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Influence of the cutting edge radius and the material grain size on the cutting force in micro cutting

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ABSTRACT

In micro cutting, both the cutting edge radius and the material grain size have a great influence on the cutting force. The study of the influence of the material grain size on the cutting force is unavoidably affected by the dual effect of the cutting edge radius. In this paper, a method for estimating the shearing force is proposed. In addition, micro turning experiments were performed to investigate the influence of the cutting edge radius and the material grain size on the cutting force. The results showed that a smaller material grain size leads to a larger cutting force and a higher specific cutting energy. Furthermore, the difference in cutting force observed for different material grain sizes increased with the cutting edge radius. By separating the shearing force, this dual effect was found to be caused by the ploughing force. The influence of the material grain size on the cutting force and the specific cutting energy is much lower than the influence of the cutting edge radius.

1. Introduction

Mechanical micro cutting can be used to produce micro parts with complex geometries by various materials. It is widely used for the manufacturing of parts used in medical, optical and fluidics devices. Micro cutting, which is accomplished with small diameter cutting tools, can be considered as a downscaled version of macro cutting [1]. However, compared with macro cutting, some new issues arise, which need to be addressed to ensure a successfully industrial application. For instance, although small diameter cutting tools can be produced by advanced tool manufacturing techniques, the cutting edge radius does not downscale proportionally with the tool diameter. While the uncut chip thickness is usually small in micro cutting, the ratio of the uncut chip thickness to the cutting edge radius is much larger than in macro cutting [2]. Furthermore, the uncut chip thickness is comparable to the grain size of the workpiece material. Chip formation may occur within a few or even only a single grain of the material [3,4]. Therefore, the assumptions of a sharp cutting tool and a homogeneous material are invalid when switching to micro cutting, and the induced size effect was demonstrated to significantly affect the cutting force and the surface quality [5–7].

Wyen et al. [8] studied the orthogonal turning of Ti-6Al-4V and found that the magnitude of certain components of the cutting force, including the ploughing force, increases with the cutting edge radius. Biermann et al. [9] investigated the micro milling of tool steel and reported that the cutting force is higher for larger cutting edge radii because more material is machined when the cutting edge radius is increased. Childs [10] reported that in micro cutting both the cutting force and the thrust force linearly increase with the cutting edge radius. He suggested that the size effect is caused by two factors, i.e., the ploughing force induced by the blunt cutting edge and the increase of the shear flow stress due to the reduced uncut chip thickness. Popov et al. [11] and Elkaseer et al. [12] investigated the influence of the material grain size on the surface quality when micro milling Al and Cu, respectively. They suggested that using materials with a smaller grain size may lead to a smaller minimum chip thickness compared with materials with a larger grain size, and hence, can significantly improve the surface integrity. Simoneau et al. [13] employed the finite element method to develop a heterogeneous cutting model and pointed out that using AISI 1045 steel with a refined microstructure is beneficial for achieving a continuous chip and a good surface quality. Ding et al. [14] also found that a change in the crystallographic structure, such as the material grain size and the grain orientation, may result in a distinct variation of the cutting force and the surface roughness.

The results above have shown that both the cutting edge radius and the material grain size significantly affect the cutting force in the micro cutting process. Furthermore, they may have a dual effect

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which makes the involved mechanism very complex and confusing. For micro cutting, the study on the influence of the material grain size on the cutting force must be performed under the condition of a non-negligible cutting edge radius. Sometimes the cutting edge radius even is comparable to the material grain size. The effective cutting force is composed of the shearing force and the ploughing force. The material grain size not only affects the shearing force but also may affect the ploughing force. In this paper, a method for estimating the shearing force is proposed. FEM simulations were performed to verify this method. In addition, micro turning experiments were performed to individually investigate the influence of the material grain size on the shearing force and the ploughing force. Then the influence of the material grain size on the cutting force and the specific cutting energy was compared with the influence of the cutting edge radius.

2. Estimation of the shearing force

2.1. Cutting force analysis

When studying the cutting mechanism, the cutting force is one of the most fundamental parameters. Various cutting force models have been proposed for different cutting conditions [15,16]. In micro cutting, the cutting edge radius cannot be ignored [17]. The material flow under the rounded cutting edge is confined to the narrow space between the rounded cutting edge and the workpiece surface. There are severe ploughing and rubbing on the rounded cutting edge. In the cutting process, the magnitude of the stress acting on the rounded cutting edge is much larger than that of the stress acting on the rake face. Based on the different stress magnitudes, the total cutting force can be divided into two components: the force F_1 acting on the rake face and the force F_2 acting on the rounded cutting edge, as illustrated in Fig. 1.

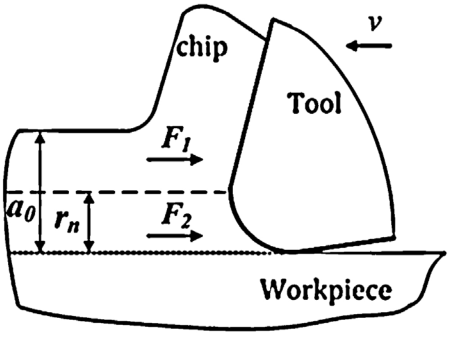

Fig. 1. Illustration of the cutting force components in micro cutting.

The material flow on the rake face is mainly due to shearing. The energy required to remove a unit amount of material is called the specific cutting energy [18]. The stress distribution on the rake face usually shows a relatively low magnitude and does not vary significantly. It is assumed that the specific cutting energy also remains constant over the cutting thickness on the rake face. The force F_1 is proportional to the uncut chip thickness:

$$F_1 = E_1(a_0 - r_n)a_w \tag{1}$$

where E_1 is the specific cutting energy, a_0 is the uncut chip thickness, r_n is the cutting edge radius and a_w is the cutting width. However, the ploughing and rubbing under the rounded cutting edge dominates the material removal mechanism. The effective rake angle deviates from the nominal rake angle and is actually highly negative [19,20]. The stress distribution on the rounded cutting edge generally exhibits a large magnitude. The specific cutting energy over the rounded cutting edge is assumed to be constant as well. The force F_2 can be written as:

Table 1
Parameters used for the FEM simulations.

Cutting speed v (mm/s)	314
Cutting width a_w (μm)	100
Uncut chip thickness a_0 (μm)	3, 11
Cutting edge radius r_n (μm)	0, 2, 5, 8

$$F_2 = E_2 r_n a_w \tag{2}$$

where E_2 is the specific cutting energy, r_n is the cutting edge radius and a_w is the cutting width. Hence, the total cutting force is given by:

$$\begin{aligned} F &= E_1(a_0 - r_n)a_w + E_2 r_n a_w \\ &= E_1 a_0 a_w + (E_2 - E_1) r_n a_w \\ &= E_1 a_0 a_w + E' r_n a_w \end{aligned} \tag{3}$$

where E' is the additional specific cutting energy induced by the severe ploughing on the rounded cutting edge.

This equation describes the fundamental cutting force model for micro cutting, and expresses the fundamental relationships between the cutting force and the cutting parameters. The force $E' r_n a_w$ is the ploughing force induced by the blunt cutting edge. It is a parasitic force and does not contribute to chip formation [21]. In macro cutting, the cutting edge radius is much lower than the uncut chip thickness. Thus, the ploughing force is relatively small and is therefore generally ignored. In contrast, in micro cutting, the ploughing force plays a more important role in the cutting process. Different approaches have been developed to determine the ploughing force, such as the extrapolation method on zero uncut chip thickness introduced by Albrecht [22] and a comparison method of the total cutting forces at different levels of flank wear, which was proposed by Popov [23]. The force $E_1 a_0 a_w$ is the shearing force required for chip formation. It cannot be determined directly because the specific cutting energy E_1 is unknown. According to Eq. (3), if only the cutting edge radius changes and the other cutting parameters remain constant, the force $E_1 a_0 a_w$ can be regarded as unchanged. Only the force $E' r_n a_w$ depends on the cutting edge radius and leads to an increase of the total cutting force. Thus, the total cutting force is proportional to the cutting edge radius. Hence, when the cutting force is determined for different cutting edge radii and a linear extrapolation is performed to obtain the value for zero cutting edge radius, the intercept can be regarded as the shearing force $E_1 a_0 a_w$. Once the shearing force is known, the ploughing force can be obtained by subtracting the shearing force from the total cutting force. This method is an indirect approach to separate the shearing force and the ploughing force.

2.2. Validation of the method by FEM simulations

To validate the proposed method FEM simulations were carried out utilizing the DEFORM software. Oxygen free copper and diamond were selected as workpiece material and tool material, respectively, and the J–C constitutive material model was adopted. The rake and flank angle were 10° and 5°, respectively. The shear friction model based on the assumption of a constant shear was used, and the friction factor was fixed at 0.6. Four different values were selected for the cutting edge radius, including zero. Two different values were used for the uncut chip thickness; one was selected to be smaller than the cutting edge radius, and the other one was larger than the cutting edge radius. The other cutting parameters were fixed and are listed in Table 1.