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Origins for the size effect of surface roughness in diamond turning

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A R T I C L E I N F O

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A B S T R A C T

In this work, a novel surface roughness prediction model, in which the kinematics, plastic side flow, material spring back and random factors are considered, is theoretically formulated to reveal the underlying mechanisms for the observed size effect of surface roughness in diamond turning. In this newly developed model, the copy effect of tool edge waviness is successively integrated into the kinematic component, and a yield stress and minimum undeformed chip thickness related function is constructed for calculating the material spring back. For the component of plastic side flow, the effects of minimum undeformed chip thickness, tool nose radius, feed rate as well as cutting width are took into account. Moreover, the component of random factors is assumed to follow a Gaussian distribution. Theoretical predictions and experimental validations show that the feed rate dependent size effect of surface roughness as observed on the fine grain substrate is derived from the decrement of the kinematic component being less than the increment of the plastic side flow component. For the coarse grain substrate, the large and hard inclusion inevitably appears in the matrix. Therefore, the size effect of surface roughness can be attributed to the formation of pit defect and deep groove on the finished surface at large feed rate and the protrusion of hard inclusion from the finished surface at low feed rate.

1. Introduction

Single point diamond turning (SPDT) process plays an important role in advanced manufacturing industries, especially in the field of optics, aerospace technology, information technology and clean energy [1]. It is capable of achieving a super-smooth surface with a nanometer surface roughness, which heavily reduces the requirement for time-consuming post polishing.

In order to improve surface roughness when performing SPDT, a comprehensive understanding of the factors that affect the achieved surface roughness is essential. Regarding this subject, Wang et al. [2] developed an empirical prediction model of surface roughness, which considers the effects of workpiece hardness, tool feed rate, tool point angle, depth of cut and spindle speed, and so forth. Singh et al. [3] conducted an experimental investigation to determine the effects of tool geometries and cutting conditions on the finished surface roughness in hard turning the bearing steel, and a surface roughness prediction model was finally developed by using response surface methodology. Palanikumar et al. [4] employed Taguchi method and response surface methodology to model the surface roughness in machining the glass fiber reinforced plastics with a polycrystalline diamond tool. Although the above models have a satisfactory accuracy in predicting the achieved surface roughness, they were all developed with the empirical method. As is known, the experience dependent surface roughness model heavily relies on the process parameters, which cannot give an explicit analysis for the influence of size effect that appears frequently in diamond turning. Moreover, the output results of an empirical model can be easily affected by the random errors.

In order to avoid the disadvantages of empirical modeling, the theoretical modeling on the surface roughness had also been performed. Brammertz et al. [5] proposed a Spanzipfel formula for finish turning to correct the kinematic surface roughness, in which the minimum undeformed chip thickness was considered. Grezesik et al. [6] revised Brammertz's model by making an assumption to accurately determine the minimum undeformed chip thickness in relation to the cutting edge radius. Takasu et al. [7] modeled the influence of steady vibration with small amplitude and low frequency on the surface roughness in diamond turning. Lee and Cheung [8,9] put forward a dynamic surface model to predict the 3D surface topography and calculate the surface roughness of machined non-ferrous metals. They analyzed the factors affecting the surface generation, such as tool nose radius, feed rate, cutting depth as well as tool-tip vibration induced by the fluctuation of cutting force or the motion error of spindle. Liu et al. [10] presented a surface roughness model that takes the effects of plastic side flow, tool geometries and process parameters into account. Zong et al. [11] recently developed a surface roughness model, into

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Nomenclature

σ	True stress at the interface between the machined surface and tool flank face
σ_n	Normal stress at the interface between the machined surface and tool flank face
σ_t	Variance value for the residual error
μ_t	Expected value for the residual error
μ	Friction coefficient between diamond cutting tool and workpiece
τ	Shear stress at the interface between the machined surface and tool flank face
θ	Opening angle of diamond cutting tool
ε	Total effective strain
ε_y	Yield strain of workpiece
ε_p	Plastic strain appearing on the machined surface of workpiece
ε_t	Residual error caused by the random factors
η	Prediction error
f	Feed rate
a_p	Depth of cut
b_D	Effective cutting width
h_{min}	Minimum undeformed chip thickness
e	Tool edge waviness
n	Hardening exponent of the workpiece material
k	Coefficient in relation to the material properties of workpiece and tool geometries
k_σ	Empirical coefficient for the calculation of normal stress
k_d	Scale coefficient accounting for the material properties of workpiece
k_t	Variable coefficient in relation to tool corner nose radius
k_f	Variable coefficient dependent on the feed rate
k_1, k_2	Corner nose radius of an assigned reference tool
$r_{\varepsilon\text{-ref}}$	Corner nose radius of an assigned reference tool
r_ε	Tool corner nose radius
r_n	Tool cutting edge radius
r_{out}	Outer radius of test region on the workpiece surface
r_{in}	Inner radius of test region on the workpiece surface
s	Surface roughness component in relation to the material spring back
w	Surface roughness component in relation to the plastic side flow
A, B, C	Fitted coefficients
E	Young's modulus of the workpiece material
H	Hardness of the workpiece material
L	Cutting distance
R_{th}	Theoretical peak-valley surface roughness
R_{tew}	Surface roughness component due to the kinematics
$R_{th\text{-calculation}}$	Peak-valley surface roughness acquired in experiment
$R_{t\text{-measuring}}$	Peak-valley surface roughness acquired in experiment

which the effects of material spring back, plastic side flow, minimum undeformed chip thickness and size effect were successively integrated. They claimed that a conservation law of surface roughness appears in diamond turning.

From the theoretical modeling as outlined above, it can be found that the minimum undeformed chip thickness, material properties of workpiece, tool geometries and size effect jointly play important roles in determining the diamond turned surface roughness. Regarding the contributions of these factors, Chou et al. [12] further carried out a series of finish turning experiments on the hardened steel. They found that a large tool nose radius will increase the specific cutting energy, which creates a better surface roughness. Tauhiduzzaman et al. [13] analyzed the influences of size effect, tool geometries and material microstructures, e.g. the grain boundary density and inclusion, on the surface roughness. They claimed that refining grain size reduces the grain boundary and inclusion, in which the size effect can be controlled. Khan et al. [14] investigated the strain rate and crystalline orientation affecting the plastic deformation behaviors of high purity aluminum single crystals.

In the interest of calculating the minimum undeformed chip thickness, Yuan et al. [15] established a relationship between the minimum undeformed chip thickness and tool cutting edge radius. Liu et al. [16] developed an analytical model to account for the thermal softening, strain hardening, cutting velocity and tool cutting edge radius affecting the minimum undeformed chip thickness. They found that the normalized minimum chip thickness, i.e. the ratio of minimum undeformed chip thickness to cutting edge radius, almost stays constant over a range of cutting velocities and tool cutting edge radii when micromachining aluminum alloy.

For the calculation of material spring back, Arcona and Dow [17,18] developed an empirical model in relation to cutting edge radius and material properties of workpiece, such as the hardness and elastic modulus. Lee et al. [19] investigated the influence of material swelling on the surface roughness in diamond turning of aluminum and copper single crystals. They found that the profile of tool marks will distort due to the material swelling of workpiece in machining. Chen et al. [20] analyzed the material swelling effect by defining a swelling proportion in terms of the acquired surface profile.

In addition, a great of efforts had also been made to analyze the size effect in micromachining. Zhang et al. [21] carefully explored the size effect of surface roughness in diamond turning, and they found that the best surface roughness can be finished when the ratio of feed rate to cutting edge radius reaches 0.1. Resorting to the stretching experiments and finite element simulations, Xu et al. [22] investigated the size effect dependent formability of sheet metals in micro/meso scale plastic deformation. Aramcharoen et al. [23] investigated the size effect in micro milling the hardened tool steel, in which the ratio of maximum undeformed chip thickness to cutting edge radius affecting the process performance was obtained. By developing an analytical force model for micro milling, Lai et al. [24] discussed the material removal mechanisms in the micro scale with a consideration of size effect, tool cutting edge radius and minimum undeformed chip thickness.

For the calculation of plastic side flow, Kishawy et al. [25] investigated the effects of tool nose radius, feed rate and tool wear on the plastic side flow in hard turning. Liu et al. [10] presented an empirical model to predict the plastic side flow in micro-cutting. According to the experimental observations, they declared that the discrepancy between the theoretical surface roughness and the measured one is primarily owing to the additional surface roughness caused by the plastic side flow. Kong et al. [26] analyzed the contributions of plastic side flow and material spring back to the surface roughness in diamond turning of ductile materials, and a distribution model of plastic side flow was presented finally. Kishawy et al. [27] put forward a prediction model for the plastic side flow generated in hard turning, in which a 3D thermo elasto-viscoplastic finite element model was established to simulate the