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Research paper

On the instability of chip flow in high-speed machining

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ABSTRACT

High cutting speed usually gives rise to a breakdown of steady chip flow and results in a serrated flow pattern, which is one of the most fundamental and challenging problems in metal cutting. Here, we systematically analysed the experimental results of high-speed cutting on various typical metallic materials over wide ranges of cutting speeds. With considering the coupling effects of inertial, tool-chip compression and material convection, the critical condition for the onset of serrated chip flow is determined based on a stability analysis of the deformation inside primary shear zone. It is found that the emergence of the serrated chip flow is dominated by a dimensionless number which characterized the competition among the effects of inertia, thermal softening, strain hardening, elastic unloading, viscous diffusion and thermal diffusion. More interestingly, a power law between the serration frequency and the *Reynolds* thermal number *Pe* is clearly revealed.

1. Introduction

Cutting is a ubiquitous activity in daily life, science and technology (Atkins, 2009; Dodd and Bai, 2012; Shaw, 2005). The metal cutting operation referred to as the chip formation process has been widely studied for its obvious economic and technical importance. Its roots go back at least 130 years to when Tresca (1878) presented pictures of viscoplasticity in metal cutting and Mallock (1881) drew sketches of chip formation. The growing demand for enhanced production efficiency and product quality has led to the rapid development of high-speed machining (HSM) technology. In spite of extensive studies, several fundamental aspects of the metal cutting process are poorly understood. One of these aspects is the onset of serrated chip flow. The puzzle of why continuously smooth chip flow in metal cutting gives way to periodically serrated chip flow as the cutting speed increases still remains elusive.

The formation of serrated chip flow has been extensively studied (Sutter and List, 2013; Vyas and Shaw, 1999). It is found that the emergence of serrated chip flow is usually related to shear banding occurring in the primary shear zone (PSZ), which is fuelled by a complex nonlinear coupling of high strain, high strain rate and high temperature rise during HSM (Recht, 1964; Ye et al., 2014). Because thermoplastic instability-induced shear banding is a major failure mechanism in impact loading (Bai and Dodd, 1992; Dodd and Bai, 2014), a fundamental understanding of the shear banding mechanism is of considerable interest to both the mechanics and the materials science communities. A large amount of excellent work regarding shear banding can be found in the literature (Aifantis, 1987; Daridon et al., 2004; Dodd et al., 2015; Grady, 1994; Meyers, 1994; Molinari, 1985; Nemat-Nasser and Okada, 2001; Rittel, 1998; Rittel and Wang, 2008; Walley, 2007; Zhang et al., 2005; Zhang et al., 2008).

The onset of thermoplastic instability-induced shear banding has been extensively examined, either through a maximum stress criterion, through linear stability analyses (Bai, 1982; Batra and Wei, 2006; Molinari, 1997), or through nonlinear analyses (Wright, 2002). How the shear band develops after instability and how it interacts with the boundaries or neighbouring localizations have also been extensively studied. The defining experimental results in shear localization were determined using a torsional Kolsky bar to generate shear bands within thin-walled tubes (Ramesh, 1994). By using a Kalthoff-type experiment, the initiation and propagation of shear bands in steel plates was examined by Zhou et al. (1996). The fully developed shear bands can be easily studied with collapsing cylinders (Xue et al., 2002). Batra and his co-workers (Batra, 1987; Batra and Kim, 1990) have performed some impressive research on the influences of material parameters and flow rules on both shear band initiation and growth. In the study of shear band interactions, Zhou et al. (2006b) analysed the interactions between a single shear band and its surroundings using a numerical

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Nomenclature

English alphabet

V	cutting speed
b	uncut chip thickness
L	contact length between tool and chip
L_c	serration spacing
f	serration frequency
F	fb/V
f_{int}	friction stress along the tool surface
V_{chip}	material velocity along shear direction
V_s	tool velocity along shear direction
V_f	material convection velocity
Δu	compression displacement
c	work material specific heat
C	strain rate coefficient in J-C law
w	width of PSZ
n	work-hardening exponent in J-C law
E	work material elastic modulus
m	thermal softening coefficient in J-C law
Re	*Reynolds* number
k	wave number
$\bar{k}$	$\sqrt{\rho/Q_h}\lambda k$
Q_h	$(\partial\tau/\partial\gamma)_h$, strain hardening effect
R_h	$(\partial\tau/\partial\dot{\gamma})_h$, strain rate hardening effect
P_h	$-(\partial\tau/\partial\theta)_h$, thermal softening effect
C_L	$\sqrt{E/\rho}$, elastic wave velocity
C_{SP}	$\sqrt{Q_h/\rho}$, plastic shear wave velocity
C_λ	λ/b, thermal diffusion velocity
C_υ	$R_h/\rho b$, viscous diffusion velocity
Da	$\rho V^2\sin^2\varphi/Q_h$,effective damage number
Pr	C_υ/C_λ,*Prandtl* number
Pe	Vb/λ, *Péclect* number/thermal number
B	$\beta\tau_h P_h/\rho c Q_h$

Greek alphabet

ω	tool rake angle
φ	shear angle
σ	local compression stress
σ_x	normal stress along the x direction
ε	elastic compression strain
δ	scale of the local compression zone
τ	shear stress
γ	shear strain
$\dot{\gamma}$	shear strain rate
ρ	work material density
λ	work material thermal diffusion
μ	friction coefficient
β	Taylor–Quinney coefficient
θ	temperature
θ_o	room temperature in J-C law
θ_{melt}	melting temperature in J-C law
τ_A	initial yield stress in J-C law
τ_B	hardening modulus in J-C law
$\dot{\gamma}_{ref}$	reference strain rate in J-C law
υ	kinematic viscosity
α	Initial growth rate of perturbation
$\bar{\alpha}$	$\rho\lambda\alpha/Q_h$
Ω	b/w
ζ	$1+\mu\tan(\omega-\varphi)$
Γ	$2[1+\mu\tan(\omega-\varphi)]^{1/2}\sin\varphi$
Λ	$2\pi[4\cos(\omega-\varphi)/\Gamma^2\cos\omega]^{1/4}$
Φ	tool compression coefficient

Subscripts

h	homogeneous deformation solution
$*$	initial magnitude of perturbation

approach. Rittelet al. (2008; 2006) addressed adiabatic shear localization from a different point of view. They stated that the shear banding can be viewed as being triggered by dynamic recrystallization instead of being the result of thermal softening. In recent years, the formation and mechanism of shear banding have still received extensive attentions (Love and Batra, 2010; Osovski et al., 2013; Rodríguez-Martínez et al., 2015; Su and Stainier, 2015; Tvergaard, 2015; Yuan et al., 2015).

With regard to metal cutting, the shear band of the serrated chip almost forms inside the PSZ. So, considerable efforts have also been carried out to investigate the initiation of shear banding by analysing the flow stability of the PSZ, and several classical models have been developed to derive conditions under which the continuously smooth chip flow becomes unstable. The first explanation for the emergence of serrated chip flow was presented by Recht (1964), who stated that once the thermal softening effect of material in the PSZ overcomes the tendency to harden with plastic deformation, shear instability occurs. This model was later developed by Hou and Komanduri (1997) to predict the critical cutting speed for the onset of serrated chip flow. Semiatin and Rao (1983) provided another model for chip flow instability, in which a flow localization parameter is presented to judge whether serrated chip flow could take place. Later, by applying ideas from the theory of shear banding in torsion, Molinari and Dudzinski (1992) derived the conditions under which continuous chip flow becomes unstable. Burns and Davies (1997, 2002) explained the serrated chip flow as a bifurcation phenomenon. More recently, by considering the effect of the strain gradient, which becomes important in the case of shear banding, Aifantis and his co-workers (Huang and Aifantis, 1997; Huang et al., 2007) presented a method for thermo-viscoplastic instability in chip formation to describe the serrated chip flow. Childs (2013) predicted the onset of serrated chip flow using a thermal number or *Reynolds* thermal number Pe. Recently, Cai et al. (Cai et al., 2015; Cai and Dai, 2014) found that the serrated chip flow can be suppressed by imposing an extrusion constraint on the chip, and a theoretical model was developed to uncover the underlying mechanism. These pioneering works provide important clues to the study of the onset of serrated chip flow.

Most of the previous works studied the onset of serrated chip flow by modelling the PSZ as a simple shear. However, the deformation inside the PSZ is different with the simple shear, and the high speed makes the problem much more complex. The complexities of the high speed cutting can be characterized by the three following points:

1) First, the chip flow is very rapid at high cutting speed. The rapid chip flow takes material away from the PSZ, which gives rise to the material convection (Burns and Davies, 2002). The material convection removes heat and momentum from the PSZ and hence influences the plastic flow stability significantly.
2) Second, the shear deformation inside the PSZ is caused by the compression between chip and tool. The loading and unloading of the local compression of the chip affects the thermoplastic deformation behaviour in the PSZ.
3) Third, the high cutting speed results in a significant inertia effect though the PSZ is thin. Indeed, whether the inertia effect is significant or not depends upon the competition between the inertia time $t_{inertial}$ and the deformation time $t_{deformation}$ (Wu et al., 2003). The inertia and deformation time are defined as $t_{inertial}=\sqrt{\rho b w/\tau_A}$ and $t_{deformation}=1/(V_s/w)$ respectively, where ρ is work material density, b uncut chip thick-

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