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ORIGINAL ARTICLE

Investigation on the ploughing force in microcutting considering the cutting edge radius

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Abstract Ploughing force is a parasitic force induced by the blunt cutting edge and the contact at flank face. Investigation on the ploughing force is necessary for the cutting mechanism understanding, the tool wear monitoring, and the tool sharpness evaluation. In this paper, a new comparison method to determine the ploughing force is developed by considering the cutting edge radius. This method is verified in the FEM simulation. Cutting experiments are performed to investigate the ploughing force in microcutting. Not only the cutting edge radius but also the uncut chip thickness is found to have great effects on the ploughing force. The nonlinear increase of the total specific cutting energy is also attributed to the ploughing force.

Keywords Microcutting · Cutting force · Ploughing force · Specific cutting energy

1 Introduction

Microcutting is capable of manufacturing micropart with complexly three-dimensional features in various materials [1]. It is widely used in manufacturing of micromedical part, microengine part, and microoptics device. Cutting force which contains important mechanical and dynamical information of cutting process is one of the most fundamental parameters to research the cutting mechanism. In microcutting, cutting edge radius does not downscale as much as the tool diameter. The uncut chip thickness is comparable to the cutting edge radius. Since there is elastic recovery of the machined material at the flank face ploughing easily occurs and becomes an important factor that affects the cutting process [2]. In addition, cutting edge radius increases quickly with the tool wear. This even induces more serious ploughing. Ploughing often results in poor surface quality and deteriorated dynamic stability [3–5]. Ploughing force is induced by the relatively blunt tool cutting edge compared with the small uncut chip thickness in microcutting. Ploughing force is a parasitic force and has no contribution to the chip formation process. It has also unshirkable responsibility for the size effect and minimum chip thickness phenomenon [6–8]. Determination of the ploughing force is desirable for the cutting mechanism understanding, the tool wear monitoring, and the tool sharpness evaluation.

Many methods have been used to reveal the ploughing force. Stevenson [9] applied feed-dwell approach to measure the ploughing force directly. The insufficient of this method is that because of nonideal system rigidity, it is impossible always to cut with the so-called zero uncut chip thickness. Since it is extremely difficult to measure the ploughing force directly, indirect method has been widely used. Albrecht [10] used extrapolation method on zero uncut chip thickness to determine the ploughing force. He suggested that the force just prior to the onset of cutting is the ploughing force, and it can be calculated indirectly by extrapolating the experimental cutting force to zero uncut chip thickness. The extrapolation method is widely used even to the present day [4, 11]. However, it is highly controversial since its occurrence. Stevenson [9] found that the ploughing force measured by the extrapolation method is much larger than that directly measured by the feed-dwell method. Arsecularatne [12] also gave evidence indicating that the ploughing force is smaller than

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the extrapolation of experimental cutting force to zero uncut chip thickness. Then, Lipatov [13] and Popov [14] used comparison method of cutting force at different flank wear to determine the ploughing force. By comparison, Popov stated that the ploughing force determined by the extrapolation method is considerably larger than the comparison method as well. To increase the accuracy, Popov [15] later improved this method to comparing the cutting force of different contact area at the flank face. The comparison method is more reliable and acceptable. Actually, both the tool wear and the contact area at flank face are closely related with the tool cutting edge radius. The increase of cutting edge radius is one of the main tool wear pattern in microcutting. Hence, the cutting edge radius also cannot be ignored in determination of ploughing force by the comparison method [16].

As stated above, the determination of ploughing force is significantly important, but there are still seldom researches on it. This paper develops the comparison method to determine the ploughing force in microcutting by considering the cutting edge radius. The new comparison method is verified in FEM simulation. Then, the influences of cutting edge radius and uncut chip thickness on ploughing force are investigated in microcutting experiments. This paper also provides a new viewpoint to study size effect in microcutting.

2 The new comparison method to determine the ploughing force

The extrapolation method determines the ploughing force by extrapolating the cutting force to zero uncut chip thickness [10]. It is based on two assumptions: (a) the cutting force is proportional to the uncut chip thickness, and (b) the ploughing force remains constant with the uncut chip thickness. Actually, these assumptions are invalid in microcutting. It is doubtless that the cutting force increases with raising the uncut chip thickness. And then, the stress on the cutting edge round and the contact area at flank face increase. Hence, the ploughing force should be different as well. Since the extrapolation method is based on the false assumptions, it is improper for the determination of ploughing force.

Microcutting can be considered as a downscaling version of the macrocutting. As the macrocutting force, microcutting force also is mainly composed of shearing and ploughing components [17, 18]. The force extra attaching on the cutting edge round and the flank face is called the ploughing force, as shown in Fig. 1. The total cutting force can be given as follows [19]:

$$F_c = \left[K_s a_0 + K_p r_n\right] a_w \tag{1}$$

where F_c is the total cutting force, K_s is the shearing force coefficient, K_p is the ploughing force coefficient, a_0 is the

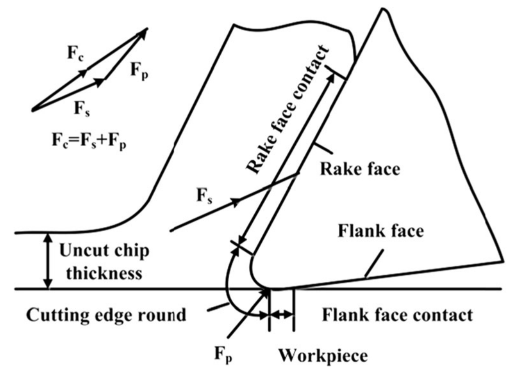

Fig. 1 The cutting force components. F_c is the total cutting force, F_s is the shearing force component, and F_p is the ploughing force component

uncut chip thickness, r_n is the cutting edge radius, and a_w is the cutting width. This is the fundamental model about the relationship between microcutting force and cutting parameters [20]. If only the cutting edge radius changes and all other cutting parameters are constant, from the cutting force model, it is seen that the shearing force component can be regarded as unchanged. However, the ploughing force increases with the rise of the cutting edge radius lead to the total cutting force increases as well. Hence, the observed increase of total cutting force can be regarded as the ploughing force. If the shearing force component (i.e., the cutting force of zero cutting edge radius) is known, the ploughing force can be calculated by the total cutting force of given cutting edge radius subtracting the shearing force component. It can be expressed as follows:

$$F_p = F_c - F_s \tag{2}$$

where F_p is the ploughing force, F_c is the total cutting force, and F_s is the shearing force component. Hence, the key point is to separate the shearing force component.

Yet, in practice cutting tool with zero cutting edge radius cannot be manufactured, the shearing force component cannot be measured directly as well. It has been known that when only the cutting edge radius changes and other cutting parameters keep constant, the shearing force can be considered as unchanged. And, the total cutting force has a linear relationship with the cutting edge radius [21, 22]. Based on this conclusion, if linear extrapolation is performed on the total cutting force to zero cutting edge radius, the intercept is the cutting force of zero cutting edge radius. This cutting force also can be regarded as the shearing force component of the given uncut chip thickness. Since the shearing force component is known, the ploughing force can be determined as well, as shown in Eq. (2). This is a new comparison method to determine the ploughing force in microcutting by considering the cutting edge radius, the procedure as shown in Fig. 2.

This method first is verified in the FEM simulation by DEFORM software. The used material was copper. The tool rake and flank angle were 10° and 5°, respectively. The tool

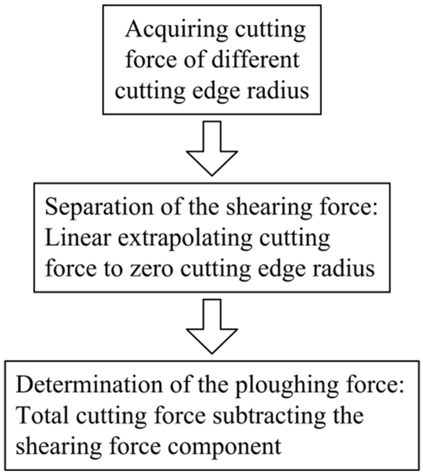

Fig. 2 The procedure of the determination method

was regarded as rigid. The cutting edge radius was set at six levels including zero. The uncut chip thickness was set at general level. All the parameters are listed in Table 1. The cutting force of nonzero cutting edge radius is used for the linear extrapolation to determine the shearing force component. The directly simulated cutting force of zero cutting edge radius is compared with the linear extrapolation result to verify the accuracy.

Figure 3 shows the results of the ploughing force determination. The linear fitting curve is also shown. And, the linear fitting equation is expressed as follows:

$$F_c = 0.86 + 0.07 \times r_n \quad (3)$$

where F_c is the total cutting force and r_n is the cutting edge radius. The intercept of the linear fitting curve 0.86 N is regarded as the shearing force component for the uncut chip thickness of 11 μm. The directly measured cutting force of the zero cutting edge radius from the simulation is 0.79 N. The error is as small as 8.9 %. The linear extrapolation value is highly consistent with the directly simulated value. It indicates that the separation of the shearing force component is valid. By the Eq. (2), the ploughing force component is calculated, as shown in Fig. 3. It is seen that the ploughing force increases with the increase of cutting edge radius. It is only 0.07 N with the cutting edge radius of 1 μm. And, it increases to 0.53 N with the cutting edge radius of 8 μm. This is because an increasing cutting edge radius leads to more materials being removed by the cutting edge round. The force extra attaching

Table 1 Simulation parameters

Cutting speed v (mm/s)	314
Cutting width a_w (μm)	100
Uncut chip thickness a_0 (μm)	11
Cutting edge radius r_n (μm)	0, 0.5, 1, 3, 5, 8

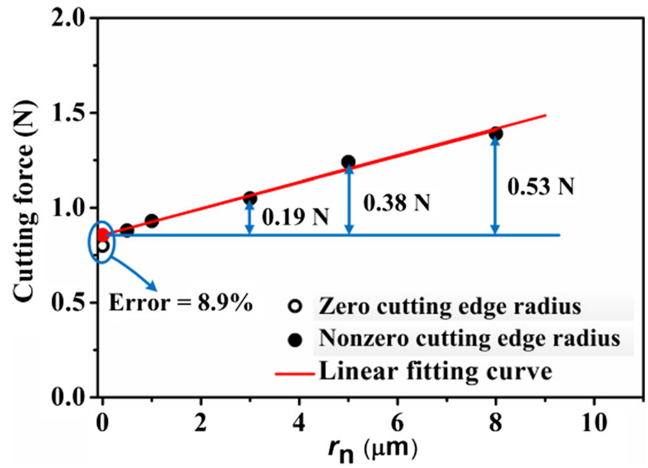

Fig. 3 Determination of the ploughing force

on the cutting edge round and the flank face also increase. When the tool is sharp enough the cutting edge radius is small, the ploughing force is low even can be ignored. As the cutting tool is blunt to be comparable to the uncut chip thickness, the ploughing force is large and becomes an important part in the microcutting force. The proportion of ploughing force in the total cutting force can be formulated as follows:

$$P = 0.07r_n/(0.86 + 0.07r_n) \quad (4)$$

where P is the proportion of ploughing force in the total cutting force and r_n is the cutting edge radius. The increaseing ploughing force results in not only the total cutting force increase but also the proportion of the ploughing force raises. When the cutting edge radius increases to 12 μm, the ploughing force even is equal to the shearing force. With further increase, the ploughing force exceeds the shearing force. Ploughing force is dominant in the total cutting force.

Figure 4 shows the stress distribution around the cutting edge round. With increasing the cutting edge radius the stress on the cutting edge round raise due to the incremental ploughing. The incremental ploughing lead to the primary deformation zone becomes fuzzy as well. It indicates that ploughing is dominant in the cutting process. Furthermore, the stress effect area on the machined surface is deeper. This exacerbates the work-hardening phenomenon and leaves large residual stress that has bad effect on the part life. Ploughing often results in bad machining quality. The sharpness of the cutting tool has great effect on the ploughing and then affects the machining quality. The sharper cutting tool is more likely to manufacture high quality part. Hence, it is especially important to manufacture cutting tool sharper. As the sharper cutting edge is easy to wear, the wear resistance of microcutting tool must also be in balanced consideration.

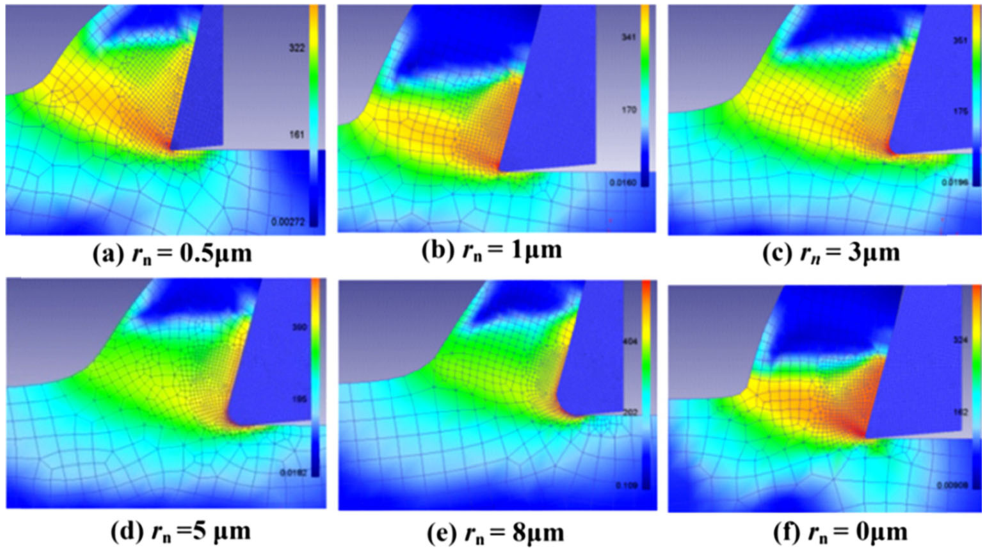

Fig. 4 Stress distribution versus the cutting edge radius

3 Experimental study on the ploughing force in microcutting experiment

3.1 Experiment setup

In this section, ploughing force was determined during the microturning process. The microturning experiment was conducted on a microturning machine, as shown in Fig. 5. The machine is specifically designed to manufacture micropart. It can provide positional accuracy and repetition accuracy of ±1 μm. The workpiece used in the experiment was copper bar with diameter of 6 mm. The cutters were fresh PCD microturning tool of the same batch. The rake and flank angles were 10° and 5°, respectively. The cutting edge radius was measured by the Leica DVM5000 microscope. The tool was fixed in the horizontal holder, which in turn was fixed on the KISTLER 9256C1 dynamometer. To reduce the flexure deformation, the extended lengths of copper bar and the tool were clamped as short as possible. In the experiment, the spindle rotating rate n and cutting depth a_p were fixed. The feed rate f_r and the cutting edge radius r_n were set at four levels, respectively. All the parameters are listed in Table 2. The turning process was conducted in dry condition. A stereo microscope and image processing system were used for tool setting and process monitoring. The natural frequency of the machine system was measured to be about 203 Hz. The spindle rotation frequency was 16.7 Hz. The sampling rate was set at 15 kHz to keep away from these interference frequencies. Every measurement of the cutting force was repeated three times, and the average value was adapted.

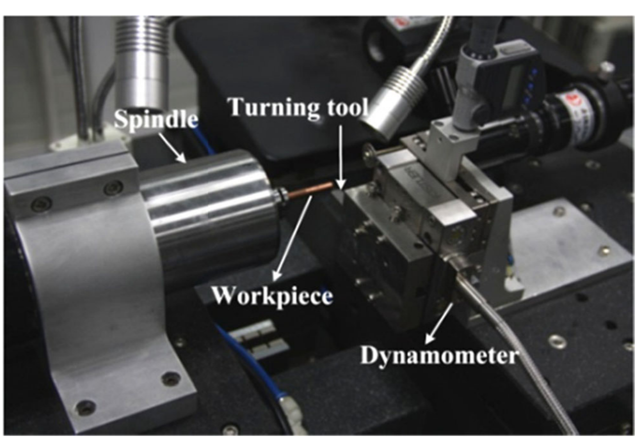

Fig. 5 The experiment setup

4 Results and discussion

Figure 6 shows the cutting force varying with cutting edge radius in the experiment. The cutting force presents a linearly increasing trend with increasing the cutting edge radius. This is consistent with the simulation result. It is caused by the ploughing force increases with raising the cutting edge radius. Linear extrapolation of the experimental cutting force to zero cutting edge radius is performed to all the tested feed rates, as shown in Fig. 6. The linear extrapolation curve also is shown in

Table 2 Machining parameters

Spindle rotating rate n (rpm)	1000
Cutting depth a_p (μm)	50
Feed rate f_r (μm)	5, 10, 15, 20
Cutting edge radius r_n (μm)	2, 5, 8, 10

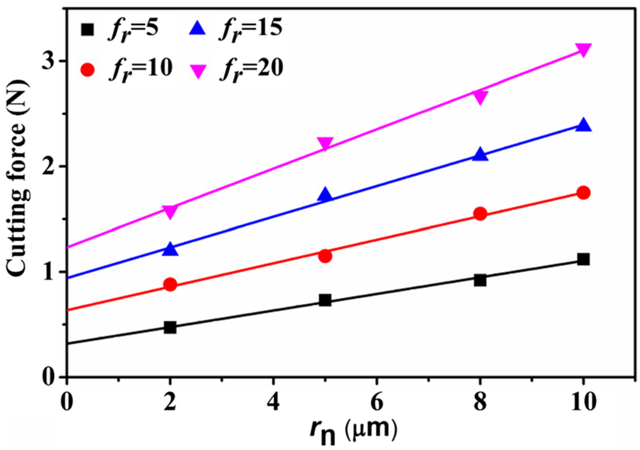

Fig. 6 Separation of the shearing force component

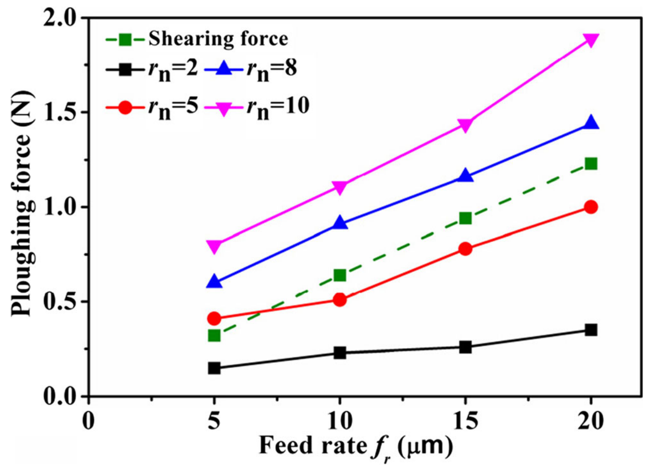

Fig. 8 The determined ploughing force versus feed rate

the picture. The intercept is the shearing force component for the tested feed rate. The separated shearing force component varying with the feed rate is shown in Fig. 7. Both the total cutting force and the shearing force component are found to linearly increase with raising the feed rate due to more materials being machined. It is consistent with the cutting force fundamental model shown in Eq. (1).

The total cutting force subtracted by shearing force component is the ploughing force for the tested cutting edge radius. Figure 8 shows the determined ploughing force varying with the feed rate. The shearing force component also is shown in the picture by the dotted line. As concluded in the simulation with the larger cutting edge radius, the ploughing force is greater due to more materials being removed by the cutting edge round. And, the proportion of ploughing force in the total cutting force is greater as well. Furthermore, it is interestingly found that the ploughing force also increases with raising the feed rate. In microcutting, the material flow under the cutting edge round is limited in narrow space. With the larger feed rate, the shearing force is greater. Its force component which is perpendicular to the cutting edge round and the flank face is also greater. This means that the stress on the cutting edge round and the contact area at the flank face increase as well. It leads to the greater ploughing force. The result experimentally confirms the based assumption of the extrapolation method on zero uncut chip thickness to determine the ploughing force is false. The simple linear extrapolation of cutting force to zero uncut chip thickness is improper for the determination of the ploughing force. When the cutting edge radius is small, the ploughing force is low and changes slowly with raising the feed rate. As tool cutting edge is blunt, the ploughing force becomes great and increases rapidly with the raise of the feed rate. For a given feed rate, there always exists a critical cutting edge radius that the ploughing force will exceed the shearing force component. And, this critical cutting edge radius is found to increase with raising the feed rate. This is because of the larger feed rate is accompanied with the greater shearing force component, and the larger cutting edge radius in accordance with the greater ploughing force also is need to equal with. When the cutting edge radius exceeds the critical value, the ploughing force also exceeds the shearing force component. The ploughing becomes dominant in the cutting process. The dominant ploughing usually leads to poor surface quality and large residual stress.

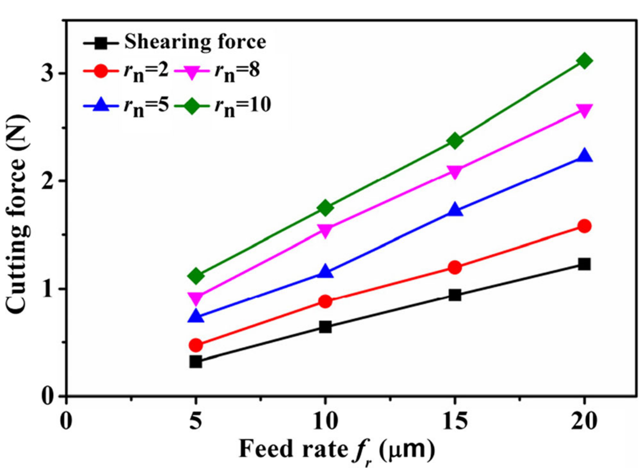

Fig. 7 Cutting force and shearing force component versus the feed rate

Figure 9 shows the specific cutting energy of total cutting force varying with the feed rate. It is found that as long as the cutting edge radius is nonzero, the specific cutting energy nonlinearly increases with reducing the feed rate. This is called the size effect in microcutting. The nonlinearity is more serious with increasing the cutting edge radius. However, the specific cutting energy of cutting force with zero cutting edge radius (i.e., the shearing force component) almost does not change with varying the feed rate. This result indicates that the blunt cutting edge is the mainly origin of the size effect in

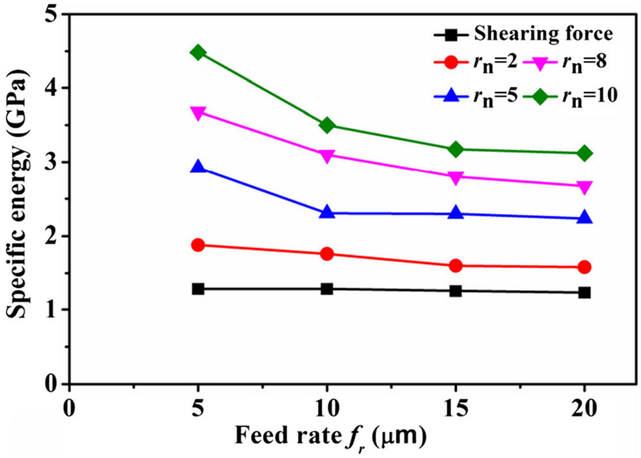

Fig. 9 Specific cutting energy of the total cutting force and shearing force component

microcutting. Figure 10 shows the specific cutting energy of the determined ploughing force varying with the feed rate. The specific cutting energy of ploughing force presents nonlinear increase with reducing the feed rate as well, completely same to the variation of the total specific cutting energy. As the cutting force is completely composed of shearing force, the specific cutting energy of ploughing force always is zero. It also indicates that the nonlinear increase of the total specific cutting energy is originated from the ploughing that induced by the blunt cutting edge. With more materials being machined by the round part of the cutting edge, more cutting power is consumed by the ploughing. At the critical cutting edge radius, when the ploughing force exceeds the shearing force component, as shown in Fig. 8, the specific cutting energy of ploughing force also exceeds the specific cutting energy of shearing force. The cutting power is mainly consumed by the serious ploughing.

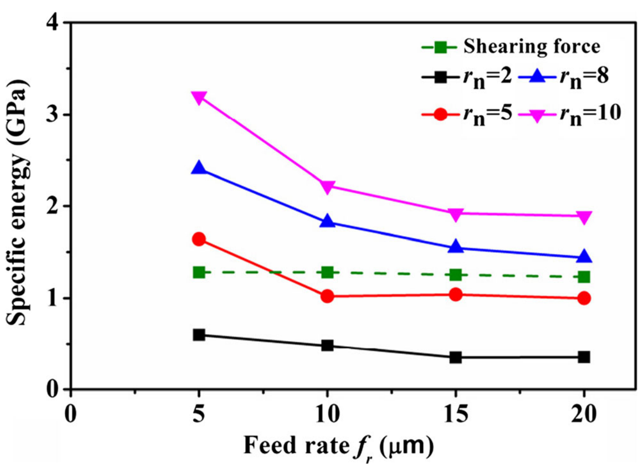

Fig. 10 Specific cutting energy of the ploughing force

The cutting edge radius and the uncut chip thickness have great effect on the ploughing force and then affect the cutting process. Large ploughing force results in large cutting force, poor surface quality, and useless power consumption. The requirements of modern science and technology on micropart quality are more and more high. To manufacture those high-quality microparts by microcutting, the control of ploughing force is important. Theoretically, the smaller feed rate, the lower the ploughing force and the less residual material on the machined surface. But, when the feed rate reduces to a critical value, the ploughing force exceeds the shearing force component, the specific cutting energy rapidly increase. Ploughing is dominant in the cutting process. The size effect in turn deteriorates the machined surface quality. There is an optimal ratio of feed rate to the cutting edge radius which results in the best machined surface quality. The choice of sharper tool can decrease the critical uncut chip thickness. Then, the ploughing force and size effect is controled in low level. The optimal surface quality and machining accuracy can be further improved. It means that the sharper tool increases the optimal limit of the machined surface quality.

5 Summary and conclusion

This paper presents an investigation on the ploughing force in microcutting. A new comparison method to determine the ploughing force is developed by considering the cutting edge radius. The shearing force component is separated by linear extrapolation of cutting force to zero cutting edge radius. Then, the ploughing force is determined by the cutting force subtracting the shearing force. The larger cutting edge radius is accompanied with the greater ploughing force due to more materials being machined by the cutting edge round. It is also found that the ploughing force increases with increasing the uncut chip thickness. And, the ploughing force exceeds the shearing force at a critical cutting edge radius. Then, the ploughing becomes dominant in the cutting process. The nonlinear increase of the total specific cutting energy is attributed to the ploughing force induced by the blunt cutting edge.

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