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Adiabatic Shear Mechanisms for the Hard Cutting Process

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Abstract: The most important consequence of adiabatic shear phenomenon is formation of sawtooth chip. Lots of scholars focused on the formation mechanism of sawtooth, and the research often depended on experimental approach. For the present, the mechanism of sawtooth chip formation still remains some ambiguous aspects. This study develops a combined numerical and experimental approach to get deeper understanding of sawtooth chip formation mechanism for Polycrystalline Cubic Boron Nitride (PCBN) tools orthogonal cutting hard steel GCr15. By adopting the Johnson-Cook material constitutive equations, the FEM simulation model established in this research effectively overcomes serious element distortions and cell singularity in high strain domain caused by large material deformation, and the adiabatic shear phenomenon is simulated successfully. Both the formation mechanism and process of sawtooth are simulated. Also, the change features regarding the cutting force as well as its effects on temperature are studied. More specifically, the contact of sawtooth formation frequency with cutting force fluctuation frequency is established. The cutting force and effect of cutting temperature on mechanism of adiabatic shear are investigated. Furthermore, the effects of the cutting condition on sawtooth chip formation are researched. The researching results show that cutting feed has the most important effect on sawtooth chip formation compared with cutting depth and speed. This research contributes a better understanding of mechanism, feature of chip formation in hard turning process, and supplies theoretical basis for the optimization of hard cutting process parameters.

Keywords: adiabatic shear, FEM simulation, hard cutting process, sawtooth chip

1 Introduction

Hard cutting has become the primary recommended process of grinding in precision mechanics, due to its flexible process, economic efficiency, and environmental protection. As the process is still developing, much of the hard cutting mechanism hasn't been held completely, such as the formation mechanism related to the adiabatic shear phenomenon. It has been experimentally determined that at room temperature 90%–95% of the deformation work goes into heat. Ideally, if the deformation occurred instantaneously, all of the heat would be retained locally and the deformation would be truly adiabatic. During the dynamic deformation process, however, a certain fraction of the heat generated is lost to the surrounding metal, the exact amount depending both on the rate of deformation and the thermal properties of the material. In any case, if sufficient heat is retained, the deformation process is thought to be significantly modified and the deformation is referred to as adiabatic.

Multiple scholars have completed a number of research projects on adiabatic shear, including DODD, et al[1], DAFERMOS, et al[2] and ROGERS[3]. They summarized the work done on the prediction of ductile fracture initiation and propagation in orthogonal cutting operations. CERETTI, et al and CHRISTIAN, et al[4–7], established many simulation model to research this phenomenon. The results obtained from the FEM program show the potential of the customized FEM software DEFORM 2D in predicting cutting variables and serrated chip formation. LIN, et al[8], proposed a method based on combining the concepts of shape functions used in the finite element method with a molecular dynamics (MD) technique. This method was developed to evaluate the chip formation and strain as well as the stress distribution in the cutting of a single-crystal copper with a nano-scale mechanism. As a result, the shape and cutting force of discontinuous chip crack, the stress and strain distribution of the workpiece and chip, and the variation of various nodal forces on the chip–tool interface were derived by LIN, et al[9–10]. Over the last decade, the development and use of FEM to evaluate the effect of tool coatings, cutting environment and chip formation on cutting forces and temperatures, etc, has increased dramatically. The studies describe in detail the different chip separation criteria and FEM software used by MATSUMURA, et al[11] and NG, et al[12]. Refs. [13–16] presented a new approach for chatter modelling in micro-milling. The influence of the run-out effect on the

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stability lobes was investigated at different feed rates, demonstrating the developed chatter model's capability to quantitatively consider the run-out phenomenon. The results of this study showed that the stability limits decrease as the run-out length increases. Mathematical algorithms and formulations for integrating micro-scale residual stresses into axisymmetric FE models are developed and successfully implemented in the ABAQUS FEM code by employing a user-defined subroutine. For example, micro-scale residual stresses are integrated into an axisymmetric FE model of a shaft subjected to turning by AFAZOV, et al[16], and YE, et al[17], proposed a new theoretical model to predict the segment spacing in high speed cutting, and the model could satisfactorily capture the process of chip segmentation over a wide range of cutting speeds. Influence of material constitutive models and elastic–viscoplastic finite element formulation on sawtooth chip formation for modeling of machining was investigated by SIMA, et al[18] and MOLINARI, et al[19]. The results revealed that material flow stress and finite element formulation greatly affects chip formation mechanism.

When the tool rake angle is positive, the simulation is comparatively simple. When the tool is chamfered the simulation becomes difficult, as it could result in a bigger plastic deformation which would then lead to greater distortion. In order to analyze the effect of cutting edge preparation on the hard cutting process, a FEM model for PCBN tool, a hardened, high-speed cutting steel GCr15 is established. The characteristics of the cutting force in adiabatic shear are represented in the study as well as the cutting temperature field characteristics. Consequently, the effects of the cutting parameters on adiabatic shear and sawtooth formation are researched.

2 Constitution of FEM

2.1 Constitutive model of workpiece material

Flow stress is a function which concerns strain, stress and temperature. The Johnson-Cook model chosen by this study effectively combines the effect of strain hardening and strain rate strengthening as well as the effect of temperature softening, which could well describe the properties of metal materials under the conditions of large deformation, high strain rate effect and high temperature. Choosing flow stress is the main issue in the cutting simulation, which is adopted in the material constitutive model. The Johnson-Cook model is the most convenient in describing the properties of the material, as expressed in Eq. (1), which was proposed by JOHNSON, et al[20] and GUO, et al[21]:

$$\sigma = (A + B(\varepsilon^p)^n)\left(1 + C\ln\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_{\text{melt}} - T_0}\right)^m\right], \quad (1)$$

where A, B, C, m, n are material constants, σ is equivalent stress, ε^p is equivalent strain, $\dot{\varepsilon}^p$ is plastic strain rate, $\dot{\varepsilon}_0$ is reference strain rate, T_0 is reference temperature, and T_{melt} is melting temperature of workpiece. In this research, the workpiece material is grade GCr15 (HRC56-62), which is equivalent to US grade AISI52100. All of the parameters above could be obtained from experiments, as shown in Table 1.

Table 1. Johnson-Cook material hardened parameters

Parameter	A/MPa	B/MPa	C	n	m
Value	2482.4	1498.5	0.027	0.19	0.66

2.2 Material failure model of workpiece

Material failure is a phenomenon which involves complex physical mechanisms. According to the failure model, when a character parameter reaches the appointed critical value, the element is completely failed, and the FEM deletes it. This work adopts the Johnson-Cook failure model as shown in Eq. (2):

$$\varepsilon^f = (d_1 + d_2\exp(d_3\sigma^*))\left(1 + d_4\ln\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)[1 - d_5 T^{*m}], \quad (2)$$

where d_1, d_2, d_3, d_4, d_5 are material damage parameters and $\sigma^* = -R$, $\dot{\varepsilon}_0$ is the reference attributing strain. The shear failure model is based on the equivalent value of plastic strain at the integral unit. Failure phenomena occur when the failure parameter exceeds 1. Failure parameter is defined as shown in Eq. (3):

$$\omega = \sum\frac{\Delta\varepsilon^p}{\varepsilon_f^p}, \quad (3)$$

where $\Delta\varepsilon^p$ represents theequivalent plastic strain, and ε_f^p is failures strain. Equivalent plastic strain increment summation includes all increments in the analysis process. When ω is equal to 1, the material point will be deleted. Accordingly, the element is deleted in mesh, as shown in Table 2.

Table 2. Johnson-Cook failure model parameters

Parameter	d_1	d_2	d_3	d_4	d_5
Value	0.036 8	2.340	−1.484	0.003 5	0.411

2.3 Establishment of FEM model

Since hard cutting is a process involving high temperatures and pressure conditions, there is a large amount of deformation that occurs between the workpiece and its cutting tool. Furthermore, the process produces a complex nonlinear contact effect also affecting the workpiece and cutting tool. The FEM model uses an explicit method that continuously optimizes the motion model in a small increment of time. In order to reduce the cutting simulation time without negatively affecting the accuracy of the simulation, the model uses local mesh refinement. The rake angle of the tool is 0°, while the back angle of three other tools is set to 7°. Fig. 1 below introduces the cutting parameters.

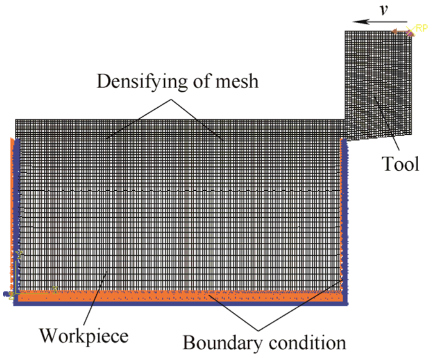


Fig. 1. Finite element simulation results

3 Results of FEM Simulation

To research the character of the formation of sawtooth in hard cutting process, the following cutting parameters are chosen: the cutting feed is set to 0.1 mm/r, cutting depth at 0.5 mm, and the cutting speed is 200 m/min.

3.1 Formation mechanism of adiabatic shear

The serrated chip formed from machining hardened steel is regarded as a "crack", which possesses a certain length as well as an extremely sharp crack at the endpoint. The crack stress and displacement characteristics can be abstracted into the following three basic types (as shown in Fig. 2). (1) Open crack: External loads of normal stress are perpendicular to the crack plane, and the relative displacement of the crack surface is perpendicular to the crack plane. (2) Sliding mode crack: External loads of the in-plane shear stress are perpendicular to the crack front, and there is evidence of crack sliding in the direction perpendicular to the crack front in its own plane. (3) Tearing mode crack: External loads are off-plane shear force, and the crack surface parallel to the crack front reveals dislocation movement in its own plane. Any kind of crack can be regarded as one of these three basic types. This paper uses the principle of linear elastic fracture mechanics to analyze serrated chip formation mechanisms in machining-hardened bearing steel. The workpiece material is linear elastic and does not consider the yield issues within the minimum range of the crack tip.

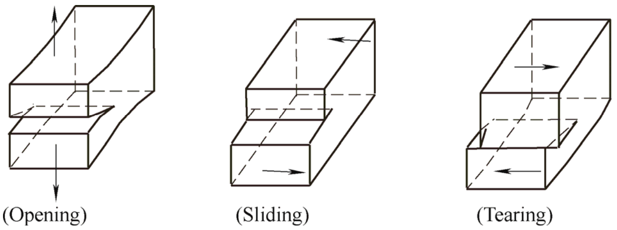

(Opening) (Sliding) (Tearing)

Fig. 2. Basic types of crack

The simulation results are shown in Fig. 3. The sawtooth chips are gradually formed from cutting forward of the tool.

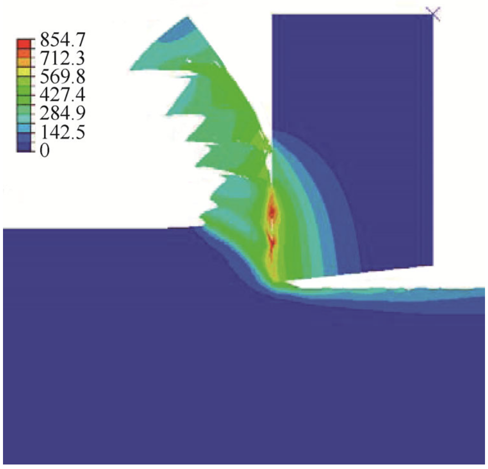
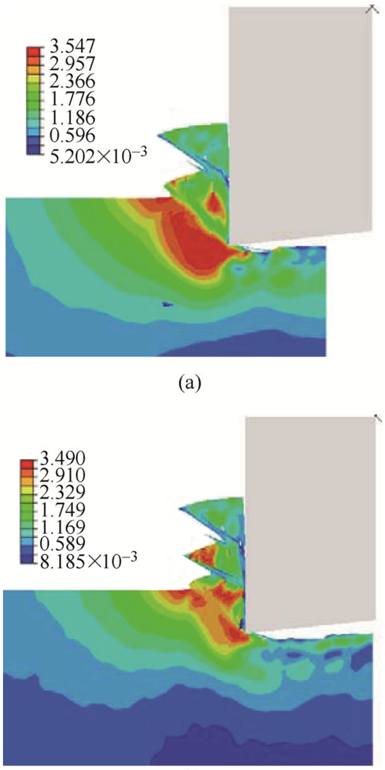


Fig. 3. Simulation result of temperature for sawtooth chip (℃)

The adiabatic shear formation process is shown from beginning to end in Fig. 4. Under high heat and heavy cutting forces, the plastic deformation is clearly caused above the joint of the rake face. Plastic deformation and energy accumulation is aggravated with the movement of the tool, which then causes sudden local shear and adiabatic shear bringing the energy accumulation level to a critical load, as shown in Figs. 4(a)–4(b). With the release of energy after the formation of the first sawtooth chip, the cutting system is instantaneously balanceable again; however, this balance is broken by the sharp increase in stress and stain caused by plastic deformation. As a result, the reciprocating cycle causes sawtooth chips again.



(a)

(b)

Fig. 4. Formation of adiabatic shear (10^3 MPa)

3.2 Formation Mechanism of Adiabatic Shear

Fig. 5 shows the course of cutting force changes. Analyzing the changes of the cutting force trend reveals that the dominant feature is cyclical fluctuations. The cutting force trend conforms to the frequency of sawtooth chip. The curve is almost linear in its growth at the beginning, and then slowly the growth reaches a certain value where finally the cutting force decreases rapidly. That is to say, this pattern is consistent with the jagged generated frequency identified in the timeline. This result shows that the first deformation zone began to focus on sliding deformation. Accordingly, its carrying capacity drops and geometric instability will accrue. Sawtooth chip is then completely generated and the cutting force reaches a minimal value, the deformation zone focused on a line. When the tool continues to move forward cutting the material, the cutting force gradually increases. When the tool is pointed, the cutting force once again reaches its maximal value. This analysis shows that the frequency of chip formation is related to the frequency of cutting force fluctuations.

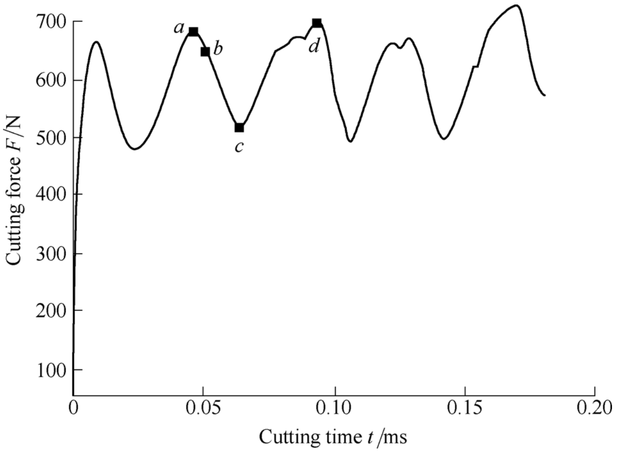


Fig. 5. Changing curve of cutting force

3.3 Research of cutting temperature field

Cutting temperature is a key parameter in analyzing the cutting processing. It has an important influence on the life of the tool as well as its surface quality. Simulation results indicate the heat of cutting concentrate at the contact area between the tool and workpiece. When the cutting speed is set at 250 m/min, the highest temperature reaches 820°, as shown in Fig. 3, which allows the rake face of the cutting tool to withstand the mechanical and temperature-related effect. In order to analyze the mechanical effect of adiabatic shear on machined surfaces during the cutting process, this research extracted data from 3 points on the machined surface. Its distribution is shown in Fig. 6 below.

Fig. 7 reveals changing temperature curves related to the 3 points. By comparing the change results, we find that the curves' change law remains the same; the temperature instantly increases 20° above room temperature. Then, the temperature drops slowly after it reaches the highest point. The highest temperature is 660°. When point 16 reaches its highest temperature, it becomes clear that sawtooth chip scraps have formed. As the tools of move forward, the highest temperature between points 16–25 rises and the energy accumulates gradually. This is when the condition of adiabatic shear occurred. At this time, point 25, which is located in the adiabatic shear roots, releases heat violently as its temperature also, reaches the maximum. From there, the highest temperature gradually reduces between points 25 and 30. When the temperature reaches 420° (the highest temperature measured at point 30), the new sawtooth chip formed. When the cutting tool continues to work, the temperature begins to rise again and the cutting process enters a new cycle.

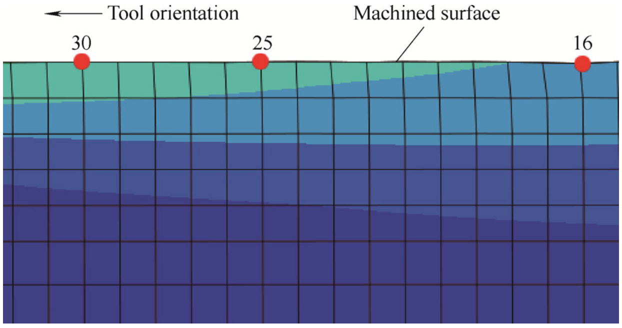


Fig. 6. Select points on machined surface

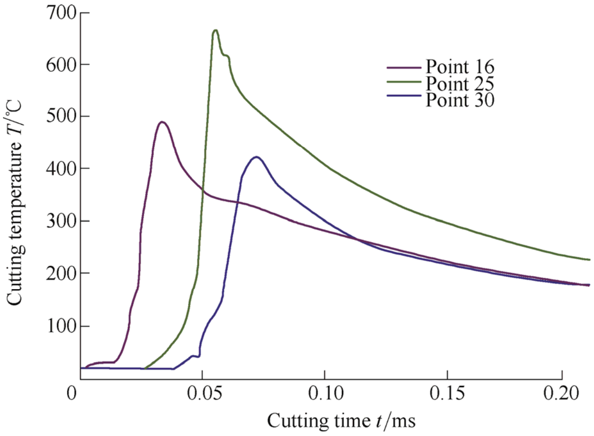


Fig. 7. Temperature changing curve of selected points

4 Impact of Cutting Parameters on Sawtooth Chip Formation

To verify the accuracy of the optimization platform, this research project designed an experiment to test the optimization results. The measurement of its cutting force adopts the KISTLER 9257B piezoelectricity force measure instrument. The cutting temperature is measured by a ThermoVision A40 infrared thermal imager. The PCBN tool is used to cut hardened steel. The experimental field device is shown in Fig. 8.

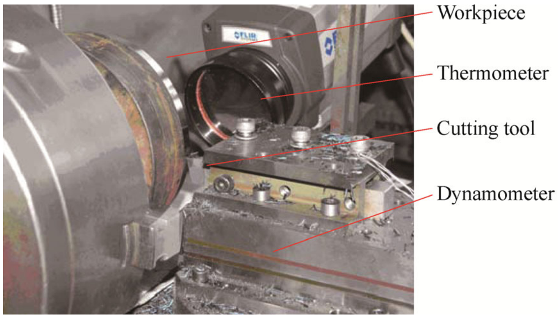


Fig. 8. Setting of experimental device

4.1 Characteristic parameter of sawtooth chip

Different parameters can be used to describe certain shape characteristics of sawtooth chip, including the macroscopic shape of the t chip, width of chip, spacing, and frequency of adiabatic shear band in sawtooth chip. Schulz and colleagues proposed a formula to describe the jagged chip *Gs*. This characterization method is easy and suitable for all materials that generate a sawtooth chip. The processing and quantitative analysis of the geometry of the sawtooth chips is expressed below:

$$Gs = \frac{h_1 - h_2}{h_1}, \tag{4}$$

where *Gs* could be described as the degree of sawtooth chip, h_1 is the distance measured from the chip top surface, and h_2 is the root of the distance measured from chip underside sawtooth. In order to reduce possible error inmeasurement, as well as improve the accuracy of the data analysis, the measurement process included each set of cutting parameters to select four section blocks, which were used to measure the h_1, h_2 and *Pc*, and *Pc* is sawtooth pitch. These statistics should then be generated by the chip morphology and draw a zigzag degree pattern with the corresponding cutting parameters and pitch curve, as shown in Fig. 9. And *Pc* is pitch of sawtooth.

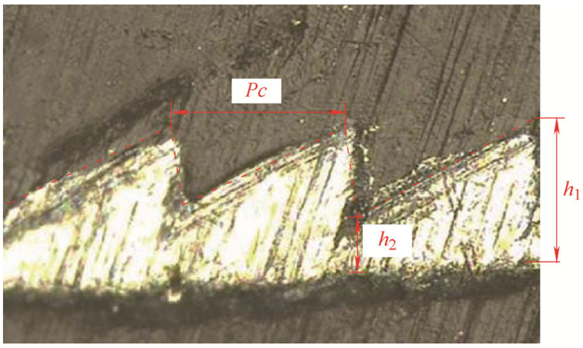


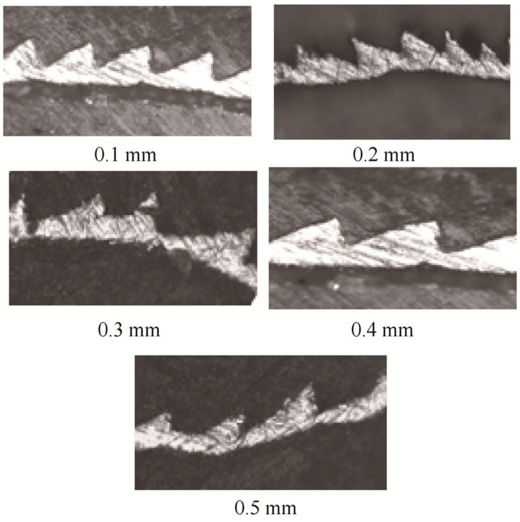
Fig. 9. Characteristic parameters of sawtooth

4.2 Effect of cutting parameters on chip formation

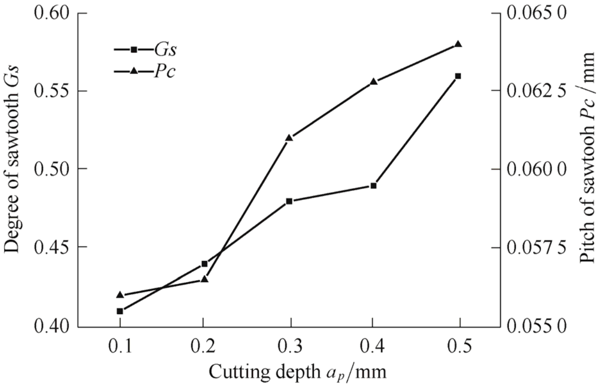
To research the effect of cutting conditions on sawtooth formation, experiments under different cutting parameters were completed. The single coefficient factor research programmed for cutting speed, feed and depth was adopted. The changes of cutting speed, cutting depth and feed rate influence the chip shape are researched.

4.2.1 *Effect of cutting depth on chip formation*

When the cutting speed is 200 m/min, and cutting feed equals 0.1 mm/r. Fig. 10(a) shows the changes of chip topography. As shown in Fig. 10(b), the change of sawtooth chip form is not particularly obvious in relation to the change in cutting depth. However, when the cutting depth increases from 0.1 mm to 0.5 mm, the sawtooth degree increased from 0.41 to 0.55, and pitch changed from 0.055 mm to 0.064 mm.



(a) Topography of sawtooth chip

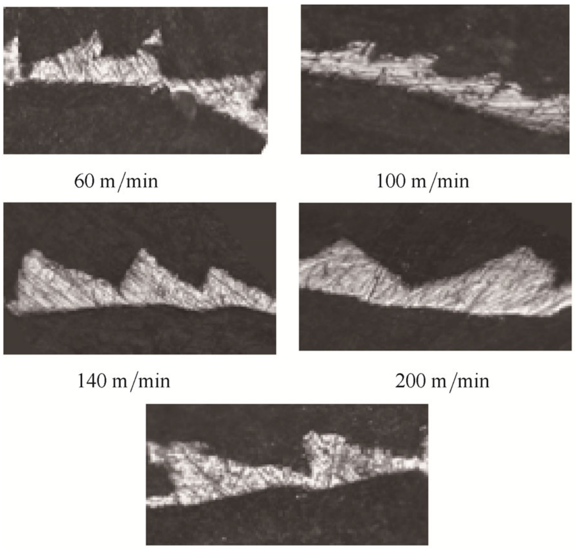


(b) Effect of cutting depth

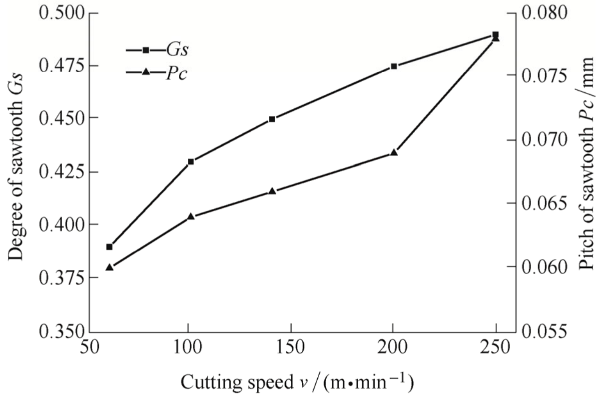
Fig. 10. Effect of cutting depth on chip formation

4.2.2 *Effect of cutting speed on chip formation*

When cutting feed equals 0.1 mm/r and cutting depth is 0.15 mm, the effect of cutting speed on sawtooth formation is researched. Fig. 11 shows that the degree of sawtooth chip and the pitch have a linear increasing trend in relation to increases in cutting speed although the degree of change is small. The reason for this result is that the increase of cutting speed causes an increase of material strain and strain rate as well. It produces heat in the deforming zone. And since hardened steel has poor heat conductivity, the heat cannot expand to other zones. Therefore, it causes the temperature to increase, which in turn softens the metal. It also leads to a gradual increase in the adiabatic shear effect as well as a gradual increase in the sawtooth chip degree.


60 m/min
100 m/min
140 m/min
200 m/min
250 m/min

(a) Topography of sawtooth chip

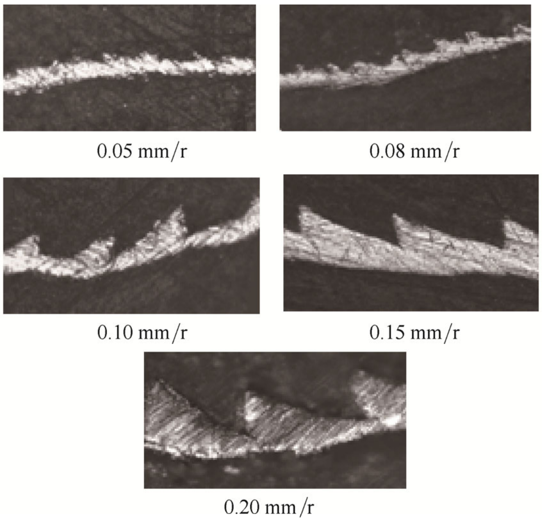


(b) Effect of cutting speed

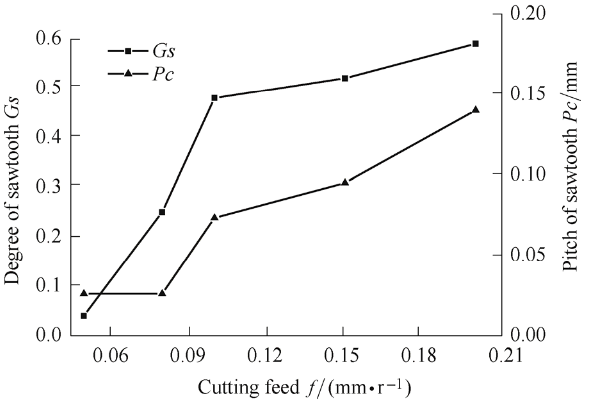
Fig. 11. Effect of cutting depth on chip formation

4.2.3 *Effect of cutting feed on chip formation*

When the cutting speed is 200 m/min and cutting depth is 0.15 mm, the effect of cutting feed on sawtooth formation is researched. As shown in Fig. 12, when the cutting feed rate is 0.05 mm/r, the chip shape does not transform into the sawtooth shape completely. Instead, the lateral chip presents a smooth wave shape, at which point *Gs* is 0.05. When the feed rate increases to 0.20 mm/r, the sawtooth degree of chip would change from 0.05 to 0.55, as shown in Fig. 12. As indicated, the pitch of generated chip segments changes from 0.03 mm to 0.14 mm. The results suggest that the plastic deformation of adiabatic shear region increases remarkably with an increase in the feed rate. Compared with cutting speed and depth, the most obvious parameter for the formation of sawtooth is the cutting feed rate reversely. Therefore, there appears to be an intimate relationship between the cutting feed and chip deformation.


0.05 mm/r
0.08 mm/r
0.10 mm/r
0.15 mm/r
0.20 mm/r

(a) Topography of sawtooth chip



(b) Effect of cutting feed

Fig. 12. Effect of cutting feed on chip formation

5 Conclusions

(1) Fluctuation frequency of cutting force is the same as the generated frequency of sawtooth chips. In one cycle, the cutting force first decreases and then increases when an adiabatic shear cycle is completed. The cutting force then reduces to a minimum value.

(2) The adiabatic shear process involves energy accumulation and release. The machined surface influenced by the heat source shows a cyclical trend. It is influenced most dramatically by the heat source and when an adiabatic shear cycle is completed.

(3) The formation of sawtooth chips has an increased trend aligned with increasing cutting parameters. The most obvious parameter is the cutting feed rate reversely. There is only a slight increase of the sawtooth degree and pitch is slight in connection with an increase of the cutting depth and cutting speed. The softening effect of heat has an important role in the formation of sawtooth when changing the cutting speed.

References

[1] DODDB, BAI Y. *Adiabatic shear localization, second edition:*

Frontiers and Advances [M]. Burlington, 2012.

[2] DAFERMOS C M, HSIAO L. Adiabatic shearing of incompressible fluids with temperature-dependent viscosity[J]. *Quarterly of Applied Mathematics*, 1983, 41: 45–58.

[3] ROGERS H C. Adiabatic shearing-general nature and material aspects[M]//*Material Behavior Under High Stress and Ultrahigh Loading Rates*. Springer US, 1983: 101–118.

[4] CERETTI E, LUCCHI M, ALTAN T. FEM simulation of orthogonal cutting: serrated chip formation[J]. *Journal of Materials Processing Technology*, 1999, 95(1): 17–26.

[5] CHRISTIAN H, SVENDSEN B. Simulation of chip formation during high speed cutting[J]. *Journal of Materials Processing Technology*, 2007, 186: 66 –76.

[6] CERETTI E, FALLBÖHMER P, WU W T, et al. Application of 2D FEM to chip formation in orthogonal cutting[J]. *Journal of Materials Processing Technology*, 1996, 59(1): 169–180.

[7] CERETTI E, LAZZARONI C, MENEGARDO L, et al. Turning simulations using a three-dimensional FEM code[J]. *Journal of Materials Processing Technology*, 2000, 98(1): 99–103.

[8] LIN Z C, LO S P. 2-D discontinuous chip cutting model by using strain energy density theory and elastic-plastic finite element method[J]. *International Journal of Mechanical Sciences*, 2001, 43(2): 381–398.

[9] LIN Z C, HUANG J C. A nano-orthogonal cutting model based on a modified molecular dynamics technique[J]. *Nanotechnology*, 2004, 15(5): 510.

[10] LIN Z C, HUANG J C, JENGY R. 3D nano-scale cutting model for nickel material[J]. *Journal of Materials Processing Technology*, 2007, 192: 27–36.

[11] MATSUMURA T, USUI E. Simulation of cutting process in peripheral milling by predictive cutting force model based on minimum cutting energy[J]. *International Journal of Machine Tools and Manufacture*, 2010, 50(5): 467–473.

[12] NG E G, ASPINWALL D K. Modelling of hard part machining[J]. *Journal of Materials Processing Technology*, 2002, 127(2): 222–229.

[13] RATCHEV S M, AFAZOV S M, BECKER A A, et al. Mathematical modelling and integration of micro-scale residual stresses into axisymmetric FE models of Ti6Al4V alloy in turning[J]. *CIRP Journal of Manufacturing Science and Technology*, 2011, 4(1): 80–89.

[14] RATCHEV S M. Concurrent process and facility prototyping for formation of virtual manufacturing cells[J]. *Integrated Manufacturing Systems*, 2001, 12(4): 306–315.

[15] PANTALÉ O, BACARIA J L, DALVERNY O, et al. 2D and 3D numerical models of metal cutting with damage effects[J]. *Computer methods in applied mechanics and engineering*, 2004, 193(39): 4383–4399.

[16] AFAZOV S M, RATCHEV S M, SEGAL J, et al. Chatter modelling in micro-milling by considering process nonlinearities[J]. *International Journal of Machine Tools and Manufacture*, 2012, 56: 28–38.

[17] YE G G, XUE S F, JIANG M Q, et al. Modeling periodic adiabatic shear band evolution during high speed machining Ti-6Al-4V alloy[J]. *International Journal of Plasticity*,2013, 40: 39–55.

[18] SIMA. Mohammad, OZEL Tugrul. Modified material constitutive models for serrated chip formation simulations and experimental validation in machining of titanium alloy Ti–6Al–4V[J]. *International Journal of Machine Tools & Manufacture*, 2010, 50: 943–960.

[19] MOLINARI A, MUSQUARC, SUTTERG. Adiabatic shear banding in high speed machining of Ti–6Al–4 V: experiments and modeling[J]. *International Journal of Plasticity*, 2002, 18: 443–459.

[20] JOHNSON G R, COOK W H. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures[J]. *Engineering Fracture Mechanics*, 1985, 21(1): 31–48.

[21] GUO Y B, WEN Q, WOODBURY K A. Dynamic material behavior modeling using internal state variable plasticity and its application in hard machining simulations[J]. *Journal of Manufacturing Science and Engineering*, 2006, 128(3): 749–759.

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