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

W.S. Yip*, S. To

State Key Laboratory in Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region

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A B S T R A C T

Ultra precision machining (UPM) is extensively used to fabricate high accuracy products. However, the problematic material swelling/recovery effect due to the elastic recovery of materials in UPM remains unresolved. It causes a ragged surface and extra engineering tolerances which are unadoptable in extremely precise components. In particular to high elastic recovery rate with low thermal conductivity materials like titanium alloys, the swelling effect is intensified during machining processes. In this study, a magnetic field was superimposed on titanium alloys during the single point diamond cutting which aimed to minimize the material swelling effect on the machined surface using the magnetic field influence. In the experiments, titanium alloys were located at the center of two permanent magnets with intensity 0.02T and undergone a diamond groove cutting. The experimental results showed the material swelling/recovery on the machined surface was significantly reduced in presence of magnetic field in comparison to that of diamond cutting without a magnetic assistance; the accuracy of depth of cut, width and radius of cutting groove in a magnetic field reached satisfactorily over 98%. 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.

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 Fig. 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 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 author.
E-mail address: 13903620r@connect.polyu.hk (W.S. Yip).

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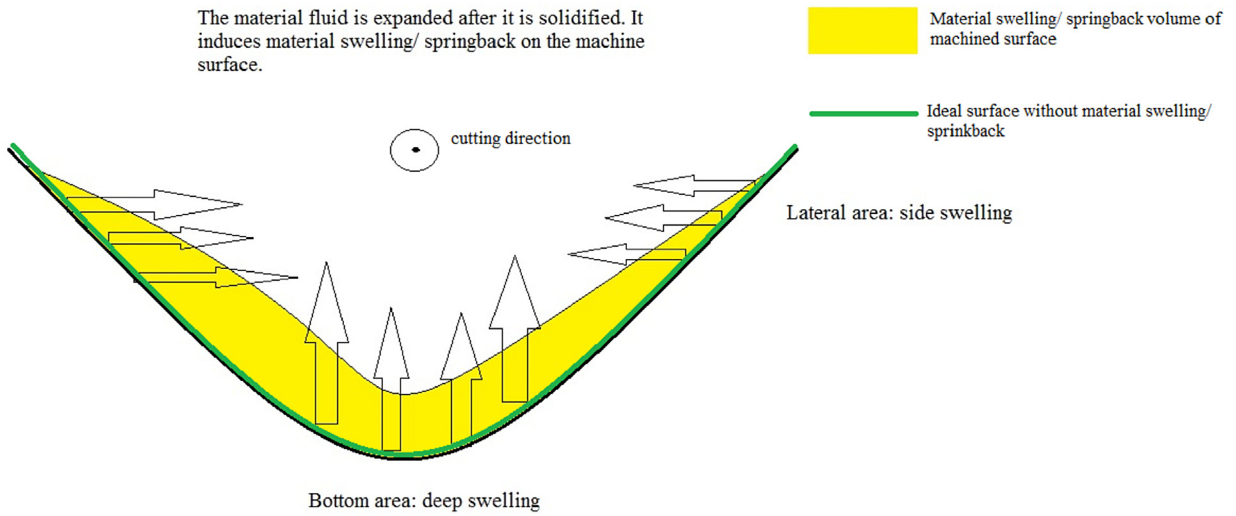

Fig. 1. The illustration graph of material swelling/recovery of machined surface.

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]: