Available online at www.sciencedirect.com
ScienceDirect
International Journal of Machine Tools & Manufacture 48 (2008) 275–288
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

# A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al–4V

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Received 28 June 2007; received in revised form 18 October 2007; accepted 20 October 2007
Available online 30 October 2007

**Abstract**

A new material constitutive law is implemented in a 2D finite element model to analyse the chip formation and shear localisation when machining titanium alloys. The numerical simulations use a commercial finite element software (FORGE 2005®) able to solve complex thermo-mechanical problems. One of the main machining characteristics of titanium alloys is to produce segmented chips for a wide range of cutting speeds and feeds. The present study assumes that the chip segmentation is only induced by adiabatic shear banding, without material failure in the primary shear zone. The new developed model takes into account the influence of strain, strain rate and temperature on the flow stress and also introduces a strain softening effect. The tool chip friction is managed by a combined Coulomb–Tresca friction law. The influence of two different strain softening levels and machining parameters on the cutting forces and chip morphology has been studied. Chip morphology, cutting and feed forces predicted by numerical simulations are compared with experimental results.


*Keywords:* Machining; Finite element method; Chip segmentation

## 1. Introduction

Machining (turning, milling, drilling, etc.) is one of the oldest industrial processes and it is the most frequently used in the manufacture of industrial workpieces. It is estimated that approximately 15% of the value of all mechanical components manufactured in the world comes from a machining operation. In spite of its economic and technical importance, metal cutting remains one of the least understood processes because of the bad predictive capacity of the models. A study made in the USA showed that a correct tool choice is made in less than 50% of the cases and only in 38% of the cases it is used until its real "tool life" [1].

Numerical models are very important in the machining process comprehension and for the reduction of experimental tests necessary for the optimisation of cutting conditions, tools geometries and other parameters like the choice of the tool material and coating. None of the analytical models can predict with enough precision the adequate conditions of a machining practical situation. Numerical models are interesting candidates because they might explain the observed phenomena and help in defining the optimal cutting conditions.

Numerical simulation of machining is not yet reliable enough for predictive results. On the mesoscopic level, adequate constitutive laws are needed for both the machined material and the tool. However, these properties are often unavailable or incomplete and constitute a brake for the numerical simulation.

A correct simulation enables good predictions in terms of temperature, strain and stress distribution. This will contribute to cost reductions for the machining process optimisation which is still experimentally done and thus expensive.

Ti–6Al–4V titanium alloy is often used in the aircraft industry due to the good compromise between mechanical resistance and tenacity, together with its low density and excellent corrosion resistance. However, this material is

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0890-6955/$ - see front matter 
doi:10.1016/j.ijmachtools.2007.10.014

known to be difficult to machine. One of the reasons is due to its low thermal conductivity which gives rise to (a) high pressures and temperatures at the tool–chip interface, (b) a plastic instability localised in adiabatic shear bands, (c) tool wear by thermal fatigue and diffusion.

The high chemical reactivity with many tool materials and the low elastic modulus, which generates harmful vibrations for the tool and the workpiece, also contribute to the difficult machinability of this aeronautic material.

At high cutting speeds, many materials give rise to segmented chips. The Ti–6Al–4V titanium alloy is one of the materials often generating segmented chips (also named "saw-tooth" chips) at relatively low cutting speeds. The chip segmentation affects the machining process (cutting forces, temperature and workpiece surface quality) so that a thorough understanding of this phenomenon is important.

Two theories about saw-tooth chip formation predominate, namely (i) the thermoplastic instability and (ii) the initiation and propagation of cracks inside the primary shear zone of the workpiece material. Shaw et al. [2], Komanduri and Turkovich [3] explain that the titanium chip morphology is due to a plastic instability during the cutting process resulting from the competition between the thermal softening and work hardening in the primary shear zone.

Vyas and Shaw [4] and Hua and Shivpuri [5] explain the titanium alloy chip segmentation by a crack initiation followed by propagation inside the primary shear zone.

The presence of adiabatic shear bands does not exclude the theory of saw-tooth chip formation by crack initiation. Bai and Dodd [6] suggested that the adiabatic shear bands are commonly the precursors to fracture.

The cutting speed ($V_c$) and the feed ($f$) are the main parameters controlling the shear frequency during the chip formation [7]. According to Bayoumi and Xie [7], the chip load, defined by the factor $V_c \times f$, should be considered as a good criterion for the appearance of shear bands. In the case of Ti–6Al–4V alloy, the chip load should be around $0.004\,m^2/min$ [7].

On the other hand, Hou and Komanduri [8] suggested that the important parameter is the cutting speed and propose a critical cutting speed around 9 m/min above which a thermoplastic instability takes place.

Different methods have been used to simulate the saw-tooth chip formation in machining such as the pure deformation model without taking into account any fracture criterion [9,10] and many material laws such as the Johnson–Cook (JC) material model, the Baummann–Chiesa–Johnson (BCJ) law [11], Obikawa and Usui, Rhim and Oh [12,13] models, etc., coupled with a fracture criterion such as the JC damage law [14–18], deformation energy-based criterion [5,19], ductile fracture criterion [12]. Therefore, apart from pure deformation model [9,10], a fracture criterion is implemented in most numerical simulations to obtain the saw-tooth chip geometry [12,14–19].

An important factor to be considered for a correct simulation of Ti–6Al–4V machining is the material constitutive law. Classically, the JC material law, the Obikawa and Usui [12] model or the Marusich material law [20] are used to correlate the material flow stress to strain, strain rate and temperature. The parameters identified for these laws are usually fitted to the stress–strain curves obtained by split Hopkinson bars. The levels of strain, strain rate and temperature achieved with this experimental device are lower than those developed during the machining process. These experiments can achieve a maximum strain of about 0.5 and strain rate around $10^3\,s^{-1}$, whereas the cutting process generates higher strains ($>1$) and strain rates ($>10^4\,s^{-1}$) in the workpiece material. Within the experimental range of strain, strain rate and temperature, the material model correlates quite well the experimental results. Outside the experimentally studied range, the flow stress is extrapolated which may be considered as an incorrect hypothesis unable to take into account presumed microstructural changes.

Some attempts have been made to account for microstructural transformations of the material, the history of loading, the kinematic and isotropic hardening and the recrystallisation and recovery phenomena [11,13,21]. For example, an interesting phenomenon called strain softening has been introduced in the flow stress model in order to explain the saw-tooth chip formation [5]. Strain softening is represented by a decrease in stress with increasing strain beyond a critical strain value. Below that critical strain, the material exhibits strain hardening.

The strain softening was identified by carrying out torsion tests at high temperature on pure aluminium [22] and on different AlMgSi alloys [23]. Kassner et al. [22] affirm that for pure aluminium, the peak stress is reached at strains less than 0.5. Increasing the strain further leads to a gradual material softening before a relatively constant level is reached. This type of flow stress–strain curves has also been obtained for Ti–6Al–4V titanium alloy [24,25].

The physical phenomena giving rise to the softening effect are not completely understood. The main reasons would be related with a texture softening (decrease of the Taylor factor) or a microstructural softening induced by a dynamic recovery and/or dynamic recrystallisation. The most wide-spread theories agreed that large deformation results in a dramatic increase in the high-angle grain boundary (HAB) areas which are annihilation sites for dislocations [22]. Pettersen and Nes [23] confirmed that the flow stress decrease is due to a change in the grain size and a new operating deformation mechanism (such as grain-boundary sliding) due to the dramatic increase in the HAB area with increasing strain. The dynamic recovery and/or recrystallisation have also been observed in Ti–6Al–4V titanium alloy microstructure after hot processing at temperatures above the $\beta$-transus [26]. Another cause of strain softening in Ti–6Al–4V would be a texture change corresponding to an $\alpha/\beta$ platelet kinking [25]. According to Ding and Guo [26], the dynamic