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Finite element simulation and analysis of serrated chip formation during high–speed machining of AA7075–T651 alloy

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ABSTRACT

High–speed machining (HSM) is widely used in the manufacturing of monolithic aluminum components for automotive and aeronautical industries. However, previous research studies on HSM of high strength aluminum alloys have shown that serrated and/or elemental chips can form at critical cutting conditions, impacting the machining stability and final parts quality. Hence, understanding the physical mechanisms governing the chip serration is essential to improve HSM part quality especially when machining high strength aluminum alloys. In the present work, this was achieved by developing a 2D finite element modelling (FEM), based on a lagrangian approach, for simulating and analysing the serrated chip formation during HSM of the AA7075-T651 alloy. The FEM was developed using Abaqus/Explicit v6.13 software. The Johnson–Cook (J–C) constitutive equation combined with a damage criterion implemented into Abaqus was used to account for the shear localization during the serrated chip formation. The proposed finite element model was validated using experimental data obtained upon high speed orthogonal machining. The results showed that the serrated chip morphology was accurately predicted over a large range of cutting speed. In particular, the finite element model captured properly the fact that the chip segmentation intensity increases with cutting speed. Furthermore, physical phenomena governing the serrated chip formation were highlighted and discussed in depth using finite element numerical data and an analytical modelling of chip serration.

1. Introduction

Under specific conditions, the machining of metallic materials often generates serrated chip type, also known as segmented/saw-toothed chips. There are two cases in which the serrated chip formation can take place. The first case happens when hard–to–cut materials such as hardened steels, super-alloys, and titanium alloys are machined at relatively low cutting speeds (less than 70 m/min) [1]. The second case is when ductile materials are machined with cutting speed higher than a critical value [2]. Research studies [3–5] raised evidence of such serrated chip formation during the HSM of high strength aluminum alloys, such as 2xxx and 7xxx series. The serrated chip formation not only impairs the stability of the machining processes, but can also affects the surface integrity of the machined parts. Thus, to enhance the HSM of aeronautical aluminum parts, it is imperatively required to understand the physical mechanisms governing the serrated chip formation in order to guarantee stable machining conditions.

Various theories and models were developed in order to understand the serrated chip formation origins. On one hand, according to Astakhov [6], segmented chip formation is attributed to high variations in stress and plastic deformation, and to the resulting temperature rise in the cutting zone. Later, Liyao et al. [7] stated that segmented chip formation was mainly attributed to adiabatic shear instability/catastrophic strain localization. On the other hand, Vyas and Shaw [8] suggested that the fracture/crack propagation mechanism is at the root of the chip generation. The location where the crack may initiate is also a point of contention. For Poulachon et al. [9], the crack initiates on the free surface of the work material and propagates to the tool tip. However, other researchers [2,6] argued that the crack actually occurs at the tool tip and propagates partway to the free workpiece surface.

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Most of FEM based studies on serrated/discontinuous chip formation have mainly focused on steels and titanium alloys [5,10–15]. However, only few studies [3–5] have concerns with aluminum alloys. Mabrouki et al. [3] studied numerically and experimentally the dry cutting of aluminium alloy A2024-T351, but only the cutting forces and chip segmentation frequencies were used to validate the developed FEM model. Other chip segmentation characteristics such as morphology features (shear band and pick/valley heights) were not considered. Later, Atlati et al. [4] have introduced a segmentation intensity ratio (SIR), which is defined as the ratio of the plastic deformation into the shear band to the one found outside the shear band. However, this ratio does not describe properly the chip segmentation during the machining of A2024 alloy as two extreme cutting speeds tested (60 m/min and 1000 m/min) are associated with the same *SIR* but with very different segmentation features and frequencies so that limiting its applicability to a large speed range. More recently, Ye et al. [5] proposed an empirical model to define the critical cutting speed for the onset of serrated chip flow for the high speed machining of ductile and hard-to-cut metallic materials. Their model needs extensive numerical sensitivity analysis of the effects of material properties and cutting parameters on the critical cutting speed. Among the materials tested was the non-heat treated aluminum 7075 alloy. However, the effects of cutting speed on the adiabatic shear banding mechanism and state variables evolution have been neglected.

In view of the foregoing literature review, the present study aims to develop a finite element model for simulating and analysing the serrated chip formation during the HSM of age hardened aluminum alloy AA7075-T651. The serrated chip mechanisms will be discussed based on the evolution of the critical state variables and the thermo-mechanical loading calculated numerically using the proposed finite element model. This was done by using (a) a J–C constitutive equation combined with a damage evolution criterion to describe the material behaviour; (b) a Lagrangian formulation to simulate the serrated chip formation; and (c) adequate managing of the element ditortion issues using a distortion control function with the proper hourglass mode in ABAQUS/Explicit v6.13 software. In addition, the accuracy of the proposed finite element model will be confirmed by comparing the obtained numerical data with the analytical solution of the shear band spacing parameter.

2. FEM of serrated chip formation

In this paper, as a Lagrangian formulation is adopted, the mesh follows the material during deformation and there is no need for a predefined chip form. The workpiece is modeled as an elasto–plastic material with damage, whereas the tool is modeled as a rigid body. This approach will allow as to predict the serrated chip geometry and to understand the shear localization phenomenon accompanying the serrated chip formation of the AA7075-T651 alloy.

2.1. Governing equations of the coupled thermo–mechanical analysis

In metal cutting, the chip formation process involves large plastic deformation at high temperature and strain rate, where the stress and temperature fields mutually influence each other. Hence, the problem is solved by applying a fully coupled thermo–mechanical simulation algorithm. For simplicity, the governing equations will be briefly presented in the following sections. For more details about the finite element method applied to thermo-elasto-visco-plastic material behaviour with damage, readers can refer to [16].

2.1.1. Mechanical analysis

During the mechanical analysis step, the displacement, the strain, and the stress fields are calculated at every integration point of an element in the model. These fields satisfy the linear momentum equation written at any point of the continuum medium as the local conservation equation:

$$div(\bar{\sigma}) + f_d = \rho\ddot{u} \tag{1}$$

where ρ is the material density, $\ddot{u}$ is the acceleration, $\bar{\sigma}$ is the Cauchy stress tensor and f_d is the body force.

The weak variational form associated with the equation Eq. (1) is derived from the principle of virtual work as follows:

$$-\int_V \bar{\sigma} : \delta\bar{D} dV + \int_V f_d \delta\dot{u} dV + \int_{S_F} t\delta\dot{u} dS + \int_{S_C} t_C \delta\dot{u} dS - \int_V \rho\ddot{u}\delta\dot{u} dV = 0 \tag{2}$$

where V denotes the volume occupied by the body, S_F and S_C the surfaces of the volume V where the surface forces t and the contact surface forces t_C are applied. $\delta\dot{u}$ is the virtual velocity, and $\delta\bar{D}$ is the virtual strain rate. The Eq. (2) is strongly nonlinear (as the stress and strain depend on temperature and hardening parameters) and is numerically solved using the Newton-Raphson's method.

2.1.2. Thermal analysis

The steady–state thermal energy governing the orthogonal machining process is derived from the principle of conservation of energy, which for mainly heat conduction dominated problem, is as written below:

$$\rho\dot{\bar{e}} = \bar{\sigma} : \dot{\bar{\varepsilon}} - div\vec{q} + \pi \tag{3}$$

where $\dot{\bar{e}}$ denotes the internal energy variation, π the density of internal heat production, $\bar{\sigma} : \dot{\bar{\varepsilon}}$ is the mechanical power dissipated into heat, $div\vec{q}$ is the heat dissipated by conduction. Assuming Fourier law of heat conduction to apply:

$$\vec{q} = -k.\overrightarrow{grad}(T) \tag{4}$$

Applying the entropy inequality and taking account of damage dissipated energy, one can show that the final energy equation for coupled thermo-visco-elasto-plastic behaviour with damage can be written as [16]:

$$\begin{aligned} & div(K\overrightarrow{grad}(T)) + \pi + \bar{\sigma} : \dot{\bar{\varepsilon}}_p - \bar{X} : \dot{\bar{\alpha}} - R\dot{r} + Y\dot{D} - \rho C_v \dot{T} \\ & \quad + T\left[\frac{\partial\bar{\sigma}}{\partial T} : \dot{\bar{\varepsilon}}_e + \frac{\partial\bar{X}}{\partial T} : \dot{\bar{\alpha}} + \frac{\partial\bar{R}}{\partial T} : \dot{\bar{r}} + \frac{\partial Y}{\partial T} : \dot{D}\right] = 0 \end{aligned} \tag{5}$$

assuming

$$\begin{aligned} R_{pl} = & \ \bar{\sigma} : \dot{\bar{\varepsilon}}_p - \bar{X} : \dot{\bar{\alpha}} - R\dot{r} + Y\dot{D} \\ & + T[\frac{\partial\bar{\sigma}}{\partial T} : \dot{\bar{\varepsilon}}_e + \frac{\partial\bar{X}}{\partial T} : \dot{\bar{\alpha}} + \frac{\partial\bar{R}}{\partial T} : \dot{\bar{r}} + \frac{\partial Y}{\partial T} : \dot{D}] \end{aligned} \tag{6}$$

where $\bar{\sigma} : \dot{\bar{\varepsilon}}_p$ represent the mechanical power induced by plastic deformation and dissipated into heat, $\bar{X} : \dot{\bar{\alpha}}$ represents the isotropic hardening, $R\dot{r}$ the kinematic hardening, $Y\dot{D}$ the isotropic ductile damage, and $\dot{\bar{\varepsilon}}_e$ the elastic strain rate.

The final heat equation, including the mechanical dissipation in visco–plastic flow, hardening, and damage can be written as [16]

$$\rho C_v \dot{T} = div(K\overrightarrow{grad}(T)) + \pi + R_{pl} \tag{7}$$

where T is the temperature (in Kelvin), K is the thermal conductivity, C_v is the thermal capacity, π is the internal heat source, and R_{pl} is the internal heat generated by the mechanical load.