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Adiabatic shear banding and scaling laws in chip formation with application to cutting of Ti–6Al–4V

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ABSTRACT

The phenomenon of adiabatic shear banding is analyzed theoretically in the context of metal cutting. The mechanisms of material weakening that are accounted for are (i) thermal softening and (ii) material failure related to a critical value of the accumulated plastic strain. Orthogonal cutting is viewed as a unique configuration where adiabatic shear bands can be experimentally produced under well controlled loading conditions by individually tuning the cutting speed, the feed (uncut chip thickness) and the tool geometry. The role of cutting conditions on adiabatic shear banding and chip serration is investigated by combining finite element calculations and analytical modeling. This leads to the characterization and classification of different regimes of shear banding and the determination of scaling laws which involve dimensionless parameters representative of thermal and inertia effects. The analysis gives new insights into the physical aspects of plastic flow instability in chip formation. The originality with respect to classical works on adiabatic shear banding stems from the various facets of cutting conditions that influence shear banding and from the specific role exercised by convective flow on the evolution of shear bands. Shear bands are generated at the tool tip and propagate towards the chip free surface. They grow within the chip formation region while being convected away by chip flow. It is shown that important changes in the mechanism of shear banding take place when the characteristic time of shear band propagation becomes equal to a characteristic convection time. Application to Ti–6Al–4V titanium are considered and theoretical predictions are compared to available experimental data in a wide range of cutting speeds and feeds. The fundamental knowledge developed in this work is thought to be useful not only for the understanding of metal cutting processes but also, by analogy, to similar problems where convective flow is also interfering with adiabatic shear banding as in impact mechanics and perforation processes. In that perspective, cutting speeds higher than those usually encountered in machining operations have been also explored.

1. Introduction

Adiabatic shear bands (ASB) are narrow zones with thickness of the order of few micro-meters where shear deformation is highly localized (Rogers, 1979; Bai and Dodd, 1992; Wright, 2002). They are observed in metals subject to fast deformation processes and are generally the result of thermal softening due to heating by plastic deformation (Tresca, 1878; Zener and

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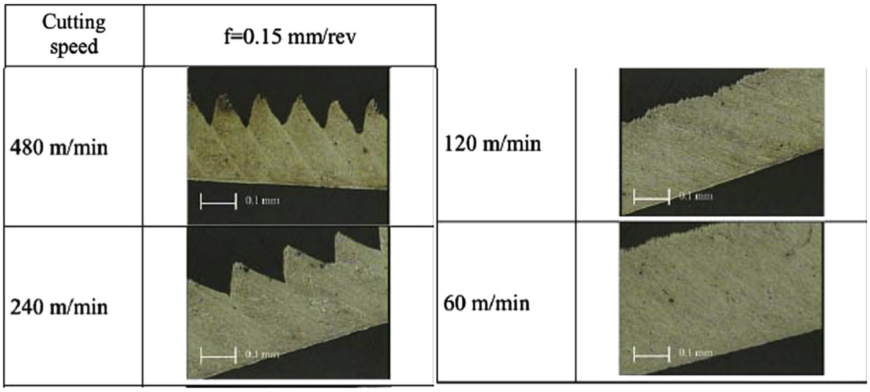

Fig. 1. Chip morphology in orthogonal cutting of 42CrMo4 steel (AFNOR: 42CD4) with a rake angle of −3°, according to Moufki et al. (2004). A transition from continuous chip to segmented chip is observed with increasing of the cutting speed. At high cutting speed the chip segments are delimited by adiabatic shear bands where plastic flow is localized.

Hollomon, 1944). ASB are associated to peaks of temperature which coincide with strain localization zones. Temperature peaks can happen in fast processes since in this case heat conduction has no enough time to smooth the temperature field.

At high strain rates, shear banding is frequently a consequence of thermal softening, but at lower rates shear bands can be generated (or at least influenced) by other softening mechanisms (decay of the stress carrying capacity) due to dynamic recrystallisation (Rittel et al, 2008) phase transformation or material damage (Cox and Low, 1974); Dodd and Atkins, 1983.

Adiabatic shearing was investigated in split torsional Hopkinson bars by Marchand and Duffy (1988). Modeling was performed with linearized stability analyses (Clifton, 1980; Bai, 1982; Molinari, 1985) non-linear analytical approaches (Molinari and Clifton, 1983, 1987; Wright, 1990, 1994; Mercier and Molinari, 1998) and numerical simulations using finite difference and finite element approaches (Batra and Ravinsankar, 2000; Bonnet-Lebouvier et al., 2002; Meyers and Kuriyama, 1986; Wright and Batra, 1985; Wright and Walter, 1987; Zhou et al., 1996b). A comprehensive modeling of adiabatic shearing has been established including the analysis of the onset, growth, interaction and propagation of adiabatic shear bands and the role of material parameters and loading conditions. Reviews on ASB can be found in Bai and Dodd (1992) and Wright (2002).

Orthogonal cutting is a quite interesting process for analyzing adiabatic shear banding. Fig. 1 shows chip serration due to adiabatic shearing during orthogonal cutting of 42CrMo4 steel (Moufki et al., 2004). At high cutting speeds a family of adiabatic shear bands with regular spacing is observed in the chip. Each chip serration is associated to a well formed macroscopic shear band.

The process of orthogonal cutting is unique by offering the possibility of generating ASB under well controlled conditions by tuning individually several control parameters: cutting speed, feed (uncut chip thickness), and tool geometry (inclination of the tool rake face and tool edge radius). There exist just few other experimental configurations where ASB can be produced under well controlled conditions. Shear banding can be triggered in a thin tube subject to rapid torsion on split torsional Hopkinson bars (Marchand and Duffy, 1988). In this experiment a single adiabatic shear band is formed along the circumference of the tube and the successive stages of the shear band development (nucleation and growth) were investigated. ASB can also be generated by direct impact (Meyers et al., 1991; Klepaczko, 1994; Rittel et al., 2002).

Multiple shear banding can be produced within the wall of a hollow cylinder subject to rapid radial collapse produced by a convergent shock wave (Nesterenko et al., 1994), or by the application of an intense magnetic field (Lovinger et al., 2011). These experiments on hollow cylinders and orthogonal cutting tests share the aptitude of generating multiple shear bands. However, in the case of hollow cylinders shear bands are nucleated almost simultaneously and mutual interactions take place between these bands. On the contrary, in orthogonal cutting shear bands are generated sequentially. After being nucleated at the tool tip an ASB propagates towards the free surface while being convected away from the chip formation region by material flow. There is no interaction between shear bands if each individual band is convected outside from the chip formation region before the next band is formed.

Adiabatic shear banding in machining has been investigated by experimental and theoretical means by Komanduri and Von Turkovich (1981), Molinari et al. (2002) and in several other papers which are presented below. Theoretical results on chip segmentation were derived by Burns and Davies (2002) by means of a one-dimensional continuum model of machining inspired by the early work of Recht (1964). Material failure due to internal damage has been incorporated in numerical simulations of chip serration by using the Johnson–Cook fracture model (Subbiah and Melkote, 2008; Obikawa and Usui, 1996; Atlati et al., 2011). Chen et al. (2011) have performed orthogonal cutting tests for Ti–6Al–4V titanium alloy and have simulated chip serration by using an energy-based ductile failure criterion. From their results, it appears that levels of peaks and valleys of the serrated chip vary nearly in proportion to the feed. Calamaz et al. (2008) have introduced a constitutive law with strain softening to analyze chip segmentation of titanium alloy Ti-6Al-4V.

Orthogonal cutting tests of Ti-6Al-4V titanium have revealed that the chip segmentation frequency is proportional to the cutting speed (Molinari et al., 2002), and decreases with the feed rate (Cotterell and Byrne, 2008). These results were