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# Conservation law of surface roughness in single point diamond turning

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ABSTRACT

In this work, a comprehensive model is established to predict the surface roughness achieved by single point diamond turning. In addition to the calculation of the roughness components in relation to the kinematics and minimum undeformed chip thickness, the newly developed model also takes the effects of plastic side flow and elastic recovery of materials as machined into account. Moreover, the 'size effect' has also been successfully integrated into the model, i.e. an inflection point appears in the trend line of predicted surface roughness as the ratio of maximal undeformed chip thickness to cutting edge radius ($h_{\mathrm{Dmax}}/r_{\mathrm{n}}$) is equal to one unit. Face turning experiments validate that the maximal prediction error is only 13.35%. As the ratio of $h_{\mathrm{Dmax}}/r_{\mathrm{n}}$ is higher than one unit, both the prediction and experiments reveal that a conservation law exists in diamond turned surface roughness, owing to the competitive effects of kinematics, minimum undeformed chip thickness, plastic side flow and elastic recovery of materials on surface formation. Under the conservation law, the freedom control for an invariable surface roughness can be fulfilled in response to a quantitative ratio of $h_{\mathrm{Dmax}}/r_{\mathrm{n}}$, either through an accurate configuration of feed rate and depth of cut with fixed tool nose radius and cutting edge radius, or by a reasonable selection of tool nose radius and controlled cutting edge radius with designed feed rate and depth of cut.

## 1. Introduction

Diamond turning is of great importance for the fabrication of precision parts in various industrial sectors, such as optics, clean energy, information and communication technology, and others [1,2]. As well known, diamond turning is capable of achieving a super-smooth surface, which is usually free from the time-consuming polishing. Such excellent capability, however, is strongly dependent on the machining environment, performance of the machine tool, process parameters, tool geometry as well as the properties of workpiece materials [1,3]. For example, the famous 'size effect' of surface roughness appears frequently, and a lot of cutting trials have to be carried out to select the process parameters and tool geometry reasonably, although it has been demonstrated that the 'size effect' is attributed to the effect of cutting edge radius of diamond tool [3–7]. In the light of previous works reviewed above, interesting questions are raised but not answered satisfactorily: is there a surface roughness law that gets across the 'size effect'? Specifically, can the law accurately direct the variations of surface roughness?

In order to fulfill the objects, Brammertz proposed a Spanzipfel formula for finish turning to correct the kinematic surface roughness, in which the minimum undeformed chip thickness was considered [8]. Subsequently, Grezesik revised Brammertz's model by making an assumption to accurately determine the minimum undeformed chip thickness in relation to the cutting edge radius [9]. Lee and Cheung put forward a dynamic surface topography model to predict the 3D topography and calculate the surface roughness of machined crystalline materials or aluminum alloy [10,11]. They analyzed the factors affecting the surface generation in detail, such as tool nose radius, feed rate, depth of cut as well as tool-tip vibration induced by the cutting force fluctuations or the motion errors of spindle. Furthermore, Lee, Cheung and Melkote emphasised that the plastic side flow or swelling and elastic recovery of materials are another two significant factors influencing the surface generation [12–15]. Kim employed the FFT (fast Fourier transform) analysis method and established a 3D topography model to simulate the machined surface of aluminum alloy and copper alloy based on the frequency domain information that was extracted from the space domain signals of the measured surface profile [16]. Wang and Zong introduced the wavelet analysis method to decompose and reconstruct the 3D surface

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topography as machined [17]. According to their work, the diamond turned surface topography can be predicted first, and subsequently the modification is performed to acquire the designed surface. Moreover, Zong et al. recently established a 3D finite element (FE) model to evaluate diamond tool geometries affecting the 3D surface topography [18]. As parameters such as tool nose radius, rake and relief angles, micro defects of tool edge and cutting edge radius are input into the FE model, the surface topography and surface roughness can be simulated in advance of machining.

Although the works reviewed above have made great advances in predicting surface roughness of diamond turned materials, little attention has been paid to the 'size effect' of surface roughness induced by the cutting edge radius of diamond tools, which essentially is a vital factor affecting the surface quality. Therefore, in this work a comprehensive surface roughness model is proposed, into which the 'size effect' is integrated. Based on the well predicting of surface roughness, a conservation law is found. According to the conservation theory, the accurate configuration of cutting edge radius, tool nose radius and process parameters can be realized in response to the assigned surface roughness, i.e. the freedom control for an invariable surface roughness is accessible.

## 2. Theoretical modeling

In diamond turning, tool feed rate and nominal depth of cuts are very fine. Such configuration of process parameters yields an extremely small undeformed chip thickness, the order of which is comparable to the cutting edge radius of diamond tool as employed. In this case, the kinematic surface roughness in relation to tool nose radius and feed rate has poor agreement with the actual achieved surface roughness. Because the plastic side flow introduced by tool nose radius and feed rate [14], as schematically shown in Fig. 1(a), the residual minimum undeformed chip thickness dependent on cutting edge radius [19], as well as the elastic recovery of materials affected by tool cutting edge radius, corner nose radius and rake angle [20], as shown in the sketch of Fig. 1(b), have reached up to the same magnitude of the residual height in kinematics. For a diamond turned surface, therefore, the final finished surface topography is pictorially described in Fig. 1(c). In this figure, $r_\varepsilon$, $f$ and $a_\mathrm{p}$ denote tool nose radius, feed rate and nominal depth of cut, respectively. $R_\mathrm{th}$ is the residual height in kinematics, and $R'_\mathrm{th}$ is the comprehensive height considering the effects of kinematics, plastic side flow, minimum undeformed chip thickness as well as elastic recovery of materials. $h_\mathrm{Dmin}$ and $h_\mathrm{Dmax}$ are the minimum and maximal undeformed chip thickness, respectively.

As revealed by previous work, the minimum undeformed chip thickness is heavily dependent on tool cutting edge radius, which can be given by

$$h_\mathrm{Dmin} = c r_\mathrm{n} \tag{1}$$

where $c$ is a coefficient ranging from 0.3 to 0.4 [19], and $c$ is equal to 0.35 in this work. $r_\mathrm{n}$ is the tool cutting edge radius.

$h_\mathrm{Dmin}$ is a significant factor affecting the surface formation in diamond turning. For the effective undeformed materials with a thickness larger than $h_\mathrm{Dmin}$, they will undergo the extrusion effect and gradually accumulate ahead of tool edge. Finally, the effective undeformed materials are removed through micro cutting. For the effective undeformed materials with a thickness less than $h_\mathrm{Dmin}$, however, chip formation disappears. In this case, the effective undeformed materials are no longer removed. Instead, the burnishing and friction take place due to the plowing of diamond tool.

As shown in Fig. 1(c), the maximal undeformed chip thickness is calculated as

$$h_\mathrm{Dmax} = r_\varepsilon - \sqrt{r_\varepsilon^2 + f^2 - 2f\sqrt{2r_\varepsilon a_\mathrm{p} - a_\mathrm{p}^2}} \tag{2}$$

For turning operation, the theoretical or kinematic ten-point height, i.e. the surface roughness, can be written as

$$R_\mathrm{th} = \frac{f^2}{8r_\varepsilon} \tag{3}$$

As discussed above, the effect of minimum undeformed chip thickness should be considered in predicting the diamond turning finished surface roughness. Therefore, the surface roughness has

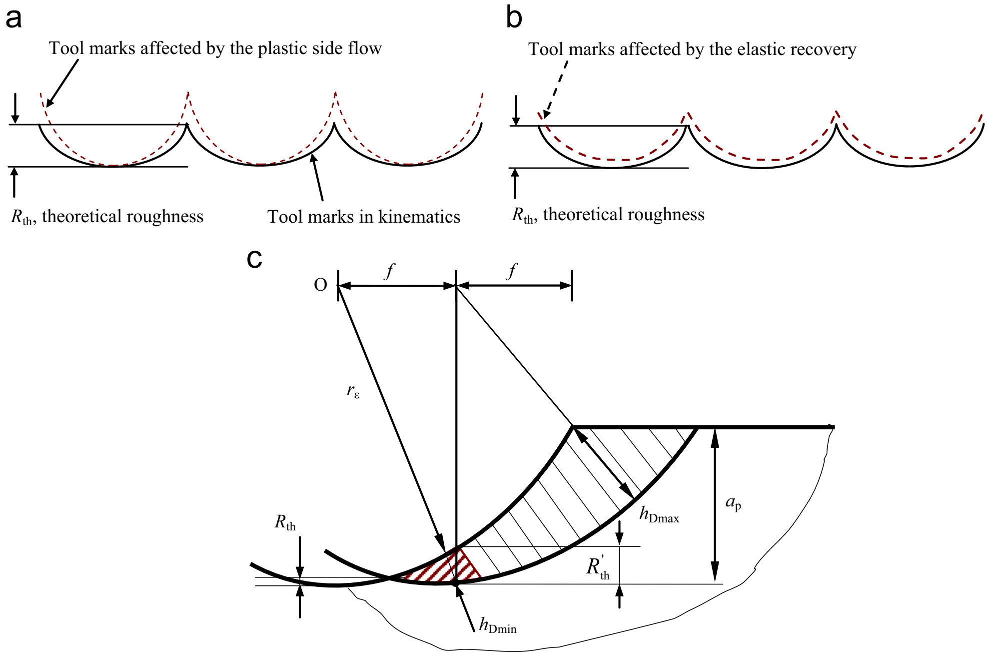

**Fig. 1.** Schematic surface topography of diamond turned surface with a round nosed tool: (a) the effect of plastic side flow; (b) the effect of elastic recovery; and (c) comprehensive height coupled with the effects of kinematics, minimum undeformed chip thickness, plastic side flow and elastic recovery.