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Prediction of the cutting forces and chip morphology when machining the Ti6Al4V alloy using a microstructural coupled model

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Abstract

Titanium and its alloys are often used in aerospace, power and biomedical applications due to their low density, high tensile strength, resistance to corrosion and high temperatures. However, these materials are well known to be difficult-to-cut materials and require to follow some special techniques to improve their machinability. It should be also noticed that some phenomena like segmentation and recrystallization can occur during the chip formation process. Therefore, fine grains are observed in the adiabatic shear bands located in the chip segments. The machined surface also presents fine grains because of the recrystallization of the microstructure. In the present work, a 2D finite element model based on Lagrangian formulation was developed in Abaqus/Explicit to simulate the orthogonal cutting process of the Ti6Al4V alloy. To take into account the recrystallization phenomenon, a new material constitutive model denoted 'Multi-Branch Model' (MB) was developed. The MB model is based on the Johnson-Cook (JC) flow stress model and its modified formulation, known as the tangent hyperbolic model (TANH), to introduce the softening effect due to the recrystallization process. This new model is coupled to a microstructural criterion in order to simulate the work-material microstructure evolution during the machining process. The recrystallized grains size field, cutting forces and chips morphology are compared to those obtained with the TANH model. Based on these results, a relationship between recrystallization and chip segmentation has been found and deeply discussed.

Keywords: Keywords: Metal machining; Titanium Alloy; Microstructure; Recrystallization; Grain size; FE Modelling

Nomenclature

A	Initial yield stress (MPa)
B	Hardening modulus (MPa)
C	Strain rate dependency coefficient
d_0	Initial grain size
d_{DRX}	Recrystallized grain size
m	Thermal softening coefficient
n	Strain hardening coefficient
Q_{act}	Dynamic recrystallization activation energy (J)
R	Boltzmann constant
T	Temperature (°K)
T_0	Reference Temperature (°K)
T_m	Melting Temperature (°K)
ε	Equivalent plastic strain
$\dot{\varepsilon}$	Equivalent plastic strain rate
ε_{crit}	Critical equivalent plastic strain
σ_{JC}	JC model Flow stress (MPa)
σ_{TANH}	TANH model Flow stress (MPa)
σ_{MB}	MB model Flow stress (MPa)
$a_1, h_1, m_1, c_1, a_2, a_8, h_8, m_8, c_8$	JMAK model constants
a, b, c, d	JC model constants

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1. Introduction

Titanium and its alloys are used in several industrial applications because of their interesting thermomechanical properties. Their resistance under high temperatures makes them more appropriate to design aeronautical engine parts. Also, they are very helpful for biomedical applications (e.g. fabrication of prosthesis) because of their low reaction with biological substances.

However, titanium alloys are considered as difficult-to-cut materials for which several microstructural phenomena can occur during the machining process.

The analysis of the microstructural evolution during the machining of these materials can help to better understand these phenomena and hence find new solutions to improve their machinability.

In this paper, the machining of the Ti6Al4V alloy, often used in aeronautic applications, was studied. Segmented chips are frequently generated and microstructure change occurs in the localized shear bands during the chip formation process. Several authors have studied the formation of such chips morphology. Kouadri et al. [1] proposed two parameters to quantify segmented chip morphology. Ma et al. [2] studied the mechanism of segmented chip formation experimentally and numerically for Ti6Al4V alloy. Hua and Shivpuri [3] used a finite elements model with a Lagrangian formulation to analyze segmentation process of Ti6Al4V alloy. Miguelez et al. [4] studied the influence of cutting speed and feed rate on segmentation using an orthogonal cutting model.

Segmented chips are generally explained by two main mechanisms: fracture and thermoviscoplastic deformation.

The first mechanism used to explain serrated chips is fracture. An example of crack due to fracture mechanism is shown in Fig.1a. Shaw and Vyas [5] explained this by cyclic fracture mechanism which is the raison of the chip segmentation. Umbrello [6] used a Cockroft and Latham's criterion to predict the segmented chip formation in a 2D simulation with DEFORM-2D software. A periodic crack initiation and propagation simulated by an element deletion feature are used. Aurich and Bil [7] used DEFORM-3D to study the formation of a chip due to fracture.

The second mechanism is the localized thermoviscoplastic deformation, characterized by the formation of Adiabatic Shear Band (ASB), Fig.1b. Different interpretations were given in Literature to this shear strain localization. Wan et al. [8] explained that the thermoplastic instability is due to the shift between the heat flux and the plastic strain rate. They observed the ASB formation process for the Ti6Al4V alloy. According to their analysis, the low thermal conductivity leads to a localized catastrophic failure of the material and then to the formation of the ASB. Aurich and Bil [7] also studied chip segmentation due to this thermoplastic instability which is attributed to the thermal softening. They modelled this phenomenon using Rhim's material model. They recalled that this thermal softening is often accompanied by dynamic recrystallization (DRX). Atmani et al. [9] [10] studied the microstructural change in metals during machining and used a multi-physics based modelling to simulate recrystallized grains during machining the OFHC copper. The Mechanical

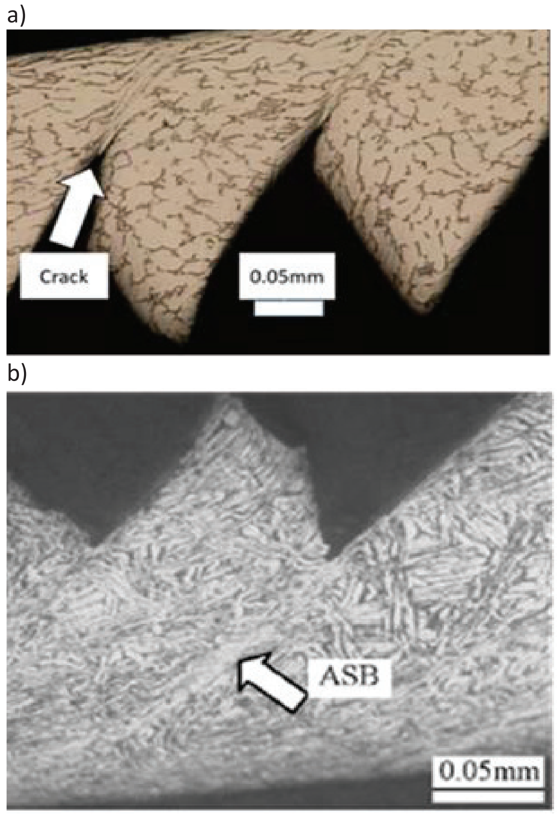

Fig. 1. Ti6Al4V serrated chip with cracks and ASB (a), Ti6Al4V serrated chip with ASB (b) [1].

Threshold Stress model (MTS) was used to describe the flow stress evolution and the dislocation density (DD) based model was used to obtain the microstructural evolution. When machining Ti6Al4V, recrystallized grains have been observed within the ASB. Nouari and Makich [11] point out the microstructural change in ASB while studying both titanium alloys Ti6Al4V and Ti-555. Wan et al. also noticed this fact [8]. Calamaz et al. [12] linked the recrystallization with a "strain softening phenomenon" by modifying the Johnson-Cook (JC) thermoviscoplastic model with a tangent hyperbolic function. The obtained behavior model, known as the Tangent Hyperbolic model (TANH), permitted to simulate serrated chips. It has been used later by several authors, like Sima and Ozel [13] or Ducobu et al. [14]. The TANH model generally predicts a good morphology of the chip. However it conducts to an overestimated segmentation frequency and lowers the amount of cutting forces [14],[15]. In this work, based on experimental observations [11], the assumption made is that the severe softening observed in ASB, only occurs when the material is subjected to dynamic recrystallization. Using a TANH model in all the chip body induces a lowering of the material rigidity and then a lowering of cutting forces. This is also the cause of the overestimation of the segmentation frequency. The new proposed Multi-Branch (MB) model takes into account the DRX triggering and changes in the material behavior. For this purpose, the well-known JC model, the