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ScienceDirect
Computational Materials Science 39 (2007) 149–154
COMPUTATIONAL MATERIALS SCIENCE
www.elsevier.com/locate/commatsci

3D finite element analysis of ultrasonically assisted turning

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Received 3 October 2005; accepted 21 December 2005

Abstract

Ultrasonically assisted turning (UAT) is an advanced machining technique, where high-frequency vibration is superimposed on the movement of a cutting tool. Compared to conventional turning (CT), this technique allows significant improvements in processing intractable materials. The paper presents a recently developed 3D model of UAT as an extension to our initial 2D model [A.V. Mitrofanov, V.I. Babitsky, V.V. Silberschmidt, J. Mater. Process. Technol. 153–154 (2004) 233]. This model allows studying various 3D effects in turning, such as oblique chip formation, as well as to analyse the influence of tool geometry on process parameters, e.g. cutting forces and stresses generated in the workpiece material. The FE model is used for transient, coupled thermomechanical simulations of elasto-plastic materials under conditions of both UAT and CT. It is used to study the effect of cutting parameters (such as the cutting speed, depth of cut and feed rate) and friction on UAT and CT. Numerical results are validated by experimental tests.

Keywords: Ultrasonic vibration; Turning; Finite element method; Thermomechanical analysis

1. Introduction

Turning is a type of metal cutting where a single-point tool is used to remove unwanted material to produce a desired product, and is generally performed on a lathe machine. Turning techniques have been improved considerably to achieve easy machining of difficult-to-cut materials and better surface finish. Methods such as high speed turning have been in use now for considerable time. But still machining of high-strength aerospace alloys, composites and ceramics causes high tool temperatures and fast wear of cutting edges, lacks dimensional accuracy and requires a considerable amount of coolant. These deficiencies of conventional turning necessitate the development of new cutting techniques.

Ultrasonically assisted turning (UAT) has proved to bring significant benefits to machining of hard-to-cut alloys. It is an advanced cutting technique, where high-frequency vibration (frequency $f \approx 20$ kHz, amplitude $a \approx 15$ mm) is superimposed on the movement of a cutting tool. Compared to conventional turning (CT), this technique allows significant improvements; a multifold decrease in cutting forces, as well as an improvement in surface finish can be achieved with the use of UAT [1,2].

Despite all its advantages, this technique has not yet been widely introduced in the industry. Problems such as instability of the cutting process that resulted in poor surface finish prevented the full implementation of this process. The development of an autoresonant control system [3] added stability to the system by making the vibrations regular, thus opening the way to the industrial introduction of UAT.

A prototype of the UAT system has been designed at Loughborough University, UK, and a program of experimental tests has been implemented confirming advantages of UAT in comparison to CT. Dynamics of UAT as a non-linear vibro-impact process was studied in [4], and the amplitude response of the cutting tool under loading was analysed for this cutting technique.

However, thermomechanics of the tool–workpiece interaction, which is of special importance for the regime

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0927-0256/$ - see front matter
doi:10.1016/j.commatsci.2005.12.045

with multiple microimpacts in the process zone, and other specific features of the cutting process in UAT have not been fully understood. The finite element method (FEM) is a main computational tool for simulation of the process zone and of the tool–workpiece interaction in metal cutting. A detailed review of FE models of conventional cutting can be found in the monographs [5,6]. In order to understand the mechanics of tool–chip interaction in UAT, and to analyse distributions of stresses and strains in the cutting region, heat transfer in the workpiece material and in the cutting tool and also to estimate the cutting forces, a 2D finite element model was developed. An initially purely mechanical finite element model was further improved, resulting in a transient, fully thermomechanically coupled one for both UAT and CT. Some computational results obtained with this mode were discussed in [7].

The current paper discusses the 3D FE model of UAT that was developed as extension to the 2D model. Up to now, 3D FE models were used to simulate conventional cutting processes. The majority of the suggested schemes employ the method of chip separation along a predefined surface, "unzipping" adjoining finite elements in the initial discretization of the area, hence reducing flexibility (and adequacy) of the analysis. Only a few schemes use other techniques, such as elements deletion based upon penetration of cutting tool tip into the elements of workpiece [8], adaptive remeshing of elements in the workpiece [9], and combination of both the manual deletion and remeshing [10].

A FEA analysis of heat generation in machining of isotropic materials was conducted in [11] in order to study the effects of the convective heat transfer. A different approach, using an orthogonal FE model coupled with an analytical 3D model of cutting, was developed in [12] to predict a chip flow angle and three-dimensional forces in the tool. Another 3D model was introduced in [9] that took into account dynamic effects, thermomechanical coupling, constitutive damage law and contact with friction in order to study the cutting forces and plastic deformation.

With 3D modelling of CT being used for the study of tool forces and chip flow for the last two decades, this paper presents the first three-dimensional FE model of UAT. It has been recently developed and the computational results, emerging from this 3D formulation, are discussed.

2. Model description

2.1. General features

A detailed description of our previously developed 2D numerical model can be found elsewhere [7,13]. The current FE model utilizes the MSC MARC/MENTAT FE code [14] and is based on the updated lagrangian analysis procedure that provides a transient analysis for an elasto-plastic material and accounts for the frictional contact interaction between the cutter and workpiece as well as material separation in front of the cutting edge.

The relative movement of the workpiece and cutting tool in CT is simulated by the translation of the tool with the constant velocity V_c. Harmonic oscillation with vibration amplitude of 15 μm (peak-to-valley) is then superimposed on this movement in the tangential direction (i.e. along X-axis in Fig. 1) in order to model ultrasonic vibration of the tool. The vibration speed is several times greater than the chosen translational speed of the tool leading to the periodic separation of the tool from the newly formed chip, thus transforming the process of cutting into one with a multiple-impact interaction between the tool and chip. Various stages of a vibration cycle are described in detail in [15].

The developed FE model is fully thermomechanically coupled in order to properly reflect interconnection between thermal and mechanical processes in the cutting zone: excessive plastic deformation and friction at the tool–chip interface lead to high temperatures generated in the cutting region. This results in thermal stresses and volumetric expansion as well as affects material properties of the workpiece, such as thermal conductivity and specific heat. More details on thermomechanical processes in UAT in comparison to CT can be found in [13].

The mechanical behaviour of the workpiece material (aged Inconel 718) at high strains, strain rates and elevated temperatures can be adequately described by the Johnson–Cook material model [16], accounting for the strain-rate sensitivity, that is employed in simulations (Fig. 2):

$$\sigma_{\mathrm{Y}} = (A + B\varepsilon_{\mathrm{p}}^{n})\left(1 + C\ln\left(\frac{\dot{\varepsilon}_{\mathrm{p}}}{\dot{\varepsilon}_{0}}\right)\right)(1 - T^{*\mathrm{m}}) \tag{1}$$

where $A = 1241$ MPa, $B = 622$ MPa, $C = 0.0134$, $n = 0.6522$, ε_{p} and $\dot{\varepsilon}_{\mathrm{p}}$ are plastic strain and a strain rate, $T^{*} = (T - T_{\mathrm{room}})/(T_{\mathrm{melt}} - T_{\mathrm{room}})$, T_{room} and T_{melt} are the room and melting temperatures, respectively. A term $T^{*\mathrm{m}}$

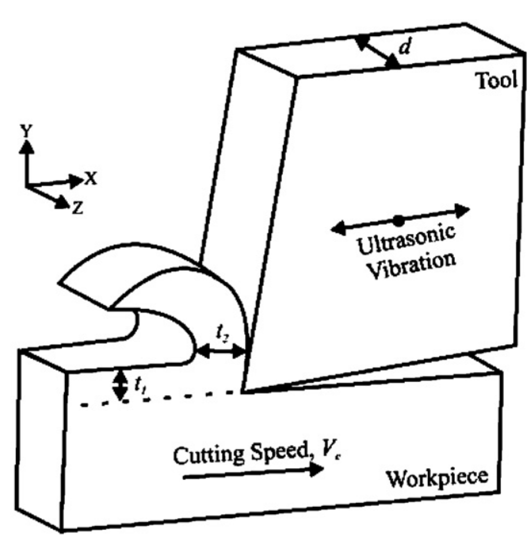

Fig. 1. A scheme of relative movements of workpiece and cutting tool in 3D simulations of UAT.