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ORIGINAL ARTICLE

An experimental study on influences of material brittleness on chip morphology

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Abstract Though several material properties such as hardness, thermal conductivity, specific heat, strain hardening, and thermal softening ability have been studied in terms of influencing segmental or serrated chip formation process, rare study about material brittleness affecting the chip formation process has been carried out. In this paper, an orthogonal cutting experiment with four steels with different brittleness was carried out. The effect of workpiece material brittleness on segmental chip formation and consequent chip morphology was investigated. The experimental results show that the material brittleness heavily affects chip formation process and chip shape. A novel chip formation model was developed to explain the mechanism of material brittleness working on the chip formation process. The mechanism is that material brittleness lowers the value of failure strain and thus makes the maximum stress in flow stress curve occur earlier, which leads to the catastrophic shear instability in primary shear zone and consequent segmented chip.

Keywords Steel · Brittleness · Chip formation · Segmentation

1 Introduction

Segmental chip is popular when machining the difficult-to-machine materials, while some easy-to-cut materials can form segmented chips as well at enough high cutting speeds. Since the chip formation has significant influences on the tool life, machined surface integrity, chip breaking, material removal rate, and automatic manufacturing, the mechanism of segmented chip formation has been a hot topic in the machining fields for many years [1–3].

By now, there have been two predominant theories about segmented chip formation, namely (a) periodic crack theory and (b) thermoplastic shear instability theory.

Nakayama et al. in 1988 [4], Shaw and Vyas in 1989 [5] suggested that segmented chip is due to the inherent brittleness of workpiece on the basis of the chip pattern observing. They presumed that crack initiates at the upside of chip due to less normal stress there and propagates along primary deformation zone down to tool tip. The crack closes until the normal stress is large enough. Hua and Shivpuri in 2004 [6] supported the periodic crack theory by numerical chip formation simulation results and argued that crack initiates within the primary shear zone and propagates to the tool tip at lower cutting speed, while to the free surface, at higher cutting speed. More recently, Kountanya et al. in 2009 [7] carried out an experimental and simulative study on steel 100Cr6 in its hardened state and found that shear crack was the dominant mechanism causing chip to segment.

Recht in 1964 [8] developed a classical model for describing catastrophic shear instability in machining and explained that catastrophic shear would occur in plastically deformed regions when the slope of the true stress true strain curve became zero. He also formulated a critical cutting speed Vcr (in terms of flow stress, thermal softening, strain hardening), above which catastrophic shear instability will initiate. In 1985, he introduced the adiabatic shear theory to describe the chip segmentation process during hard cutting [9]. Similar opinions can also be found in works of Komanduri [10], Lee [11], and Gente and Hoffmeister [12].

Based on the two theories, the influences of material properties on chip formation have been extensively studied. Poulachon and Moisan in 2001 [13] investigated the effect

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Table 1 Chemical composition of experimental materials

Materials	C	Si	Mn	Cr	Ni	P	S	Cu	Mo
18CrNiWA	0.177	0.271	0.509	1.51	4.06	0.021	0.005	0.083	W1.34
40Cr	0.403	0.287	0.577	0.0937	0.055	0.0175	0.0082	0.077	
30Cr2Ni2MoA	0.30	0.24	0.46	1.44	2.06	0.020	0.020	0.20	0.37
45#	0.47	0.26	0.70	0.008	0.004	0.019	0.030	0.006	As0.005

of hardness on chip formation during cutting different heat-treated steel 100Cr6 at different cutting speeds. They found the tendency to form serrated chip indeed increased with the increase of hardness. The FEM simulation results also showed a better agreement with the experiments when material hardness was considered as a parameter in material model [14, 15]. Costin et al. in 1979 [16] carried out an experimental study with AISI1018 cold-rolled steel and 1020 hot-rolled steel to verify the role of strain hardening on formation of shear localization and suggested that larger strain hardening slope tends to delay the onset of shear localization and in turn the appearances of chip segmentation. Hartley et al. in 1987 [17] conducted dynamic torsion experiments with steels and found that localization takes place more readily in materials with low strain rate sensitivity, low thermal conductivity, and high thermal softening rate.

Numerical simulation of machining process has been widely used to study the influences of material properties on chip formation by varying one property parameter while keeping the others constant. Martin Bäke carried out a series of FEM simulations of chip formation to investigate the influence of thermal softening parameter, strain hardening exponent, and thermal conductivity on chip shape [18, 19]. He suggested that the thermal softening and strain hardening parameters influences chip shape mainly by affecting the onset of the maximum of flow stress, that the earlier the onset of the maximum of flow stress is, the lower the cutting speed for serrated chip is required. As for thermal conductivity, Martin Bäke's FEM simulation results showed that the degree of segmentation decrease with increasing the thermal conductivity.

Though vast researches about material properties influencing the chip formation process have been experimentally or numerically carried out, few has been conducted about how material brittleness affects the chip formation, especially for segmented or serrated chip formation. Material brittleness greatly changes the value of material failure strain at which the material loses its strength and shear instability initiates. This shear instability, never mind if initiated by plastic fracture or adiabatic shear, will lead to the onset of segmental chip [19].

In this paper, four steels with different value of brittleness were used in an orthogonal cutting experiment. The role of material brittleness on chip formation and final chip morphology was validated. A model of chip formation was proposed, and the mechanism of brittleness working on chip shape was analyzed.

2 Experiment

2.1 Workpieces

Four steels were used for the experiment. They are 18CrNiWA, 40Cr, 30Cr2Ni2MoA, and 45# (AISI 1045) which are marked as M1, M2, M3, and M4, respectively, for short in following sections. The chemical compositions of these steels are listed in Table 1. The major physical and mechanical properties of these steels are listed in Table 2.

Elongation percentage (EP) of a material indicates the plastic deformation ability of the material. It is used to represent material brittleness in mechanical textbooks. The lower the EP value means the brittler the material is. It can be seen from Table 2 the brittleness order of the given materials is M1>M2>M3>M4.

2.2 Experimental setups

The experimental materials were originally sticks in shape with 100 mm in diameter. They were machined into disks by electrical discharge machining (EDM) with 3 mm in thickness. Since the surfaces machined by EDM changed

Table 2 Physical and mechanical properties of experimental materials

Materials	Yield strength (MPa)	Tensile strength (MPa)	Elongation percentage	Thermal conductivity (W/(m·K))	Specific heat (J/(kg•K))
18CrNiWA	1,221	1,261	7	52.5	490
40Cr	633	917	10.5	42.6	473
30Cr2Ni2MoA	800	903	11.5	52.5	490
45#	450	720	16	50.2	480

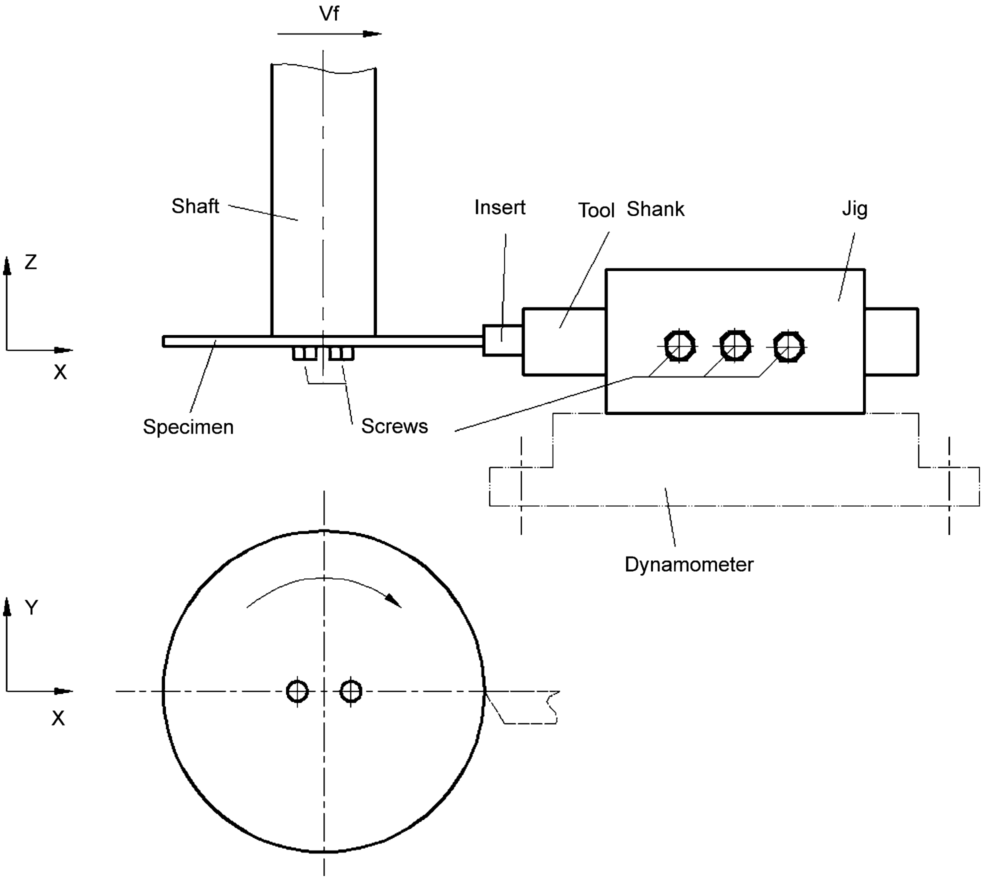

Fig. 1 Experimental setup

their matrices and in consequence their mechanical properties by the heat due to electrical discharge, fine grinding were carried out on each side of the specimens by 0.5 mm in depth. The final specimens are thus 100 mm in diameter and 2 mm in thickness (Fig. 1). Two drilled holes with 5 mm in diameter with 14 mm distance from each other are symmetrically about the center of the disk. The specimen was fixed on the shaft with two screws with M4. The shaft shown in Fig. 1 is 32 mm in diameter and 60 mm in length. The shaft was installed on the spindle of a milling machine whose type is DEAWOOD VCE 500. The tool shank passed through the rectangular hole in the center of the jig and was fixed by three screws with M6. The insert used in the experiments is a kind of MITSUBISHI coated insert type TCMT16T304 UC5115. After each specimen was machined the insert was replaced by a new one to eliminate the influence of tool wear on the experimental result. After all the assemblage, the cutting edge should be parallel to the machine spindle axis to ensure the orthogonal cutting condition.

The rake angle and uncut chip thickness were fixed at 0° and 0.1 mm, respectively. The cutting speeds varied from 50 to 2,000 m/min. At each cutting speed, the specimen disk was cut by a length of three revolutions (as one cutting circle) at the current diameter *d* which would shrink with the cutting going on and was resettled after each cutting circle. The cutting width is 2 mm, and the cutting condition is dry cutting.

The chips generated were collected, and the mediate portion of each was intercepted, mounted, polished, and photoed by optical microscope.

3 Experimental results and discussion

On the base of chip optical photos, the chip segmentation degree Gs defined as Gs = (h1 − h2)/h1 (Fig. 2) was measured. All measurements of the chip segmentation were

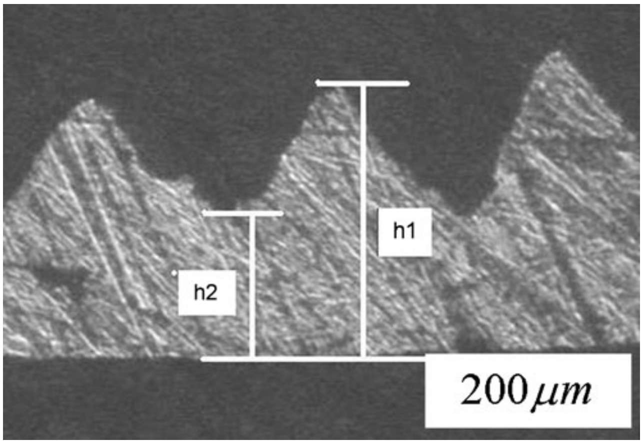

Fig. 2 Definition of segmentation degree Gs

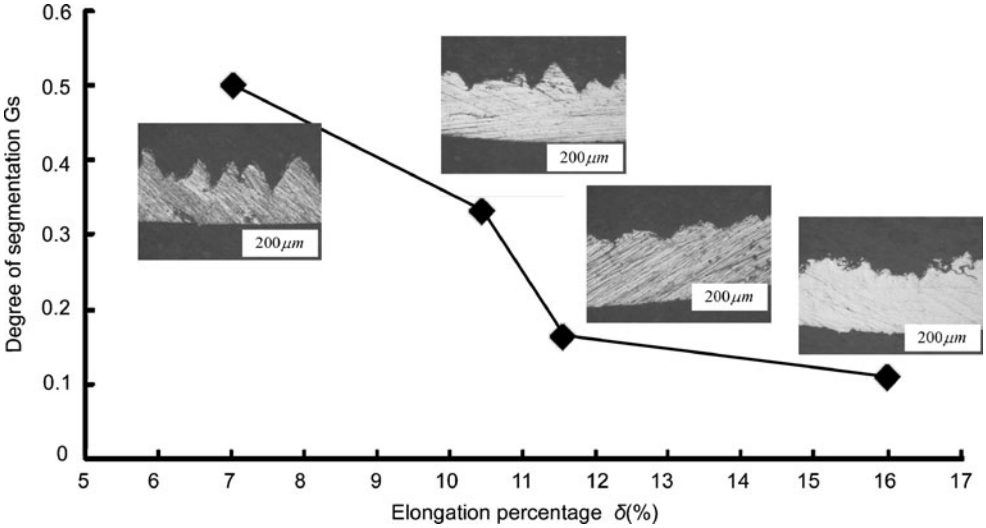

Fig. 3 Segmentation degree Gs vs. elongation percentage δ at Vc=100 m/min

carried out starting at the thicker end of the chip for ten neighboring segments.

Chips segmentation degree Gs vs. elongation percentage δ curve at lower cutting speed Vc=100 m/min was obtained as shown in Fig. 3. The chip segmentation degree Gs shows an obvious dependency on the elongation percentage δ. It can be seen from Fig. 3 that with the increase of δ from 7 to 16 Gs decreases from 0.5 to 0.11. At cutting speed Vc= 100 m/min, the Gs of materials M1, M2, M3, and M4 are 0.5, 0.33, 0.16, and 0.11, respectively. A sharp decline occurs between EP 10.5 and 11.5. The decline rate becomes smaller with the further increase of δ. The whole curve shows a gradually declining trend along which the segmentation becomes flatter.

On the other hand, at the constant segmentation degree Gs=0.5, the curve of elongation percentage δ vs. cutting speed Vc was obtained as shown in Fig. 4. It is obvious that materials with different brittleness need to reach different cutting speeds to catch the same segmentation degree Gs= 0.5, that with the increasing of elongation percentage δ the required cutting speed Vc enhances too. At δ=7, the required cutting speed is 90 m/min, while at δ=10.5, the cutting speed Vc reaches to 200 m/min. There is a Vc sharp increase between δ=10.5 and δ=11.5 at which the cutting speed is 500 m/min. And at δ=16, the cutting speed is 800 m/min. The slope after δ=11.5 is larger than that before δ=10.5.

Four steels with different brittleness were used for this experiment to verify the role of material brittleness on chip formation, especially segmental chip formation. The results of the experiment reveal that the brittler the material is, the easier the material is to be segmented.

Materials with different brittleness have different failure strain at which the materials will lose their strength. A higher value of brittleness means a lower value of failure strain. In Fig. 5, curve 1 is from a material with normal failure strain. By comparison, curve 2 is from a brittler material. The process of chip formation can be decomposed into three stages (Fig. 5 I, II, III). With the advancing of cutting tool, the strain of point A increases. For the case of curve 1 though the strain reaches its maximum value at stage III, the stress has not yet arrived its maximum value. The deformation in the primary shear zone is analytically

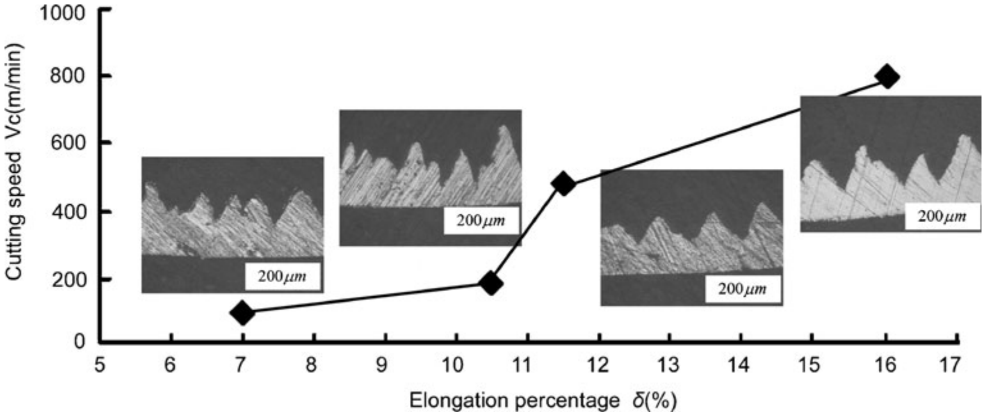

Fig. 4 Required cutting speed Vc vs. EP at Gs=0.5

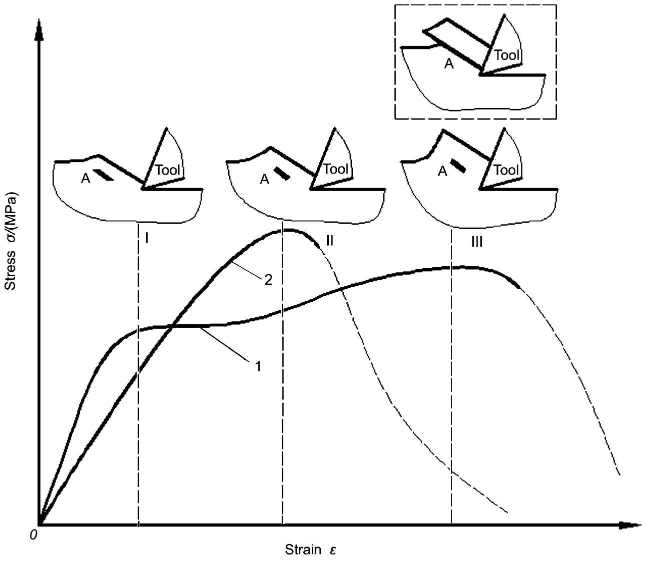

Fig. 5 The mechanism of brittleness working on chip formation

uniform, and the final chip is continuous (Fig. 5). But for the curve 2, the strain of point A gets the maximum value (failure strain) when it reaches stage II, and simultaneously, the stress reaches the maximum value. With the further advancing of cutting tool, the shear deformation will be concentrated in the shear plane passing through point A due to the decrease of the shear stress. The decrease of shear stress will further make the deformation more concentrated. Thus, the concentrated shear band formed and the final chip looks segmented (shown as the figure enclosed in dashed rectangle in Fig. 5).

So the mechanism of material brittleness working on chip formation is that it lowers the failure strain and thus the stress maximum in flow stress occurs earlier. The smaller the material brittleness is, the earlier the stress maximum appears. However if the material is too brittle, the chip may be irregularly shaped fragments due to no enough volume of chip accumulated before the main shear plane fails. This type of chip is named by Astkahov “irregularly broken chip” [20].

Materials with high hardness have been found easy to produce segmental chips. This is because the brittleness often increases when the hardness increases (the high strength of hardened metals prefers the accumulation of chip before the main shear plane catastrophically shears). Metals such as steels, aluminum alloys at hardened state have been found easy to produce segmental chips [21–23]. This is in accordance with the result of the study of this paper.

However, material brittleness varies with temperature and strain rate. Generally, material brittleness decreases with temperature rising, while increases with the strain rate increasing. The coupling between the temperature and the strain rate makes the problem so complex that it is worth a special study in another paper.

4 Conclusion

This work attempts to validate the effect of material brittleness on segmental chip formation. Orthogonal machining experiments were conducted. The findings in this study may be summarized as follows:

1. At fixed cutting speed, with the decrease of material brittleness (that is the increase of material elongation percentage), the chip segmentation degree decreases.
2. To reach the same chip segmentation degree, the required cutting speed increases with the decrease of brittleness (that is the increase of material elongation percentage).
3. The mechanism of material brittleness influencing chip formation and resultant chip shape is that it lowers the value of failure strain and thus makes the maximum stress in flow stress curve occur earlier, which leads to the catastrophic shear instability in primary shear zone and consequent segmental chip.

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