve the cutting performance of titanium alloys. with some having shown machining improvement either through optimization of cutting parameters, or by applying lubricants and means of coolants to the cutting process aimed at minimizing temperature and friction between the tool and workpiece interface or by avoiding confinement of heat in the cutting zone, or by implementing new cutting tool materials to achieve better surface quality and less tool wear. The recent studies have focused on bringing physical theories to the manufacturing operations to improve the cutting performance of difficult to cut materials, which include pre-treatment processes (Zhu et al. 2009), and magnetic fields (Yip and To 2017b). Engaging physical theories in the manufacturing processes included the electro-pulsing treatment (EPT) that aims to change the mechanical properties of the work material by lowering the yielding stress after EPT to achieve smooth plastic deformation. EPT has been applied to ultra-precision machining. Lou and Wu (2017) conducted ultra-precision machining experiments on Ti6Al4V before and after EPT and proved the effectiveness of EPT by showing the results of the surface roughness and cutting forces before and after EPT. However, since the EPT lowered the mechanical strength of the work material, its use is limited to non-heavy-duty applications. Several researchers studied the effect of a magnetic field on cutting processes with the aim of improving cutting performance (Lin and Lee 2008). Bruijn et al (CIRP and 1978 n.d.) improved the debris removal process which is a point of interest in electrical discharge machining (EDM), by applying an external magnetic field around the cutting area that made uses of the magnetic force to achieve high cutting quality. Teimouri and Baseri (2014) optimized the use of the magnetic field to improve the debris removal from the cutting gap in EDM. Kim et al. (1997) changed the path of the electrolyte through the migration of ions by applying a magnetic field to the electrolytic finishing process resulting in improved surface finish and an effective finishing process.

Several studies have focused on the magnetic field abrasive finishing method (Wu et al. 2016), in this method, the material removal is based on the relative motion between the abrasive particles and the work material surface during the application of an external magnetic field (Jayswal et al. 2005); this approach enhances the cutting performance in the finishing processes whether targeting outer or internal surfaces (Guo et al. 2017). Other studies linked the magnetic field to the finishing processes such as polishing, which used the magnetic field to produce parts with a high surface quality (C. Wang et al. 2020). D. Wang et al.(2004) applied a magnetic field to the finishing process and studied the impact of the magnetic field intensity and the working gaps on the surface roughness of the workpiece which were found to be dependent factors. Suzuki et al. (2014) utilized magnetic field-assisted polishing to finish a diffractive optical element (DOE) lens leading to low surface roughness. Wu et al. (2015) proposed a new ultra-precision magnetic abrasive finishing (MAF) process which significantly decreased the surface roughness of SUS304 stainless steel samples using a low frequency alternating magnetic field. El Mansori et al.(2003) studied the effect of an external electromotive force (EMF) by applying a magnetic field to the machining of mild steel while considering the cutting speed, the results shown low flank wear of the HSS tool leading to extended tool life. Fan et al. (2019) developed a magnetic field-assisted finishing (MFAF) tool for generating a magnetic field and used it on Ti-6Al-4V alloy that significantly improved the surface quality.

All these studies and more prove the feasibility of applying a magnetic field to the manufacturing process, as well as the effectiveness of this hybrid method and its ability to improve overall cutting performance. In ultra-precision machining(UPM), Yip and To (2017c) installed a magnetic field system and made use of a single-point diamond turning machine to achieve a high cutting performance of Ti6Al4V alloy. Yip and To (2019) achieved high surface quality as well as reducing the minimum cutting thickness of Ti6Al4V alloy in ultra-precision diamond cutting (UPDC) by using a magnetic field. Yip and To (2017a) generated a magnetic field system and made use of the eddy current damping effect to suppress the cutting force variation in single point diamond turning (SPDT) and achieved a reduction of tool wear. From a review of relevant literature, it is apparent that there is a need to improve the machinability of hard-to-cut materials like Ti6Al4V alloy. Previous studies have emphasized the feasibility of using a magnetic field to improve the performance of cutting operations and single point diamond turning (SPDT). The main goal and contribution of this research are to apply a hybrid ultra-precision machining using a magnetic field since the methods mentioned in the previous studies have not achieved the highest machining quality as titanium alloys have poor machinability, also most of the studies relied on traditional methods to reach a smooth cutting process but without achieving the preservation of the cutting tool, and since the machining of titanium alloys is still in the stage of research and development, we need to bring developed methods to address the titanium machining difficulties. This study brought physical theories and linked them to the UPM to get to a proper performance of hard-to-cut materials in SPDT.

There is a research need to study the process of machining titanium alloy and study the challenges it faces like low thermal conductivity of titanium alloys, the heat induced during cutting, high tool wear rate and poor machined surface quality , so we need to overcome the difficulties of cutting titanium alloy as there is an increasing industry demand for it. In this study, we fill up the research gap by studying the influences of magnetic field on ultra-precision machining, which provides the feasibility and allow to improve the cutting performance and produce parts of high surface quality made with titanium alloys. Accordingly, this study coupled ultra-precision turning technology with magnetic field-assisted machining (MFAM) to improve the machinability of Ti6Al4v using a single-point diamond cutting tool. One of the advantages of using this method is the low cost where the hybrid process depends on the use of a simple magnet and also is environmentally friendly and harmless to the technician. The results demonstrated that MFAM has remarkable improvements where the cutting tool wear was reduced, and the surface roughness of the samples reached 13.33 nm. The experimental results show the effectiveness of the magnetic field on the machinability of titanium alloys in ultra-precision machining, which enables to obtain parts with high-quality surfaces.

2. Methodology

2.1 Working principle of magnetic field-assisted machining (MFAM):

The force that acts on an object enclosed in a magnetic field depends on the properties of both fields and the target object (Furlani et al. 2006). Using the "effective" dipole moment method (O'Handley 1999), in which a magnetic object is replaced by an "equivalent" point dipole with a moment m, the magnetic force that acts on a magnetic microstructure can be modeled, the force acting on the dipole is defined by Eq. (1):

$$F_m = \mu_f(m_{p_{eff}} . \nabla)\, B \tag{1}$$

Where μ_f is the magnetic permeability of the medium, $m_{p_{eff}}$ is the object's "effective" dipole moment, and B is the magnetic field generated at the center of the target object by an external source, where the dipole of the equivalent point is located. The dipole moment m is dependent on the volume and magnetic characteristics of the object and can be described as:

$$m=MV \tag{2}$$

where M and V are the magnetization and the volume of the dipole, respectively. As mentioned, the force exerted on such dipole alters the features of the magnetic field sources. It also depends on the distance between the source and the target object. By considering a permanent magnet as in our study, the magnetic field density at the cutting zone can be defined in Eq. (3):

$$B = \frac{\mu_0}{4\Pi}\left(\frac{3\,(m.r)\,r}{|r|^5} - \frac{m}{|r|^3}\right) \tag{3}$$

where r is the distance vector between the field source and the object.

Fig.1 shows the setup of the MFAM system. The presence of the magnetic field during the turning machining process facilitates the transit of the chips, avoiding the formation of the built-up edge on the cutting tool by averting the sticking of the chips on the tool edge. Also, the easy egression of the formed chips prevents heat accumulation in the cutting zone which is important for the success of the machining process.

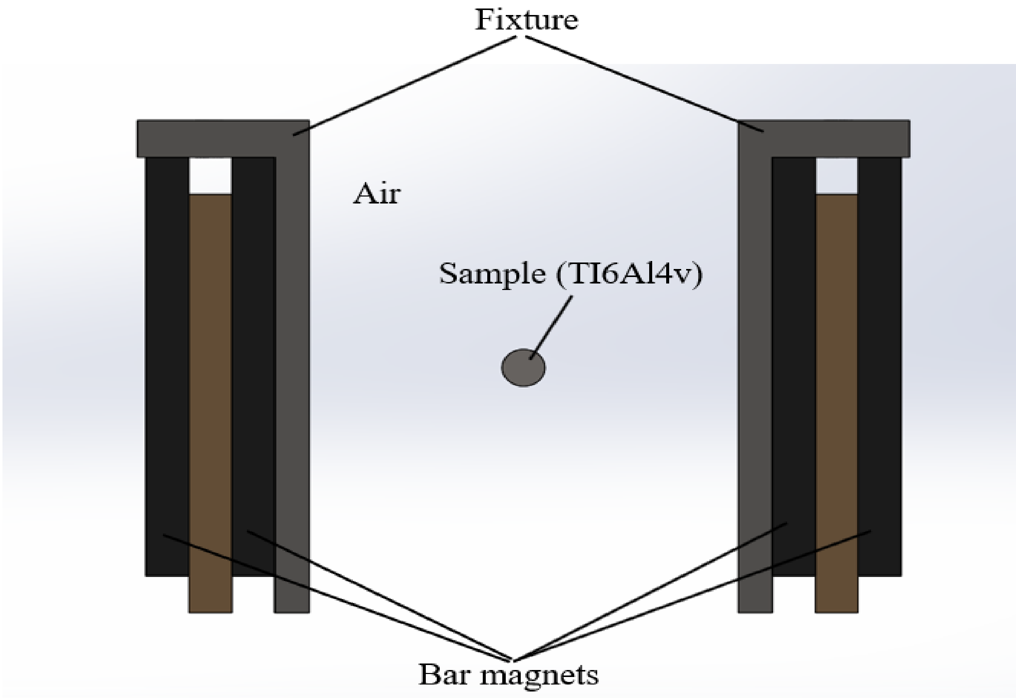


Fig. 1. Magnetic field assisted machining (MFAM) system.

2.2 Finite element analysis (FEA) of the magnetic field distribution:

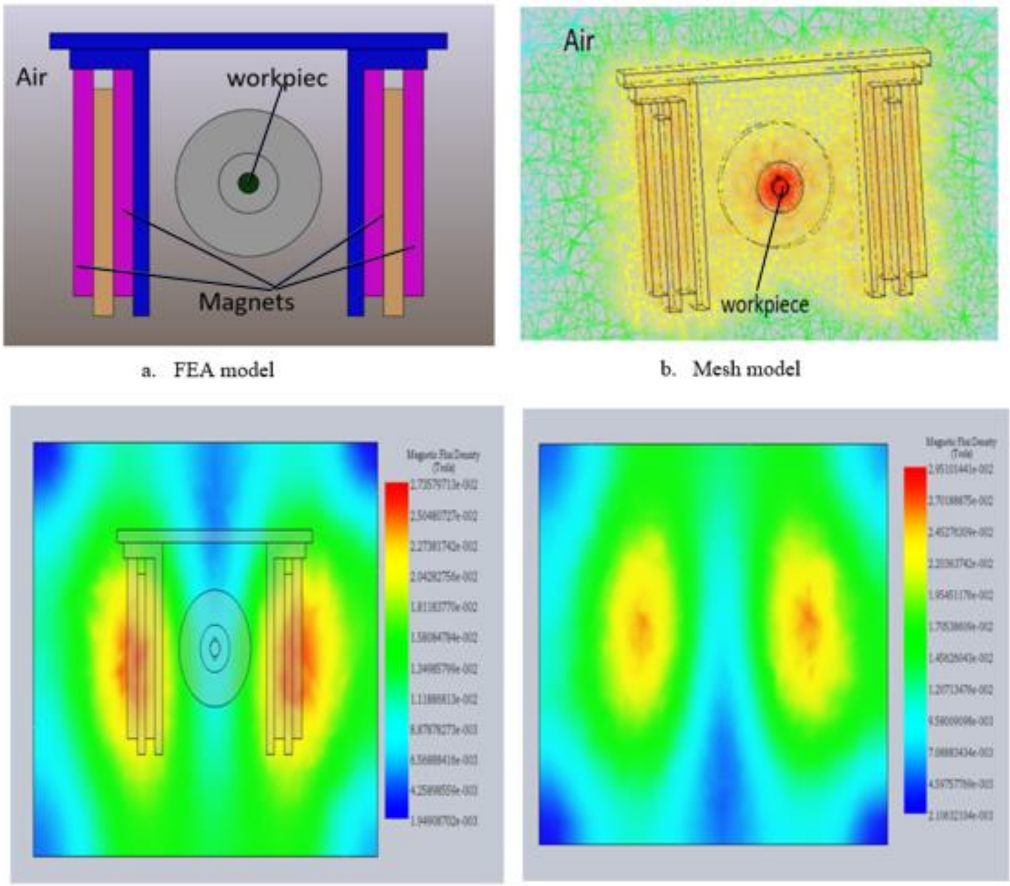
To further explain the application of the magnetic field system on the cutting experiments, Fig. 2 shows the results of the FEA modeling and magnetic field simulation in terms of magnetic flux density distribution, the finite element method (FEM) presents the effect of the permanent magnets device and the simulation of the magnetic field system using a magnet and electromagnetic software(EMS), EMS is a simulation tool capable of computing magnetic flux and the corresponding magnetic field using accurate finite element modeling and meshing techniques. The model consists of four N42 neodymium magnets, the steel fixture for holding the magnets and an aluminum fixture as a chuck for fixing the workpiece. Since the space around the magnet system is important, the geometry of this region was also modeled, and the mesh was controlled by selecting element sizes of 5mm and 50 mesh elements per diagonal of each solid body. According to Maxwell's magnetic field law, the magnetic flux is described from Eq. (4):

$$\emptyset = BAcos\Theta \quad (4)$$

Where:

Ø=magnetic flux,   B=magnetic field, A=area

and ϴ=the angle between a perpendicular vector to the area(A) and the magnetic field(B).



a. FEA model

b. Mesh model

c. Front view of the simulation results of magnetic flux density distribution

d. Plan section view of the simulation results of magnetic flux density distribution.

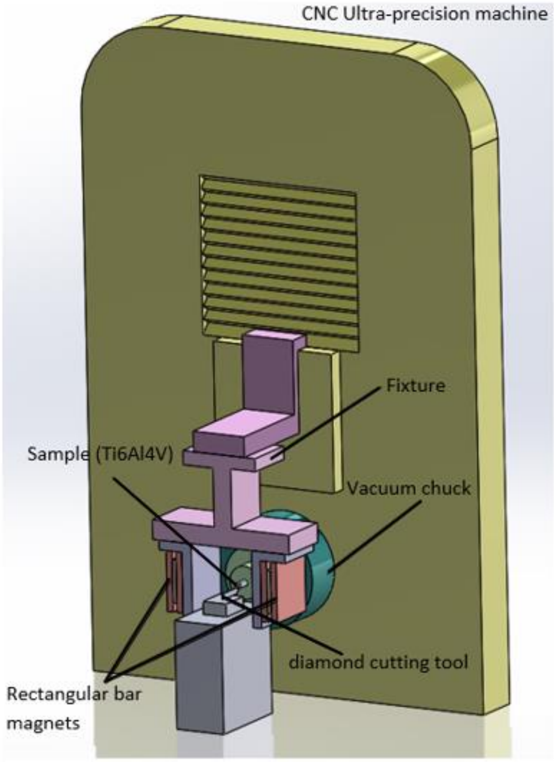
Fig. 2.Finite element analysis (FEA) of the magnetic field distribution.

3. Experiments

The experimental setup is shown in Fig.3. The workpiece material was Ti6Al4V alloy, the chemical composition of which is shown in Table 1. The workpiece was cylindrical with a diameter and length of 15mm and 25mm respectively, the cutting tool used was a single point diamond tool and the radius and length of the diamond tool were: 0.773mm and 10.476mm respectively. The source of the magnetic field was four permanent magnets, each one having the same material of neodymium and dimensions of 100*45*8 mm, fixed to a custom-made frame of steel whose primary purpose was to hold the magnet system and control the position of the magnetic bars. The workpiece was fixed to the main spindle through an aluminum fixture. A Moore Nano-tech 350FG (4 axis ultra-precision turning machine) was used as the machine tool for the diamond cutting experiments. The machining experiments were divided into two groups, the first one was conventional diamond machining and the second one was MFAM, the magnetic field was applied with two levels of intensity 0.01T and 0.02T. The cutting parameters were set as cutting depth: 4μm, feed rate: 8mm/min, rotational speed: 1200rpm, all of which remained constant throughout the cutting processes. During the experiments, the formed chips were collected and inspected under a scanning electron microscope (SEM). After conducting the experiments, the samples were investigated by a high-precision optical component, Zygo, to measure surface roughness and explore the surface quality. After cleaning the edges with hydro fluoride acid, the diamond tool edges were also explored by SEM to observe the rake and flank faces.

Table 1. The composition of Ti6Al4V Samples used in the experiments

Element composition (%)						
Al (Aluminum)	V (Vanadium)	Fe (Iron)	N (Nitrogen)	O (Oxygen)	H (Hydrogen)	C (Carbon)
6	4	0.3	0.05	0.2	0.012	0.1



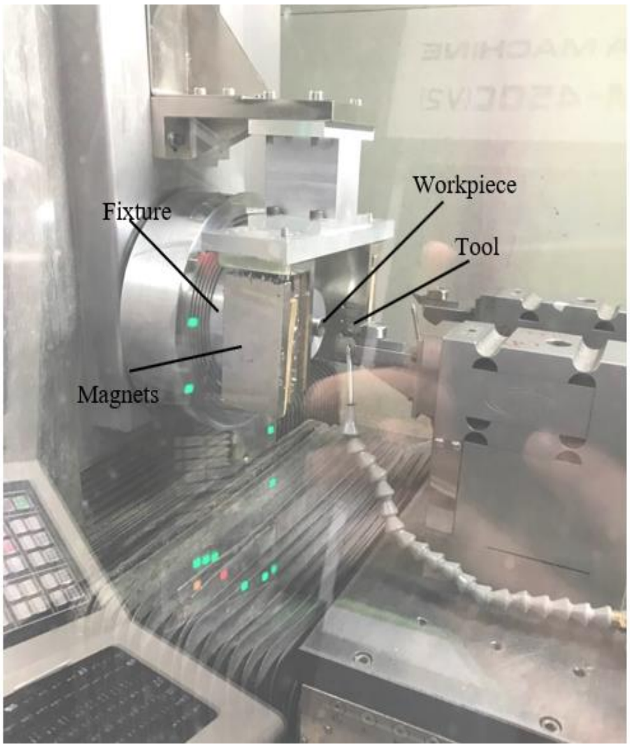


Fig. 3. Experimental setup of the magnetic field assisted machining (MFAM)

4. Results and discussion

4.1 Influence of magnetic field-assisted machining (MFAM) on the cutting tool:

Since the condition of the diamond tool is the crucial factor for estimating the quality level of machined parts, observing the cutting tool wear is very important in the cutting processes. One of the problems arising during the machining of titanium alloys is to observe the online cutting temperature. Titanium alloys have low thermal conductivity and so the temperature rises when machining at high cutting speeds, the tool is affected by the excess heat generation due to the poor dissipation of the heat outside the cutting zone (Bordin et al. 2015). The attached materials on the cutting edge/workpiece interface due to excessive heat causes relative vibrations and produces wavy machined surfaces leading to low machining performance. Due to the high cutting temperature, the formed chips attach to the cutting tool causing adhesive tool wear and weldment of chips and work material (Rahim and Sasahara 2011). Adhesive tool wear is a concern of researchers when investigating tool wear mechanisms in UPM since the condition of the tool edges controls the accuracy of the dimensions and surface finish, and ultimately determines the success or failure of the machining operation. Fig.4 shows the SEM investigation of the cutting tool as shown in Fig. 4(a) on the rake face of the diamond tool, in the case of cutting under the absence of the magnetic field, the formation of adhesive wear was observed during the machining, since the formed chips attached on the cutting edge and suffered high cutting temperature without any means of cooling, the built-up edge occurred. As stated by Dearnley and Grearson (1986), adhesive wear normally forms on the rake face and the main reason for adhesion wear formation is the weldment of the chips on the cutting tool leading to the possibility of crack formation. High induced heat in the cutting zone also causes plastic deformation between the chips and tool leading to high chemical reactivity and ultimately to tool failure. The results show the existence of much more wear on the cutting edge when machining Ti6Al4V alloy in the absence of a magnetic field compared to the corresponding results shown in Fig 4b. when MFAM is applied. Fig. 4(c) shows the flank face of the cutting tool. The undesired friction between workpiece and tool clearance face causes abrasion which results in flank wear especially when the chips stick to the tool, during the continuity of the cutting of the sample and the chipping process; the new chips are accumulated with the melted titanium layer on the cutting edge down to the surface of the flank. From the results shown in Fig. 4(d), the presence of MFAM reduces the flank tool rate in comparison to that in the absence of a magnetic field. The chips accumulated between the tool and the work material accelerate the tool wear rate.

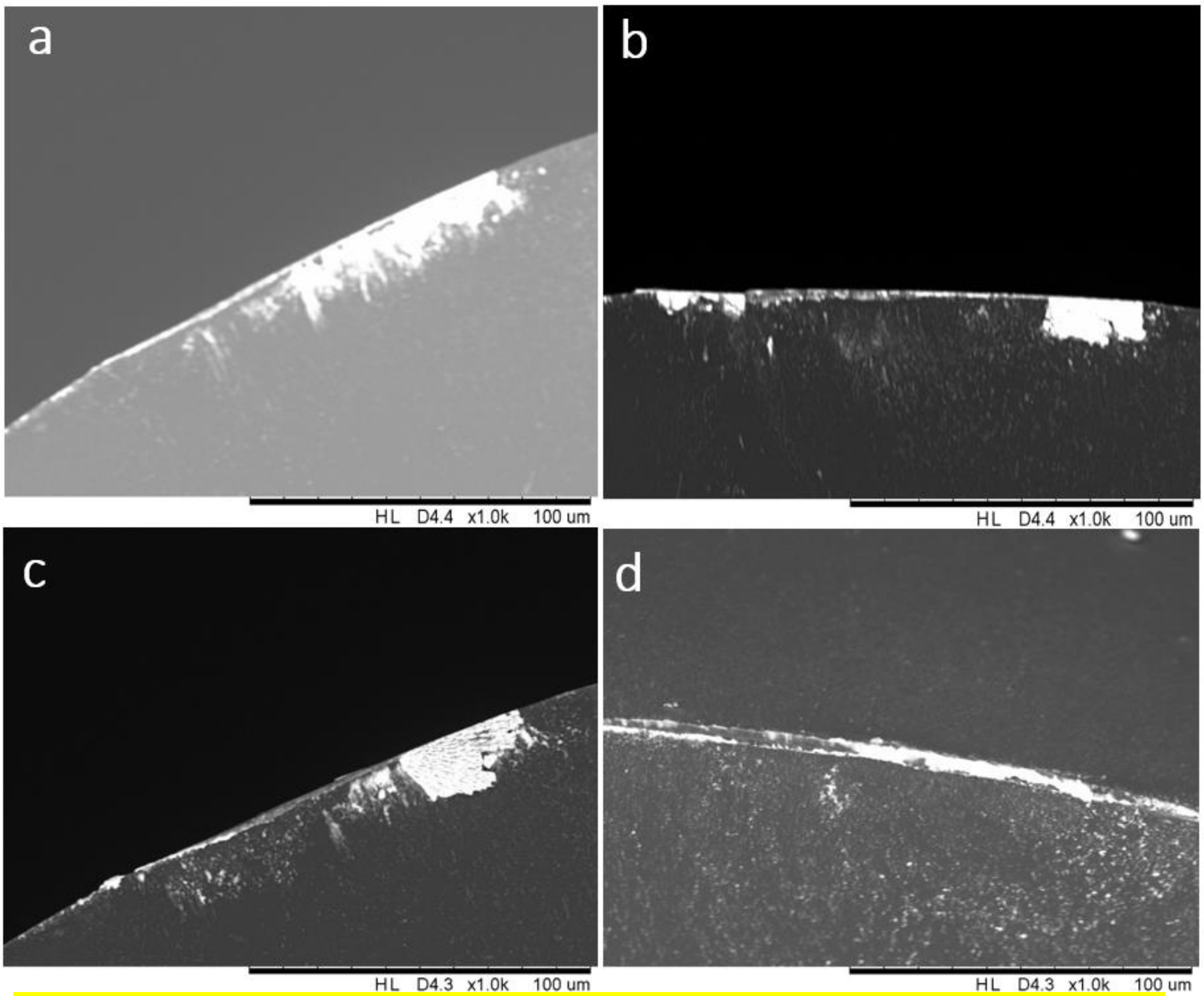


Fig. 4.SEM images of the tool: (a)tool rake face in absence of magnetic field (b) tool rake face in MFAM (c) tool flank face in absence of magnetic field and (d) tool flank face in MFAM.

4.2 Influence of magnetic field-assisted machining (MFAM) on chip formation

The chip formation in UPM is a key assessment of machining performance the state of the chips can provide significant information about the cutting, and other cutting factors like cutting force and surface roughness can also be affected by the chip formation. The process of chipping happens when the material interface deforms and suffers from a shear load, the deformation mode depends on the cutting factors, especially tool geometry and workpiece material as well as the cutting parameters. The chips were collected during machining and investigated by SEM as shown in Fig.5. Fig.5 (a) shows the SEM images of the chips formed in SPDT in the absence of the magnetic field and captured with different magnifications. The formed chips are serrated with a saw-tooth shape, which implies a low cutting performance when machining difficult-to-cut materials like titanium alloys. These chip segments stick onto the machined surface leading to low surface integrity, compared to the chips generated in MFAM. The SEM results in Fig.5(b) and Fig.5(c) show long and continuous chips with flat edges, which indicates that relatively high machining performance was achieved when applying magnetic fields with 0.01T and 0.02 T respectively.

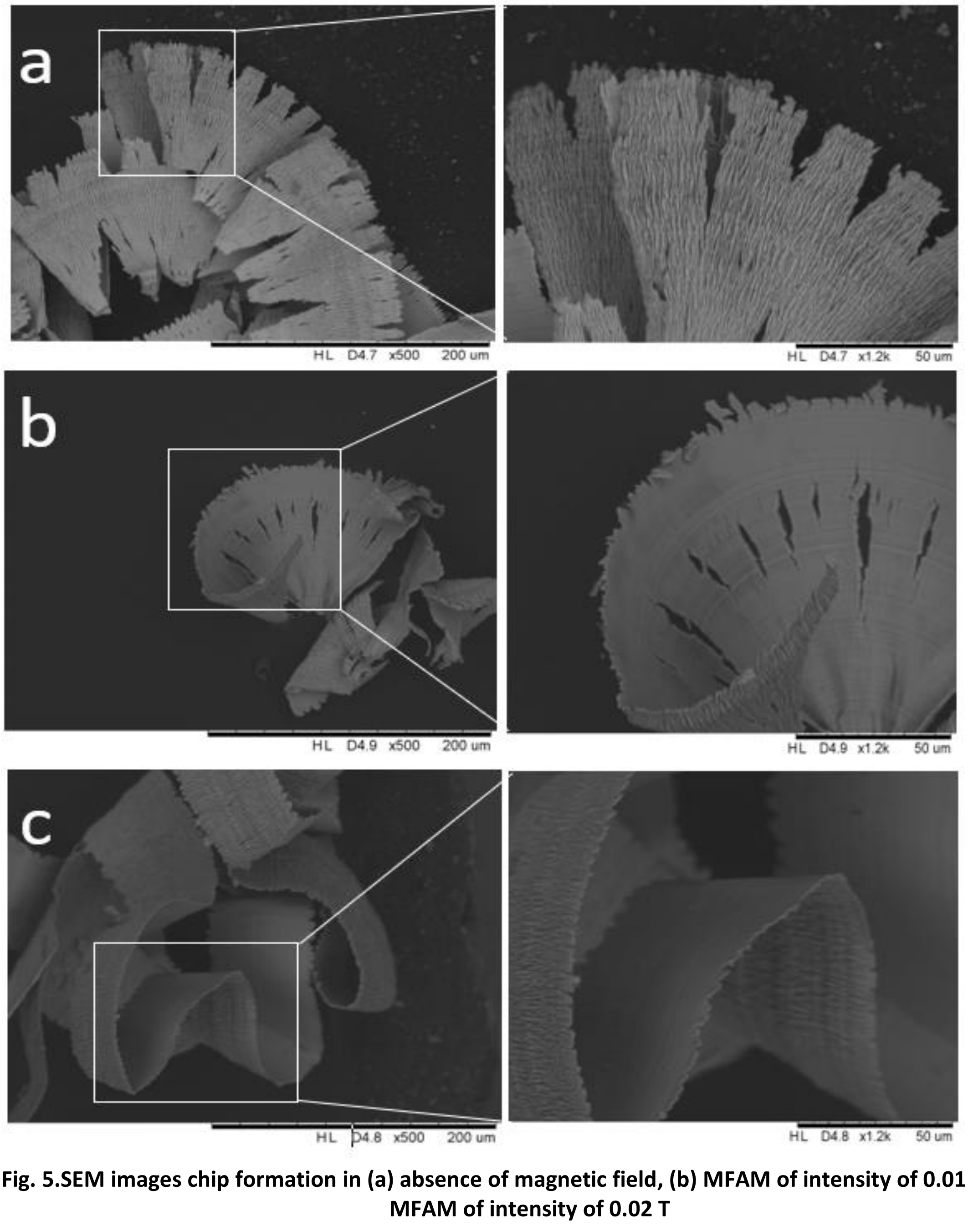


Fig. 5.SEM images chip formation in (a) absence of magnetic field, (b) MFAM of intensity of 0.01 T and (c) MFAM of intensity of 0.02 T

4.3 Influence of the magnetic field-assisted machining (MFAM) on the surface roughness:

The quality of the machined surfaces can be affected by machining factors such as spindle speed, feed rate and cutting depth. Surface integrity is also affected by cutting tool conditions such as tool material, tool geometry and tool wear rate, which impact the precise level of products. The machined surfaces of the samples were captured and investigated. Fig.6 shows the SEM images of the surface samples machined by SPDT, The sample that was machined in the absence of a magnetic field as shown in Fig 6 (a), presents relatively poor surface finishing, in which marks caused by the cutting tool can be clearly seen and the fracture of the workpiece material on the surface formed irregularities during the operation; In contrast, MFAM generated surface demonstrates a relatively flat surface indicating a smooth machining operation without any scratching by the uncut material chips and showed relatively smaller tool marks as shown in Fig.6 (b) and Fig.6(c). Since surface roughness is one of the most important assessment factors for the success of the cutting process, the values of surface roughness of both samples were measured, eight different areas were selected from each sample, the results of average surface roughness are shown in Table.2. The lowest value of surface roughness was achieved by MFAM, which represented a 33 % improvement in the surface roughness over that of the sample machined without MFAM. Also, it showed that the lower value of standard deviation for MFAM was achieved, showing the effectiveness of magnetic field on the improvement of the surface uniformity of machined surface.

Table 2. Average surface roughness of the samples

Magnetic field intensity (T)	0	0.01	0.02
Surface roughness (nm)	19.89	18.50	13.33
Standard deviation	1.88	1.66	1.63

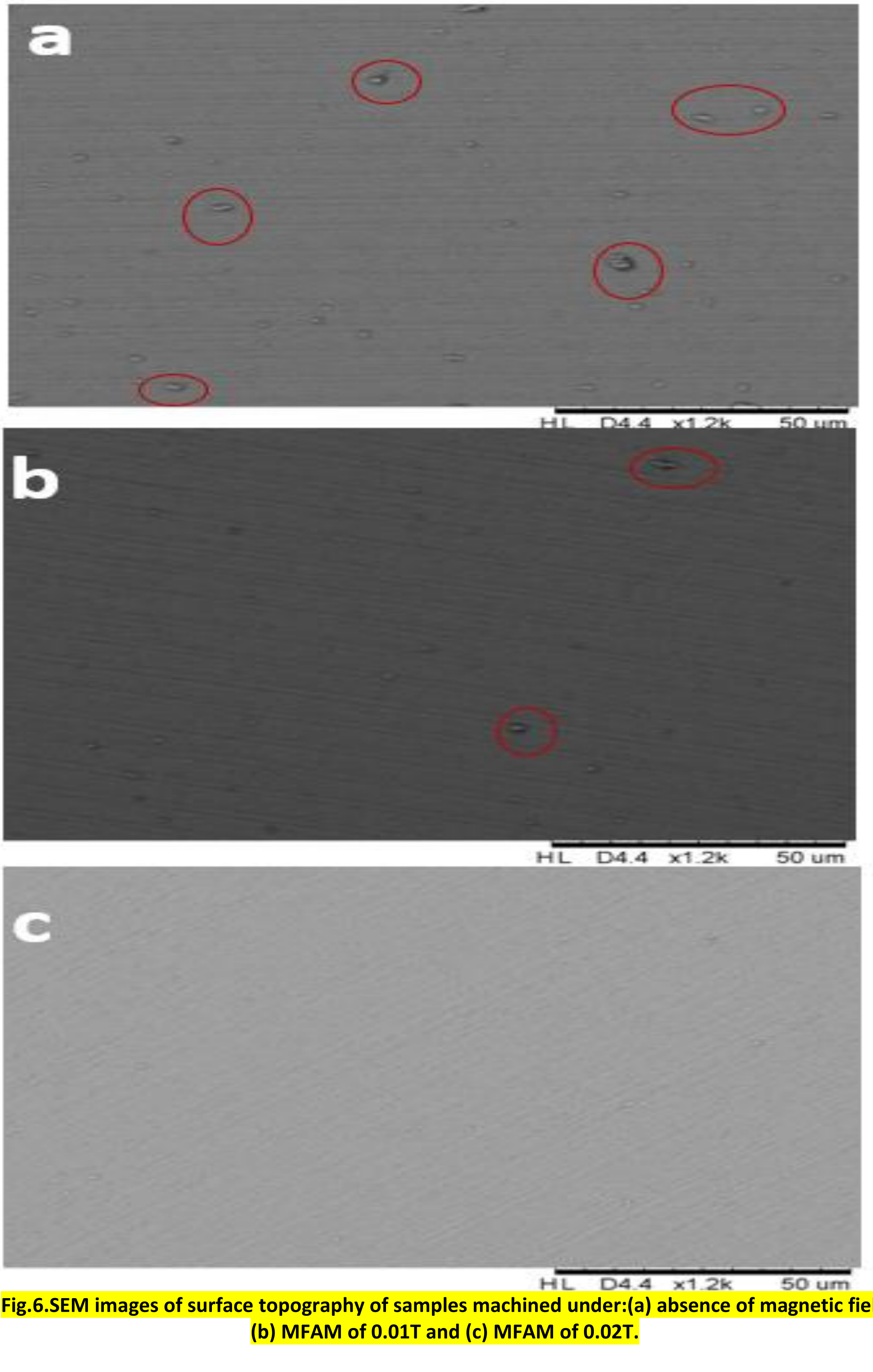


Fig.6.SEM images of surface topography of samples machined under:(a) absence of magnetic field (b) MFAM of 0.01T and (c) MFAM of 0.02T.

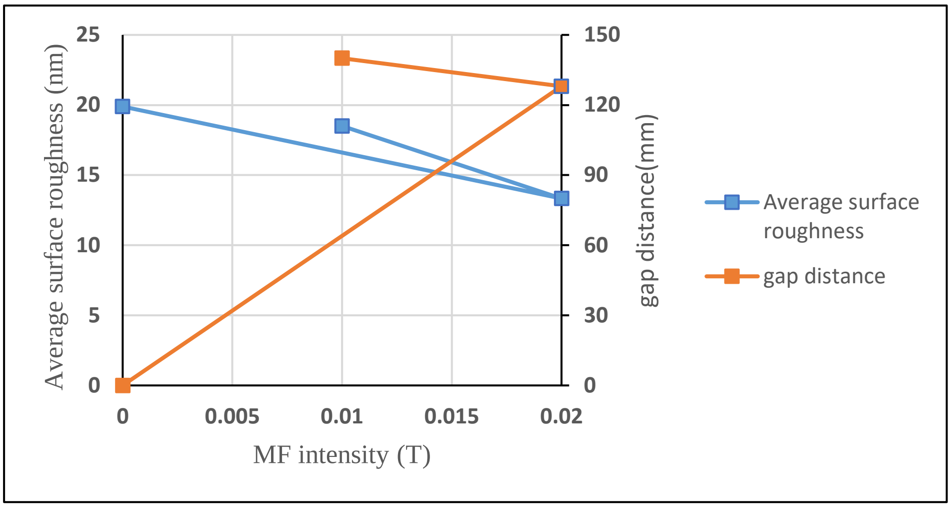


Fig.7. Average surface roughness and magnetic field intensity changing with the gap distance.

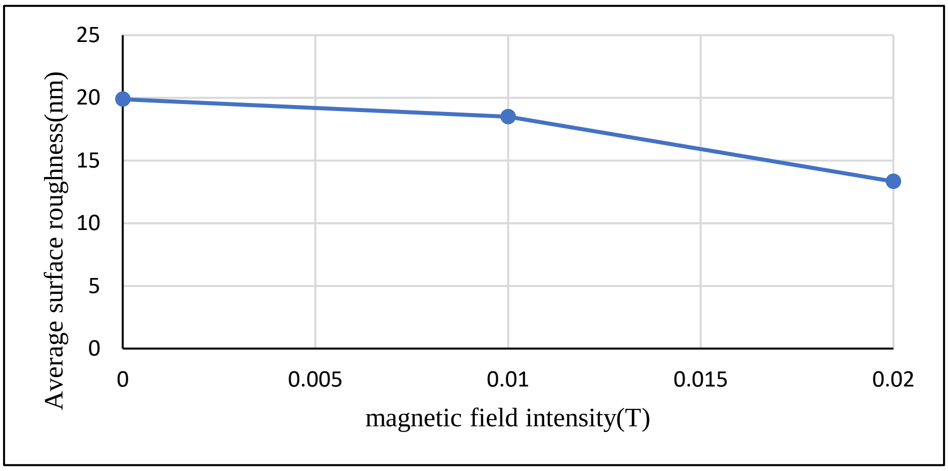


Fig.8. Magnetic field intensity Vs. Average surface roughness

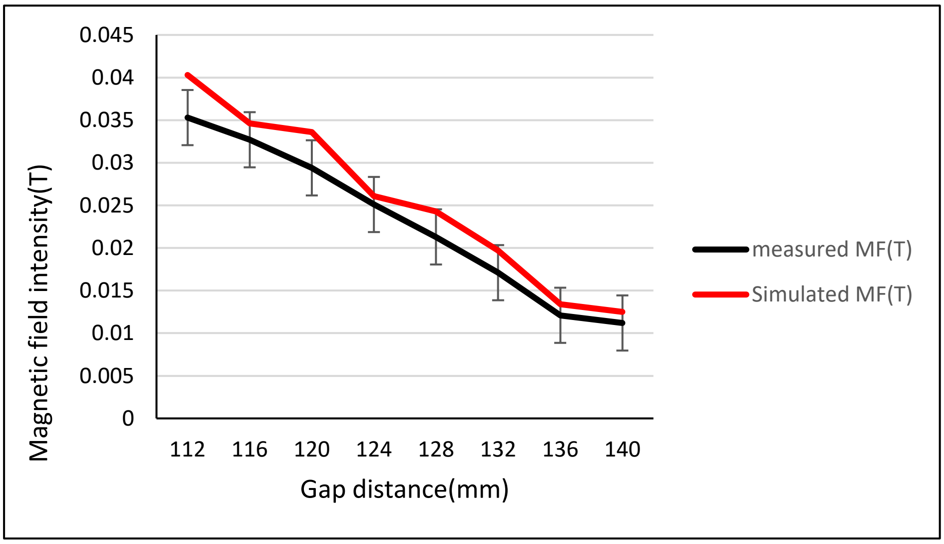


Fig.9. Distance between two magnets Vs. magnetic field intensity

4.4. Influence of the magnetic field intensity

The intensity of the magnetic field was controlled by adjusting the distance between the two magnets. Fig. 7. shows the average surface roughness and magnetic field intensity changing with the gap distance, it was found that the gab distance should be controlled properly to allow for appropriate amount of magnetic flux to cover the cutting zone and produce machined parts with high surface quality. A series of simulations and experiments with the magnets in different locations to achieve optimum magnetic field intensity for implementation of the cutting process were conducted, and the impacts of the strength of the magnetic field on the quality of the work-piece surface were studied. Fig. 8 shows the relationship between the intensity of the magnetic field and the surface roughness of the samples. It is worth noting that surface roughness decreases with the increased intensity of the magnetic field, which achieved the lowest value of surface roughness at the magnetic field intensity at 0.02 T. The reason for the increased magnetic field intensity is due to the reduction of the distance between the two magnets and the increase of the field affecting the cutting area.

To study the intensity of the magnetic field and its relation to the distance between the magnets, a series of simulation experiments were conducted by changing the distance between two magnets, as shown in Fig. 9. A parametric study was carried out and the intensity of the magnetic field was measured at different distances for comparisons with the experimental results. The simulation results were consistent with that of the experimental results, they showed that a reduced distance between the two magnets led to an increase in the intensity of the magnetic field. This explains the relation between the magnetic field intensity and the surface roughness and validates the simulation to predict the strength of the magnetic field.

It is important to understand the interactions between the parts and magnets for a good design of the magnetic field assisted diamond turning that allows us to improve the quality and exploitation of the implemented system. In most cases, the optimal parameters and specifications of the magnets are determined using experiments and attempted to reach significant values that can be used for the implementation of the process, in which the methods are considered consuming for time and resources. In this study equations and simulations were used with the finite element method (FEM) to get the essential information regarding magnets and magnetic field of the integrated magnetic system. Basically, the magnets are used to generate a permanent magnetic field, and the finite element method is utilized to predict the field strength values to avoid errors and to reach an optimal magnetic field assisted diamond turning process. The results were verified by comparing the experimental results and the simulation results obtained using finite element analysis.

5. Conclusion

In this study, the machining technology proposed provides a cutting approach that increases overall machinability and enhances the surface quality of precision components. A custom magnetic field system was designed by using permanent magnets to generate the magnetic field, the design consisted of bar magnets and steel part for mounting on the UPM. Firstly, the magnetic flux intensity was investigated by using the FEM to reach the optimized magnetic field intensity in the cutting zone and the simulation results were validated by the experimental results.

Ultra-precision machining (UPM) coupled with the magnetic field was proven to be highly effective in improving the cutting process of titanium alloys, which was validated by experimental results obtained from machining under the influences of a magnetic field. The existence of the magnetic field during cutting aided the chipping process, avoiding the built-up edge formation. And the smooth release of the chips prevented the unfavored heat accumulation in the cutting zone.

The essential machining factors of tool wear, chip formation, and surface roughness of the samples were studied. According to the experimental results, when machining under the influence of a magnetic field, the cutting tool edges of MFAM had less wear rate for both rake and flank faces in comparison with that of the tool used without MFAM. These results provided strong evidence of the capability of a magnetic field to extend cutting tool life, which consequently improves machining performance and quality of the machined product. Machining under the influences of a magnetic field formed continuous chips and achieved the minimum value of surface roughness. All the experimental results support the successful coupling of the MFAM with UPM to produce high-precision components. Moreover, the proposed FEM reveals machining environment of MFAM system especially the density of the magnetic field and magnetic flux distribution in the cutting zone, which helped to obtain the optimum magnetic field intensity in the UPM process. Further research will be conducted to study the different values of magnetic field intensity to achieve the best surface quality for Ti6Al4V.

Acknowledgment

The works described in this paper are supported partially by the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 152125/18E), the Research Committee of The Hong Kong Polytechnic University (Project code: RK2D) , State Key Laboratory of Ultra-precision Machining Technology (BBX5) and The Innovation and Technology Fund of the Government of the Hong Kong Special Administrative Region of the People's of Republic of China for providing the financial support for this research work under the Project No. ITS/246/18FX.

References

Arrazola, P. J. et al. 2009. “Machinability of Titanium Alloys (Ti6Al4V and Ti555.3).” *Journal of Materials Processing Technology* 209(5): 2223–30.

Bermingham, M. J. et al. 2011. “New Observations on Tool Life, Cutting Forces and Chip Morphology in Cryogenic Machining Ti-6Al-4V.” *International Journal of Machine Tools and Manufacture* 51(6): 500–511. http://dx.doi.org/10.1016/j.ijmachtools.2011.02.009.

Bordin, A., S. Bruschi, A. Ghiotti, and P. F. Bariani. 2015. “Analysis of Tool Wear in Cryogenic Machining of Additive Manufactured Ti6Al4V Alloy.” *Wear* 328–329: 89–99. http://dx.doi.org/10.1016/j.wear.2015.01.030.

CIRP, HE De Bruijn - Annals of the, and undefined 1978. “Effect of a Magnetic Field on the Gap Cleaning in EDM.” *ci.nii.ac.jp*. https://ci.nii.ac.jp/naid/80015098650/ (November 3, 2020).

Dearnley, P. A., and A. N. Grearson. 1986. “Evaluation of Principal Wear Mechanisms of Cemented Carbides and Ceramics Used for Machining Titanium Alloy IMI 318.” *Materials Science and Technology (United Kingdom)* 2(1): 47–58.

Fan, Zenghua et al. 2019. “Investigation of a Novel Finishing Tool in Magnetic Field Assisted Finishing for Titanium Alloy Ti-6Al-4V.” *Journal of Manufacturing Processes* 43(November 2018): 74–82. https://doi.org/10.1016/j.jmapro.2019.05.007.

Guo, Jiang, Zhien Eddie Tan, Ka Hing Au, and Kui Liu. 2017. “Experimental Investigation into the Effect of Abrasive and Force Conditions in Magnetic Field-Assisted Finishing.” *International Journal of Advanced Manufacturing Technology* 90(5–8): 1881–88.

Hou, Guanming et al. 2018. “Effect of Cutting Parameters on Surface Quality in Multi-Step

Turning of Ti-6Al-4V Titanium Alloy.” *International Journal of Advanced Manufacturing Technology* 98(5–8): 1355–65.

Jayswal, S. C., V. K. Jain, and P. M. Dixit. 2005. “Modeling and Simulation of Magnetic Abrasive Finishing Process.” *International Journal of Advanced Manufacturing Technology* 26(5–6): 477–90.

Kim, Jeong Du, Dong Xie Jin, and Min Seog Choi. 1997. “Study on the Effect of a Magnetic Field on an Electrolytic Finishing Process.” *International Journal of Machine Tools and Manufacture* 37(4): 401–8.

Liang, Xiaoliang, and Zhanqiang Liu. 2017. “Experimental Investigations on Effects of Tool Flank Wear on Surface Integrity during Orthogonal Dry Cutting of Ti-6Al-4V.” *International Journal of Advanced Manufacturing Technology* 93(5–8): 1617–26.

Lin, Yan Cherng, and Ho Shiun Lee. 2008. “Machining Characteristics of Magnetic Force-Assisted EDM.” *International Journal of Machine Tools and Manufacture* 48(11): 1179–86.

Lou, Yonggou, and Hongbing Wu. 2017. “Improving Machinability of Titanium Alloy by Electro-Pulsing Treatment in Ultra-Precision Machining.” *International Journal of Advanced Manufacturing Technology* 93(5–8): 2299–2304.

El Mansori, M., F. Pierron, and D. Paulmier. 2003. “Reduction of Tool Wear in Metal Cutting Using External Electromotive Sources.” *Surface and Coatings Technology* 163–164: 472–77.

Maurotto, Agostino, Riaz Muhammad, Anish Roy, and Vadim V. Silberschmidt. 2013. “Enhanced Ultrasonically Assisted Turning of a β-Titanium Alloy.” *Ultrasonics* 53(7): 1242–50. http://dx.doi.org/10.1016/j.ultras.2013.03.006.

Mir, Amir, Xichun Luo, and Jining Sun. 2016. “The Investigation of Influence of Tool Wear on Ductile to Brittle Transition in Single Point Diamond Turning of Silicon.” *Wear* 364–365: 233–43. http://dx.doi.org/10.1016/j.wear.2016.08.003.

O’Handley, Robert C. 1999. “Modern Magnetic Materials.” *Physics Bulletin* 13(4): 768.

“Phys. Rev. E 73, 061919 (2006) - Analytical Model of Magnetic Nanoparticle Transport and Capture in the Microvasculature.” https://journals.aps.org/pre/abstract/10.1103/PhysRevE.73.061919 (December 30, 2020).

QIN, Xuda et al. 2012. “Feasibility Study on the Minimum Quantity Lubrication in High-Speed Helical Milling of Ti-6Al-4V.” *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 6(7): 1222–33.

Rahim, E. A., and H. Sasahara. 2011. “A Study of the Effect of Palm Oil as MQL Lubricant on High Speed Drilling of Titanium Alloys.” *Tribology International* 44(3): 309–17. http://dx.doi.org/10.1016/j.triboint.2010.10.032.

Ruibin, Xiong, and Hongbing Wu. 2016. “Study on Cutting Mechanism of Ti6Al4V in Ultra-Precision Machining.” *International Journal of Advanced Manufacturing Technology* 86(5–8): 1311–17. http://dx.doi.org/10.1007/s00170-015-8304-7.

da Silva, Rosemar Batista et al. 2016. “Advances in the Turning of Titanium Alloys with Carbide and Superabrasive Cutting Tools.” *Advanced Materials Research* 1135(January): 234–54.

Suzuki, H. et al. 2014. “Fine Finishing of Ground DOE Lens of Synthetic Silica by Magnetic Field-Assisted Polishing.” *CIRP Annals - Manufacturing Technology* 63(1): 313–16.

Teimouri, R., and H. Baseri. 2014. “Optimization of Magnetic Field Assisted EDM Using the Continuous ACO Algorithm.” *Applied Soft Computing Journal* 14(PART C): 381–89.

http://dx.doi.org/10.1016/j.asoc.2013.10.006.

Wang, Chunjin et al. 2020. “A Novel Magnetic Field-Assisted Mass Polishing of Freeform Surfaces.” *Journal of Materials Processing Technology* 279(October 2019): 116552. https://doi.org/10.1016/j.jmatprotec.2019.116552.

Wang, Debin, Takeo Shinmura, and Hitomi Yamaguchi. 2004. “Study of Magnetic Field Assisted Mechanochemical Polishing Process for Inner Surface of Si3N4 Ceramic Components Finishing Characteristics under Wet Finishing Using Distilled Water.” *International Journal of Machine Tools and Manufacture* 44(14): 1547–53.

Wu, Jinzhong, Yanhua Zou, and Hitoshi Sugiyama. 2015. “Study on Ultra-Precision Magnetic Abrasive Finishing Process Using Low Frequency Alternating Magnetic Field.” *Journal of Magnetism and Magnetic Materials* 386: 50–59. http://dx.doi.org/10.1016/j.jmmm.2015.03.041.

Wu, Jinzhong, Yanhua Zou, and Hitoshi Sugiyama. 2016. “Study on Finishing Characteristics of Magnetic Abrasive Finishing Process Using Low-Frequency Alternating Magnetic Field.” *International Journal of Advanced Manufacturing Technology* 85(1–4): 585–94. http://dx.doi.org/10.1007/s00170-015-7962-9.

Yip, W. S., and S. To. 2017a. “An Application of Eddy Current Damping Effect on Single Point Diamond Turning of Titanium Alloys.” *Journal of Physics D: Applied Physics* 50(43).

Yip, W. S., and S. To. 2017b. “Reduction of Material Swelling and Recovery of Titanium Alloys in Diamond Cutting by Magnetic Field Assistance.” *Journal of Alloys and Compounds* 722: 525–31.

Yip, W. S., and S. To. 2017c. “Tool Life Enhancement in Dry Diamond Turning of Titanium

Alloys Using an Eddy Current Damping and a Magnetic Field for Sustainable Manufacturing." *Journal of Cleaner Production* 168: 929–39.

Yip, W. S., S. To, and Hong Ting Zhou. 2020. "Social Network Analysis for Optimal Machining Conditions in Ultra-Precision Manufacturing." *Journal of Manufacturing Systems* 56(March): 93–103.

Yip, Wai Sze, and Suet To. 2019. "Reduction of Minimum Cutting Thickness of Titanium Alloys in Micro Cutting by a Magnetic Field Assistance." *IEEE Access* 7: 152034–41.

Yoshiaki, Shimizu, Sakaguchi Tatsuhiko, and Shimada Hiroki. 2015. "Multi-Objective Optimization for Creating a Low-Carbon Logistics System through Community-Based Action." *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 9(5): 1–12.

Zhu, Y. H. et al. 2009. "Effects of Dynamic Electropulsing on Microstructure and Elongation of a Zn-Al Alloy." *Materials Science and Engineering A* 501(1–2): 125–32.