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On adiabatic shear fracture in high-speed machining of martensitic precipitation-hardening stainless steel

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ABSTRACT

The serrated chip produced in high-speed machining of martensitic precipitation-hardening stainless steel is inevitably tore up into isolated segments due to adiabatic shear fracture with the further increase of cutting speed. The induced mechanism of adiabatic shear fracture and the corresponding damage process in high-speed machining are investigated through quick-stop tests and chip morphology examinations. The isolated segments generated due to adiabatic shear fracture which is found in the rate-related process of adiabatic shear evolution is a cyclic process of energy convergence and release with ductile-brittle damage transition. The fracture energy of adiabatic shear band approaches a stable saturation limit with the increases of cutting speed and feed. On the basis of saturation limit model, the critical fracture energy is predicted by cutting conditions and compared with the experimental results.

1. Introduction

High-speed machining technology has been playing a critically important role on developing manufacturing industries and heatedly concerned and discussed. As it is known, for most metal workpiece materials, the serrated chip formation due to the occurrence of adiabatic shear caused by the local softening effect exceeding the strain and strain rate hardening in primary shear zone resulting from large and fast deformation and heating is the main characteristic of high-speed machining. Most of the early studies summarized by Bai and Dodd (1992) and Wright (2002) who dealt with the ASB formation criterion and the localization laws for the comprehensive theoretical and experimental foundations indicated that the formation of adiabatic shear band (ASB) induced by the occurrence of adiabatic shear would reslut in fracture subsequently. With the further increase of cutting speed, some high-speed machining tests of difficult machining materials demonstrated that when the cutting speed increased up to a critical value, the produced serrated chips were tore up into small isolated segments due to the occurrence of adiabatic shear localization fracture (or adiabatic shear fracture, ASF). The cracks in the serrated chip completely propagate along ASBs induced by the occurrence of adiabatic shear and promote the cut to be discontinuous. Komanduri et al. (1982) observed in the conducted machining of AISI 4340 steel that the serrated chip fracture alone the shear band is caused by adiabatic shear evolution due to the heat and deformation concentration in primary shear zone. Gente et al. (2001) conducted a quick-stop experiment to obtain titanium alloy chip roots by using high pressure gas gun and the formation of adiabatic shear band and crack propagation process was analyzed. Barry and Byrne (2002) observed the shear band propagation and the fractured surface of titanium alloy chip roots obtained through quick-stop tests. Hua and Shivpuri (2004) applied FEM software in simulating the crack propagation in primary shear zone of titanium alloy at various cutting speeds. Su and Liu (2010) investigated the influence of material brittleness on serrated chip formation through an orthogonal cutting experiment with four steels and suggested that the serrated chip fracture results from the brittleness enhancement. Wang and Liu (2014) suggested that the mechanism of governing chip formation and fracture was the property transition from plastic to brittle under high cutting speed. Minjie et al. (2004) observed the fracture in transformed band in serrated chip of high-strength steel due to adiabatic shear evolution. Dur-

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Table 1
Chemical composition of FV520(B) steel (wt.%).

C	Si	Mn	Ni	Mo	Cu	Nb	P
0.072–0.076	0.28–0.36	13.37–13.83	5.48– 5.62	1.56	1.58	0.33	0.03

Table 2
Thermo-physical parameters of FV520(B) steel.

ρ/(kg/m^3)	c/(J/kg K)	k/(W/m K)	T_m/°C
7800	460	17.6	1432

ing the fracture of serrated chip, it is difficult in observing the developments of shear bands and cracks in time, but the experimental methods of the existing studies provide the basis for further research. In the increasing process of cutting speed, the occurrence of adiabatic shear fracture unavoidably impacts the machining process and still needs deeper investigations. Recently, Liyao et al. (2013) found that the formation and fracture of ASB in serrated chip is energy-related regularity and built up saturation limit model to calculate the ASB energy limit in high-speed machining of hardened steel. In the present study, martensitic precipitation-hardening stainless steel which is a typical difficult machining material due to its poor thermal property and selected as the workpiece. The induced and damage mechanism of adiabatic shear fracture in high-speed machining is investigated through a quick-stop device which is designed to obtain chip roots and chip morphology observation. The physical model of adiabatic shear fracture is built up and its corresponding damage process is analyzed by using a scanning electron microscope (SEM). On the basis of saturation limit model, the critical energy during adiabatic shear fracture with the cutting conditions is predicted and compared with the experiment results.

2. Experimental

Martensitic precipitation-hardening stainless steel with good mechanical performance which is widely used in industry is a typical difficult machining material due to poor thermo-physical property and FV520(B) stainless steel with hardness of HRC 40 through normalization and tempering is selected as the workpiece in this study. The chemical composition and the thermo-physical parameters of FV520(B) steel are shown in Tables 1 and 2 and its metallographic structure is shown in Fig. 1. The cylindrical workpiece was machined for orthogonal cutting tests and the setup arrangement is shown in Fig. 2. Machining tests were conducted on OKUMA Mill-Turn CNC by using cemented carbide inserts with

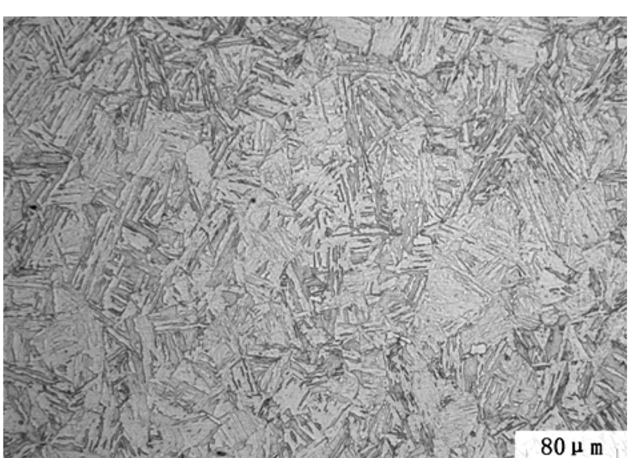

Fig. 1. Metallographic structure of FV520(B) steel with optical microscope.

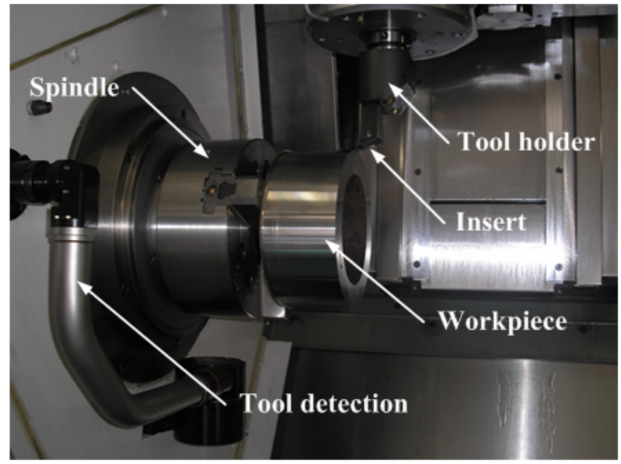

Fig. 2. General arrangement of high-speed machining setup.

rake angle of −10° under dry cutting condition. A cylindrical workpiece tube with thickness of 2 mm was machined and held by the lath chuck. This was to ensure that a plane strain condition could prevail during chip formation process. The tool feed in the X-direction determines the undeformed chip thickness. The cutting speed ranges is up to 1100 m/min and the feed is 0.3–0.5 mm/r.

In order to investigate the process of adiabatic shear fracture in serrated chip, quick-stop tests are essential to be conducted to obtain chip roots under high-speed machining. A quick-stop device used in the condition of high-speed orthogonal machining was designed based on the quick-stop method proposed by Buda (1972) who applied cutting force in snapping workpiece with a kerf to obtain chip root. The whole mechanical arrangement of quick-stop device in high-speed turning is shown in Fig. 3a. Fig. 3b illustrates the chip root arresting principle which is to record the moment of shear band fracture under different cutting condition. The quick-stop workpiece with a hole and a kerf is manufactured to obtain chip root, the incline surface can protect the tool tip broken as it cuts into the workpiece. In Fig. 3b, the dotted line is the tool tip trajectory related to the workpiece, the cutting speed is v, the cutting thickness is a_c, the feed rate is v_f, the time of tool cutting initial position is t_0, the fracture time of the tool cutting positions when the chip root departures from the workpiece is t_f. At the time t_f, the loading area between the tool tip and the hole reaches the minimum, the region of the workpiece in which the tool is engaged fractures due to the tensile force resulting from the cutting force, and thus the chip root generates and departures from the workpiece body, arresting the region of shear zones, as shown in Fig. 3a. The chip root can quickly break away from the cutting setup due to the centrifugal force resulting from the rotation of principal axes. The mass of the region of the workpiece which fractures from the workpiece body is about 0.1–0.2 g and the cutting force at fracture is about the order of 700–1000 N. Thus, the arresting acceleration can be up to nearly 10^6–10^7 m/s^2 when the cutting speed is above 800 m/min. As a result of such high accelerations, the tool advance during separating is very small to the undeformed chip thickness. The quick-stop workpieces are fixed on the workpiece holder which is held in the lath chuck through the mandrel. The cutting thickness is accurately controlled through setting the feed of the machine tool, and the new changed tool is adjusted every time through the tool detection. During the tests, cutting takes place on the straight edge of a triangular insert. The workpiece is clamped to a mandrel which is held in the lathe chuck. When the spindle is rotating at the required speed, the cutting tool is rapidly fed forward to a predefined position and held there firmly until the chip root is obtained. These quick-stop tests were performed at the onset condition of