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A study of plastic strain and plastic strain rate in machining of steel AISI 1045 using FEM analysis

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ABSTRACT

The present paper employs the finite element method to determine the plastic strain and plastic strain rate when machining an AISI 1045 steel. A validation of the process using literature experimental values was also conducted in order to verify if the obtained results with the commercial finite element software were close to those found within the literary research. The comparison shows that finite element modulation can be used to determine either plastic strain or plastic strain rate if special attention is taken into consideration when using the analytical models. The effect of high speed machining (HSM) in the plastic strain and plastic strain rate when cutting steel AISI 1045 was observed.
From the simulations, it can be concluded that both the plastic strain and plastic strain rate can be predicted with good precision when machining with the FEM model.

1. Introduction

AISI 1045 steel is widely applied nowadays because of its mechanical properties and is commonly used in mechanical constructions and also as part design. It's a material with good machinability and has proven to be capable of providing engineers a good and reliable solution when submitted to effort, corrosion, etc. Due to its characteristics, it's the steel with more applicability among them all.

High speed machining (HSM) process is being used for manufacturing complex machine parts, mould and die, aerospace and automotive components where maintaining structural integrity of materials (while removing high volumes of material) is of extreme importance [1–3]. It presents several advantages besides high removal rates such as reduction in dead times and lower cutting forces, leading to excellent dimensional accuracy and surface quality as well [4]. Having this said, HSM processes are growing industrial interest not only because they allow larger material removal rates but also because of the positive influence on the finished workpiece properties. An interesting feature of HSM processes is that specific cutting force for a great amount of materials decreases with the increase in cutting speeds and then reaching a plateau. However, the reason for the cutting forces reduction is still somewhat unclear. Thermal softening, a decrease in friction or segmental chip formation (assuming that heat evacuation through the chip is energetically favourable) at high cutting speeds are possible causes [5]. Unlike conventional machining, where chip formation is followed by plastic deformation, at HSM serrated chip or segmentation processes occur [6].

2. Plastic strain and plastic strain rate effects during HSM

Machining of metals is a non-linear process and the complex coupling between deformation and temperature is not completely understood nowadays. The deformation process is concentrated in a small zone and the temperatures that are generated in this zone greatly affect both the tool and the workpiece. High cutting temperatures strongly influence tool wear, tool life, workpiece surface integrity, chip formation mechanism and also contribute to thermal deformation of the cutting tool. An increase in temperature in the primary deformation zone softens the material, allowing for lower cutting forces and less energy in the shear process [2]. It is commonly known that during metal cutting, a great amount of deformation energy is transformed into heat near the tool cutting edge. A small percentage of this heat is transferred through conduction to the uncut material ahead of the cutting tool, having an effect in the integrity of the machined workpiece. The bigger percentage of heat remains in the removed chip and this produces a local increase of temperature in a narrow zone where high strain occurs and adiabatic shear bands are formed [4] (shear bands can be observed in a metal if the plastic strain rate is higher than $10^2\ s^{-1}$).

The nature of the plastic strain and related phenomenon of materials still remain considerably unclear nowadays. It has been realized that strain rate and temperature affect material properties, although strain rate has a greater effect on flow stress in hot-work-

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ing range and a smaller effect in the cold-working range, especially when large strains are present [7,8]. Plastic deformation of steel is temperature sensitive, the rate at which the deformation takes place also has influence on the plastic strain. This sensitivity is directly related with time and temperature dependency of the mechanisms that govern the deformation and the evolution of the deformation in the material. The main mechanism by which plastic strain takes place is thermally activated motion of dislocations past obstacles that exist within the lattice over a wide range of strain rates and cutting temperatures. The material response is significantly affected by the nature and density of the obstacles (which may change as the deformation takes place). When dealing with metals, experimental results show that the stress required for plastic strain often reduces with the increase of temperature and with the decrease of plastic strain rate. It can then be said that temperature and plastic strain rate greatly influence the material response. In general, the stress decreases with the increasing of temperature and decreasing the plastic strain rate [9]. Actually, temperature and strain rate effects are coupled, since one influences the other. Temperature affects the rate of deformation, which is controlled mainly by a thermally activated mechanism. On the other hand, plastic strain at high rate generates significant heating and cause an increase in temperature which leads to mechanical instability and the localization of deformation into narrow sheets of material (the adiabatic shear bands), which act as precursor for eventual material failure [7].

Deformation at low strain rates or under quasi-static loading, is relatively homogeneous because is governed by slip and twinning mechanisms. On the contrary, deformation at high strain rates is a much complex phenomenon that is characterized by extreme strain localization along the adiabatic shear bands. Each material has a different susceptibility to adiabatic shear because it depends on properties like heat capacity, heat conductivity, strength level, microstructure, geometry, defects and strain rates. It is also known that adiabatic shear banding precedes material failures at high strain rates. Adiabatic shear banding is usually accompanied by a loss in stress capacity owing to intense thermal softening in the shear bands and, in many cases, shear bands serve as sites for crack initiation and growth during subsequent dynamic fracture [10]. Localized adiabatic shearing can be considered a unique consequence of severe plastic deformation at high strain rates. As both thermal and strain softening lead to rapid deformation localization, a shear band forms via a nearly adiabatic process. Also of note is that grain refinement can occur within shear bands and severe plastic strain (which can reach 5–20) can also appear within these shear bands [11].

Plastic strain rate can be divided in three zones: the low strain rate region (<1 s^{-1}), the medium rate region (comprehended between the low and high strain rate region values) and the high strain rate region (above 10^3 or $10^4\ s^{-1}$). The influence of these zones on the flow stress is, respectively, weak, sensitive and great [7].

Duan et al. [12] showed that the plastic strain rate increases with the increase of the cutting speed. These authors also concluded that the hardness of the workpiece is able to influence the chip formation and the deformation mechanism.

The objective was to study the behavior of AISI 1045 steel when machined with HSM (in this case, 3000 m/min). Also of note is that a conventional machining (of 300 m/min) was also applied to the workpiece keeping the remaining machining parameters the same. This allowed for a better comparison between both conventional and high speed cutting regimes. The experimental values worth noting for the calculation of the plastic strain and plastic strain rate are presented in Table 1 (taken from Denkena et al. [13]).

From the developed work within this paper, it was possible to predict with good precision both plastic strain and plastic strain rate with the finite element analysis when compared to the literature data supplied by Denkena et al. [13].

Table 1
Literature values (presented in Denkena et al. [13])

Experimental values		
Cutting speed (V_c) (m/min)	300 (conventional machining)	3000 (HSM)
Elemental chip thickness (Δx) (μm)	21	10
Chip compression ratio (λ)	2.1	1.5
Feed (f) (mm/rev)	0.3	
Depth of cut (ap) (mm)	3	
Rake angle (γ) (°)	−6	
Relief angle (α) (°)	6	
Workpiece material	AISI 1045	
Tool material	HC P30-P40	
Tool coating	$Ti(CN)/Al_2O_3$	

3. Analytic model

Merchant theory [14] was followed to make all the calculations (all the presented results in the analytic model are based on literature values [13]).

The chip compression ratio is obtained with the following formula:

$$\lambda = \frac{t'}{t} \quad (1)$$

where t' is the measured chip thickness within the experimental process and t is the theoretical chip thickness that can be obtained by

$$t = f \times \sin\chi \quad (2)$$

where f is the feed rate and χ is the tool position angle.

The shear angle can be obtained by

$$\phi = \mathrm{arctg}\left(\frac{\cos\gamma}{\lambda - \sin\gamma}\right) \quad (3)$$

where γ is the tool rake angle. The plastic strain was calculated using the following method:

$$\varepsilon = \frac{1 + \lambda^2 - 2\lambda \times \sin\gamma}{\lambda \times \cos\gamma} \quad (4)$$

Finally, the plastic strain rate can be found with the following formula:

$$\dot{\varepsilon} = \frac{V_c \times \cos\gamma}{\cos(\phi - \gamma)} \times \frac{1}{\Delta x} \quad (5)$$

where λ is the chip compression ratio, V_c is the cutting speed, ϕ is the cutting shear angle and Δx is the elemental chip thickness.

For a cutting speed of 300 m/min:

$$\phi = \mathrm{arctg}\left(\frac{\cos(-6)}{2.1 - \sin(-6)}\right) = 33^\circ$$

$$\varepsilon == \frac{1 + 2.1^2 - 2 \times 2.1 \times \sin(-6)}{2.1 \times \cos(-6)} = 2.8$$

$$\dot{\varepsilon} = \frac{\frac{300}{60} \times \cos(-6)}{\cos(33+6)} \times \frac{1}{21 \times 10^{-6}} = 30.1 \times 10^4\ s^{-1}$$

For a cutting speed of 3000 m/min:

$$\phi = \mathrm{arctg}\left(\frac{\cos(-6)}{1.5 - \sin(-6)}\right) = 43^\circ$$

$$\varepsilon == \frac{1 + 1.5^2 - 2 \times 1.5 \times \sin(-6)}{1.5 \times \cos(-6)} = 2.39$$

$$\dot{\varepsilon} = \frac{\frac{3000}{60} \times \cos(-6)}{\cos(43+6)} \times \frac{1}{10 \times 10^{-6}} = 67 \times 10^5\ s^{-1}$$