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AN EFFICIENT IMPLEMENTATION OF BOUNDARY CONDITIONS IN AN ALE MODEL FOR ORTHOGONAL CUTTING

María H. Miguélez
Ana Muñoz-Sánchez
José L. Cantero
Universidad Carlos III de Madrid, Department of Mechanical Engineering, Madrid, Spain
e-mail: mhmiguel@ing.uc3m.es
José A. Loya
Universidad Carlos III de Madrid, Department of Continuum Mechanics and Structural Analysis, Madrid, Spain

Prediction of machining-induced residual stresses is an interesting objective in the field of modelling manufacturing processes. Although Finite Element Analysis (FEA) has been widely used for this purpose, many problems are found when the numerical model is developed. Computational cost and numerical problems related to the extreme mesh distortion make the effort of finite element modelling of machining extremely time consuming. The aim of this work is to predict machinning-induced residual stresses using a finite element model based in ALE (Arbitrary Lagrangian Eulerian) approach. The finite element general-purpose code ABAQUS is used, modifying the previous model used in scientific literature to predict residual stresses. Boundary conditions in the entrance of the workpiece and in the upper border of the chip were modified from Lagrangian boundaries in the previous model, to Eulerian boundaries in the new model.
Main advantages of the model presented in this work are low level of distortion of the mesh, the possibility of simulate long length of machined surface and time-efficiency. The model has been applied to calculate residual stresses in AISI 316L during machining. Reasonable agreement with experimental results has been found.

Key words: residual stresses, orthogonal machining, ALE, boundary conditions

1. Introduction

Finite Element (FE) models have been extensively used to simulate the cutting process for decades. Although many authors have focused their attention on the development of numerical tools to obtain accurate results from simulation, the problem of machining modelling can not be considered as completely solved. The analysis of residual stresses due to machining operations has been an active subject of research. The reliability of structural components obtained by machining operations is influenced by the state of residual stresses resulting from processing. Tensile residual stresses in the vicinity of the machined surface has negative effects on fatigue, fracture resistance and stress corrosion and, therefore, can substantially reduce life of the the component (Okushima and Kakino, 1972).

Machining is a complex process where large strains and strain rates are produced and large temperatures are generated by dissipation of the plastic work and by frictional heating. Residual stresses are related with these coupled thermo-mechanical phenomena (Liang and Su, 2007) and also with metallurgical changes related to the former (Obikawa *et al.*, 2008).

The process of creating a model for machining could be summarised as illustrated in Fig. 1. Several blocks of parameters are defined, beginning with identification of the process and materials parameters, following with numerical parameters that should be implemented and those related with the numerical analysis. Finally, typical output results are presented.

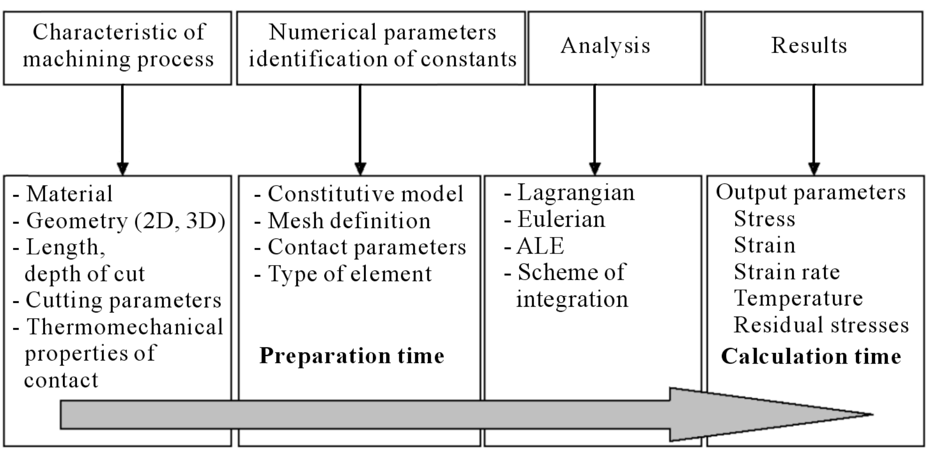

Fig. 1. Scheme of numerical modelling of the machining process

Popular commercial FE codes, mainly DEFORM and ABAQUS have been used to predict residual stresses in the orthogonal cutting. The commercial FE software DEFORM-2D is a Lagrangian implicit code with adaptive remeshing (Outeiro *et al.*, 2006a,b), meanwhile ABAQUS is one of the most versatile general-purpose code allowing both ALE and Lagrangian analysis as well as implicit and explicit integration schemes (Nasr *et al.*, 2007; Salio *et al.*, 2006).

ALE formulation presents advantages when compared with the Lagrangian approach and has been mostly used to simulate residual stresses using ABAQUS code. The model commonly used in the prediction of residual stresses is described in detail in Nasr *et al.* (2007), Miguélez *et al.* (2009) and it is schematically shown in Fig. 2. The main drawback of this model is the necessity to precisely define the previous geometry of the chip and its mesh in a way that allow the model to deal with the high level of distortion that appears in this zone. An iterative work is needed to obtain precise geometry and appropriate mesh able to deform without stopping the calculation due to the high level of distortion. Another problem is the enlargement of workpiece elements located at the interface chip-tool, due to the use of Lagrangian boundary in the upper contour of the chip. As the calculation time increases, the number of elements in contact with the tool decreases because they are enlarged, thus diminishing the accuracy of the calculation. These effects are illustrated in Fig. 3, showing the mesh deformed during simulation. Figure 3a presents the detail of the mesh when the initial geometry, not appropriate to perform the calculation, is selected. It is possible to observe excessive distortion at the curvature zone of the chip, leading to the end of the calculation. In Fig. 3b, an appropriate initial geometry and mesh of the chip were selected. However, as the calculation advances, the elements of the workpiece located at the interface enlarge, and only few elements are in contact with the tool when the calculation finishes.

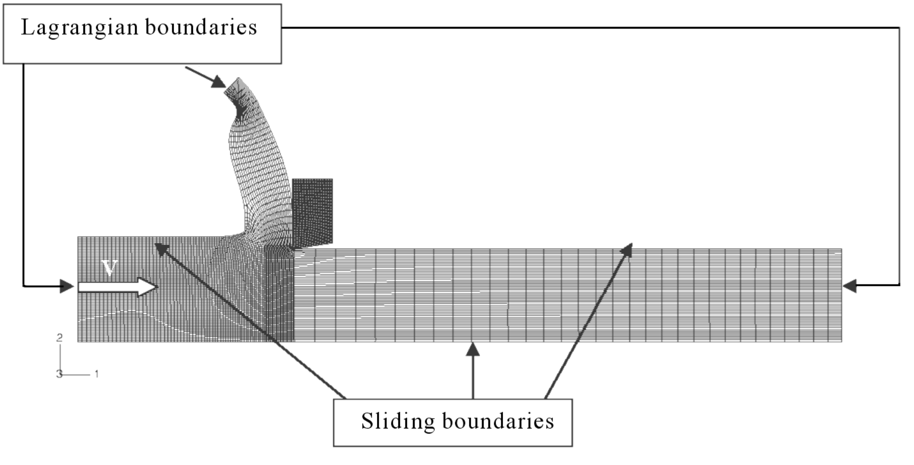

Fig. 2. Model commonly used in ALE formulation in ABAQUS to predict residual stresses. See details in Nasr *et al.* (2007) and Miguélez *et al.* (2009)

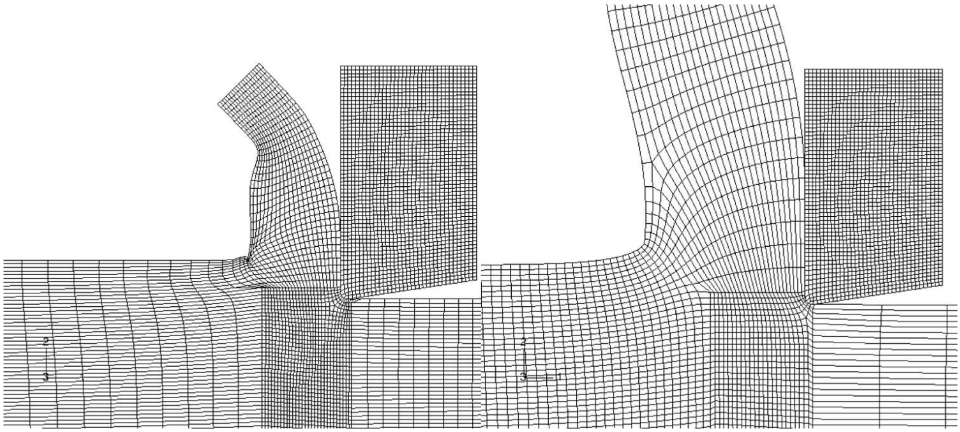

Fig. 3. Details of the cutting zone when using a model with Lagrangian boundaries; (a) deformed mesh with distorted elements in the chip curvature, (b) deformed mesh showing enlarged elements at the interface

One of the main drawbacks of simulation of machining, especially in the case of simulation of residual stresses, is the extremely high computational cost of simulations. Computational time of days or even weeks may be needed even for simulation of only few milliseconds of orthogonal cutting using 2D models. This very low time introduces several problems if the focus of analysis involves thermal issues related to heat generation and diffusion into the tool (Dogu *et al.*, 2006; Filice *et al.*, 2007). In fact, no steady-state conditions are reached during the numerical simulation. Technical literature shows that it is relatively easy to predict some process variables such as the cutting and thrust force, chip geometry, shear angle and contact length (Mamalis *et al.*, 2001) however, the numerical prediction becomes poor when the temperatures on the rake face and inside the tool are investigated (Umbrello *et al.*, 2007a).

In the case of simulation of residual stresses, strongly dependent on thermal phenomena, it is necessary to simulate a long length machined surface to ensure steady state conditions and stabilised level of residual stresses in the machined surface.

It is commonly admitted that tensile residual stresses in machining result from heating of the machined surface during the cutting operation. The large temperature level reached in a thin thermally affected layer near the workpiece surface produces thermal expansion and plastic flow. During the subsequent cooling, thermal contraction of this layer is higher than in the workpiece in-depth, and this phenomenon is believed to be at the origin of tensile residual stresses observed in machining. Although the common understanding is that in the absence of thermal effects the mechanical loading exerted onto the workpiece leads to compressive residual stresses, it is shown in Miguélez *et al.* (2009), Lin *et al.* (1991) that even in the absence of thermal effects, a substantial level of tensile residual stresses can be obtained by solely pure mechanical effects. However, the level of tensile residual stress is also strongly influenced by thermal effects, thus the prediction of temperature should be as good as possible when the prediction of residual stresses is the objective. In consequence, it is critical to achieve steady state conditions in the calculation, being necessary to perform calculations corresponding to a large cutting time.

On the other hand, the analysis should be performed in two phases, firstly the cutting process is simulated and secondly the workpiece is cooled down and unloaded. Most works based in ABAQUS used explicit integration scheme in both phases, being the second phase extremely time consuming. In a recent work, (Nasr *et al.*, 2008) developed an efficient model with an explicit scheme of integration for the cutting phase and an implicit scheme for the unloading and cooling phase.

The conditional stability is the only concern about explicit integration, requiring a very small time step. This time is in the order of the time required by a dilatational wave to cross the smallest element in the mode, typically around 10^{-9}-10^{-10} s, leading to a large calculation time. The time efficiency of this phase can be improved with the use of mass scaling as has been reported in literature (Arrazola *et al.*, 2008).

Implicit integration is unconditionally stable and the only limitation on the time step is convergence of the solution, which is based on a pre-defined criterion. The use of implicit integration in the second phase of analysis significantly diminishes the calculation time from several days to few minutes, when compared with that obtained with explicit integration.

The time efficiency of simulation should be understood not only as the resultant computational time. The preparation of the model is also complicated and needs different iterations in order to complete the simulation.

The main objective of this work is presenting a FE model for prediction of residual stresses in metal cutting using the FE commercial code ABAQUS. The model presented is a modification of the model commonly used in literature when predicting residual stresses with ALE formulation in ABAQUS, described in Nasr *et al.* (2007), Nasr *et al.* (2008), that proved its accuracy in predicting residual stresses after machining different alloys and has been used also by the authors in Miguélez *et al.* (2009). Although the results obtained with this model have been satisfactory, the preparation process of the model (initial geometry of the chip and meshing) has been a time consuming part of the work due to the need of several iterations before obtaining a mesh able to complete the desired cutting time.

The new model presented in this work combines Eulerian and Lagrangian boundaries in order to improve the preparation step during the modelling process. The use of Eulerian boundaries in the entrance of the workpiece and in the chip significantly diminishes the number of iterations needed to generate previous geometry and its associated mesh, due to the low level of distortion in the zone around the tip tool obtained with the Eulerian boundary in the chip. The boundaries also allow maintaining a constant size in the element at the interface improving the precision of the calculation of different magnitudes in this zone. It is also possible to simulate a long length of cut, reaching steady state conditions.

In order to obtain a time efficient method, the analysis was carried out in two phases. Firstly, using an explicit integration scheme, the cutting was modelled and steady state conditions were reached. Following, the workpiece was unloaded and cooled by the implicit integration scheme recently proposed in Nasr *et al.* (2008).

The study is focused on the residual stresses induced after orthogonal cutting of stainless steel AISI 316L. Results obtained through this new model are compared with experimental results showing good agreement with the simulation process and its advantages.

2. Numerical model

2.1. ALE formulation

Eulerian, Lagrangian and Arbitrary Lagrangian-Eulerian (ALE) techniques have been used to simulate orthogonal cutting. In Lagrangian analysis, the computational grid deforms with the material whereas in Eulerian analysis it is fixed in space. The Lagrangian calculation embeds a computational mesh in the material domain and solves for the position of the mesh at discrete points in time (Marusich and Ortiz, 1995). The Eulerian formulation has been used to model orthogonal metal cutting as a steady process of chip formation (Dirikolu *et al.*, 2001).

ALE is a relatively new modelling technique in machining, including a combination of the Lagrangian and Eulerian approaches without having their drawbacks. It was firstly introduced to model the cutting process by the end of the last decade. Some of recent ALE cutting models were presented in Özel and Zeren (2005), Miguélez *et al.* (2006), Pantalé *et al.* (2004). This approach became popular due to its implementation in commercial finite element codes. Explicit dynamic ALE formulation is very efficient for simulating highly nonlinear problems involving large localised strains. Detailed formulation of the ALE approach can be found in different papers, see for instance (Pantalé *et al.*, 2004). A brief summary is presented below.

As is well known, the ALE approach is an extension of both Lagrangian and Eulerian descriptions, since the mesh does not remain fixed in space neither moves attached to material points. Then, the grid points have their own governing equations of motion.

In the ALE description, material points are represented by a set of Lagrangian coordinates $\boldsymbol{X}$, spatial points with a set of Eulerian coordinates $\boldsymbol{x}$, and a reference or grid points with a set of arbitrary coordinates $\boldsymbol{\xi}$. At time t, a spatial point $\boldsymbol{x}$ is obtained by mapping a material point $\boldsymbol{X}$ with material motion $\boldsymbol{x} = \Psi(\boldsymbol{X}, t)$ or by mapping the reference point $\boldsymbol{\xi}$ with grid motion $\boldsymbol{x} = \Psi(\boldsymbol{\zeta}, t)$. The material velocity $\boldsymbol{v}$ of the particles is obtained using the classical material derivative

$$\boldsymbol{v} = \dot{\boldsymbol{x}} = \frac{\partial \boldsymbol{x}}{\partial t}\Big|_{\boldsymbol{X}=cte} \tag{2.1}$$

The grid velocity $\widehat{\boldsymbol{v}}$ is obtained after the introduction of a mixed derivative, which represents the time variation of a physical quantity for a given grid point

$$\widehat{\boldsymbol{v}} = \dot{\boldsymbol{x}} = \frac{\partial \boldsymbol{x}}{\partial t}\Big|_{\boldsymbol{\zeta}=cte} \tag{2.2}$$

Mass, momentum and energy conservation laws in the ALE description are used in a similar form as in the Eulerian description. Taking into account the definition of the convective velocity $\boldsymbol{c} = \boldsymbol{v} - \widehat{\boldsymbol{v}}$, conservation laws for ALE approach are written as follows

$$\begin{aligned} &\dot{\rho} + \boldsymbol{c}\nabla\rho + \rho\,\mathrm{div}\,\boldsymbol{v} = 0 \qquad\qquad \rho\dot{\boldsymbol{v}} + \rho\boldsymbol{c}\nabla\boldsymbol{v} = \boldsymbol{f} + \mathrm{div}\,\boldsymbol{\sigma} \\ &\rho\dot{e} + \rho\boldsymbol{c}\nabla e = \boldsymbol{\sigma} : \mathbf{D} - \mathrm{div}\,\boldsymbol{q} + r \end{aligned} \tag{2.3}$$

where ∇ is the gradient operator, ρ is the mass density, $\boldsymbol{f}$ are the body forces, $\boldsymbol{\sigma}$ is the Cauchy stress tensor, e is the specific internal energy, $\mathbf{D}$ is the rate of deformation tensor, r is the body heat generation (ohmic resistance, inductive heating...) and $\boldsymbol{q}$ is the heat flux vector. According to characteristics of the machining problem, temperature is considered as unique component of internal energy, body heat generation is neglected, mechanical dissipation is associated to plastic deformation, and Fourier's heat conduction law rules the heat flow. Then, the First Law of Thermodynamics, Eq. $(2.3)_3$, may be simplified

$$\rho c_V \dot{\theta} + \rho c_V \boldsymbol{c} \nabla \theta = \beta \boldsymbol{\sigma} : \mathbf{D}^P + k \Delta \theta \tag{2.4}$$

θ being the temperature, c_V being the specific heat, k – thermal conductivity coefficient, $\mathbf{D}^P$ – plastic rate of deformation tensor, Δ – Laplacian operator, and β – fraction of plastic work converted into heat (Taylor-Quinney coefficient) included to match experimental results.

2.2. Model description

A plane strain ALE model was developed using the commercial Finite Element code ABAQUS/Explicit. One of the requirements of the model is to avoid mesh distortion from low cutting speed to elevated cutting speed conditions. The residual stress distribution in the machined surface should be stabilised and steady state conditions should be reached. A thermo-mechanical coupled analysis was developed by CPE4RT element type, see ABAQUS manual (2003), that are plane strain, quadrilateral, linearly interpolated, and thermally coupled elements with reduced integration and automatic hourglass control, for ALE formulation.

As explained before, the analysis was carried out in two steps: cutting, using an explicit integration scheme and cooling and unloading, using the implicit integration scheme proposed in Nasr *et al.* (2008). The residual stress distribution was obtained in a section of the workpiece corresponding to stationary conditions during cutting.

Geometry of the numerical model is shown in Fig. 4. The tool is fixed and the cutting speed is applied to the workpiece. The cutting takes place in 1-2 plane under plane strain conditions. Continuous chip formation is assumed. The geometry shown in Fig. 4 corresponds with an uncut chip thickness equal to 0.1 mm and cutting edge radius of the tool equals 0.02 mm. The depth of the workpiece was selected taking into account the typical profile of machined induced residual stresses. On the other hand, it is important to note that the dimensions of the undeformed chip (curvature radius and width) are not critical, and thus, changes in these magnitudes lead to successful calculations with the model. The sensibility of the model to changes in these variables are not so accused as in the case of the previous model, in which lots of iterations were needed before obtaining a geometry able to perform the calculation during the desired cutting time.

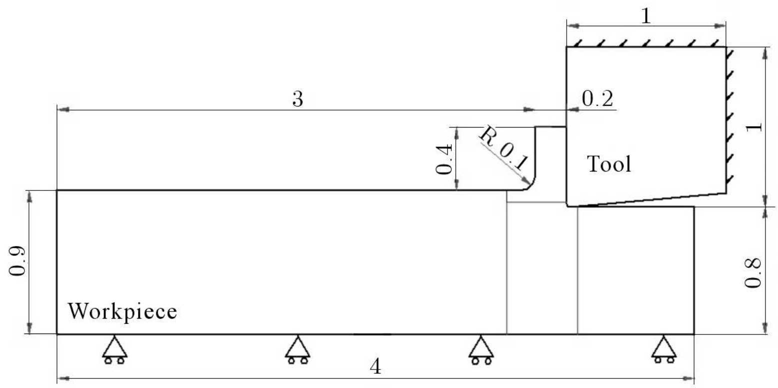

Fig. 4. Geometry of the undeformed numerical model (dimensions in mm)

The ALE model uses sliding, Lagrangian and Eulerian contours (see ABAQUS user manual) allowing the material to flow across an internal Eulerian zone surrounding the tool tip. This approach avoids extreme distortion of the mesh, allowing the simulation of a long machined surface (larger than 15 mm, 150 times the value of the uncut thickness of the chip equal to 0.1 mm).

The model was divided in several zones allowing mesh motion or material flow across the fixed mesh, depending on which zone is considered in the model (see Fig. 5). Zones 1, 2 and 3 combine Lagrangian/Eulerian boundaries with sliding boundaries (where the material is allowed to flow tangentially to the contour and not allowed to go across this boundary). Eulerian boundaries in the entrance of zone 1 and in zone 2 (chip) avoid distortion that usually appears as the calculation advances.

Zone 4 is an Eulerian region, with the mesh fixed, allowing the flow of the material across this region.

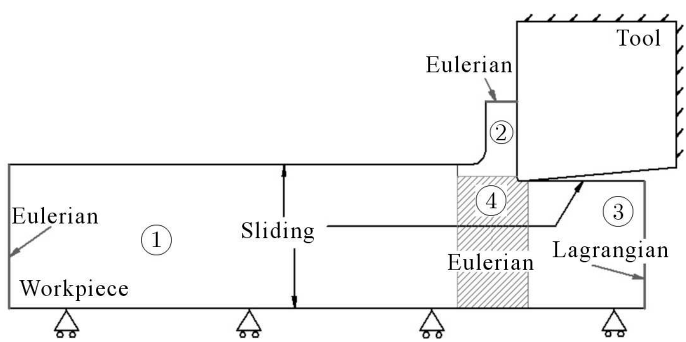

Fig. 5. Boundary conditions implemented in the model

The main advantage of this technique is that the distortion is avoided in the region surrounding the tool tip and it is possible to simulate a long machined surface (that is necessary to obtain stabilised residual stresses). Figure 6a and 6b shows respectively the initial mesh of the model and deformed configuration during the simulation.

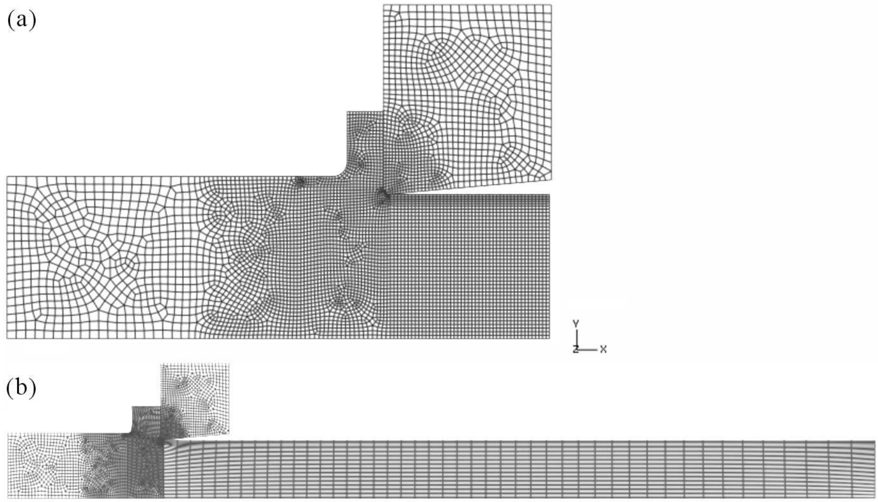

Fig. 6. (a) Undeformed mesh; (b) deformed mesh during cutting

As is widely accepted in literature (Barrow, 1973), a value of the Quinney-Taylor coefficient equal to 0.9 is assumed. An initial temperature of 293 K has been imposed. Conduction and convection to air (only in the freshly machined surface) were taken into account, radiation was neglected. The coefficient of heat convection was $20\,\mathrm{W/m^2K}$ and sink temperature was 293 K. Thermal flux was allowed in the attached contour of the tool.

Friction is one of the hardest phenomena to simulate in machining. In the present work, a constant coefficient of friction along the tool/workpiece contact length is assumed. Although it is the simplest formulation, it has been widely used in numerical simulation of machining (Moufki *et al.*, 1998).The value of the friction coefficient equal to 0.4 reproduces accurately the resultant residual stress observed in experimental tests, as will be shown later. The heat partition between the tool and workpiece was assumed to be 50-50% (Lin and Lin, 1992).

The workpiece material is modelled using the Johnson-Cook (JC) constitutive model (Johnson and Cook, 1983)

$$\sigma_Y = [A + B(\varepsilon^{pl})^n]\Big(1 + C\ln\frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0}\Big)\Big[1 - \Big(\frac{\theta - \theta_{ref}}{\theta_{melt} - \theta_{ref}}\Big)^m\Big] \tag{2.5}$$

σ_Y being the flow stress, ε^{pl} – equivalent plastic strain, θ – temperature, and all remaining parameters being material constants. This constitutive equation, available in ABAQUS/Explicit, is useful to simulate mechanical processes involving high strain and strain rates, and thermal softening, and it has been widely used to model cutting processes (Umbrello *et al.*, 2007b).

Characterisation of the workpiece material AISI 316L has received considerable attention in the literature. It is possible to found JC parameters in a wide range of values, associated with thermomechanical behaviour of this alloy. In this work, parameters presented in Table 1, proposed in Tounsi *et al.* (2002) have been used.

Table 1. Tool material properties (Tounsi *et al.*, 2002)

A [MPa]	B [MPa]	n	C	m	$\dot{\varepsilon}_0$ [s^{-1}]
514	514	0.508	0.042	0.533	10^{-3}

Physical properties of the cutting material (carbide) and workpiece material were obtained from scientific literature (Jang *et al.*, 1996; Umbrello *et al.*, 2007) and are presented in Table 2 and Table 3.

Table 2. Tool material properties (Jang *et al.*, 1996)

Properties	Carbide tool
Density [kg/m^3]	14900
Specific heat [J/kg°C]	138
Thermal conductivity [W/m°C]	79

Table 3. Workpiece material properties (Umbrello *et al.*, 2007b)

Properties	AISI 316L
Young modulus [GPa]	202
Poisson coefficient	0.3
Density [kg/m^3]	7800
Specific heat J/kg°C]	542
Thermal expansion coefficient	$1.99 \cdot 10^{-5}$
Thermal conductivity [W/m°C]	20

3. Results and discussion

3.1. Numerical results

The previous preparation of the model with the new implementation of boundary conditions is easier than that needed with the previous model. When the model based in Lagrangian boundaries was used, the elements located in the chip curvature interface and in the interface experienced great distortion as the calculation advanced, aborting numerical simulation in the case of large cutting time problems.

Therefore, new attempts were needed to modify previous geometry of the chip and/or the mesh of the workpiece had to be meshed again in order to avoid distortion. This iterative process had to be repeated several times before obtaining an optimal geometry and mesh configuration able to finish the calculation.

The statement of Eulerian boundaries at the chip and at the entrance of the workpiece, leads to a deformed mesh shown in detail in Fig. 7. It is possible to appreciate the low level of distortion in the elements in the workpiece compared to the deformed mesh shown in Fig. 3.

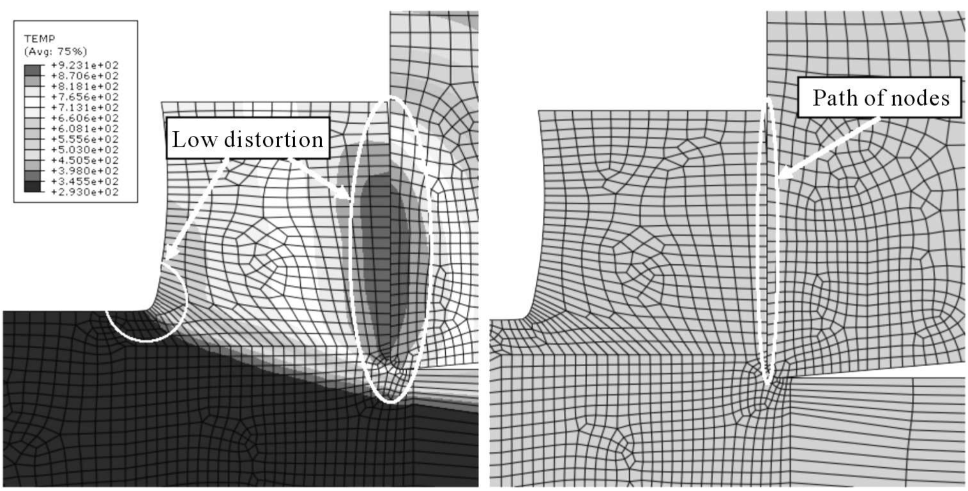

Fig. 7. (a) Detail of the deformed mesh close to the tool tip showing low distortion achieved with the model. Temperature field is shown during cutting, once steady state conditions have been reached. (b) Paths of nodes belonging to the tool and chip where the temperature in the interface is recorded at the interface

Steady state conditions were evaluated in terms of the temperature output. In Fig. 8, the evolution of temperature with cutting time in three elements of the workpiece located just beneath the tool tip is shown. Temperature increases with time and stabilises around the cutting time of 3 ms corresponding to 6 mm of the machined length.

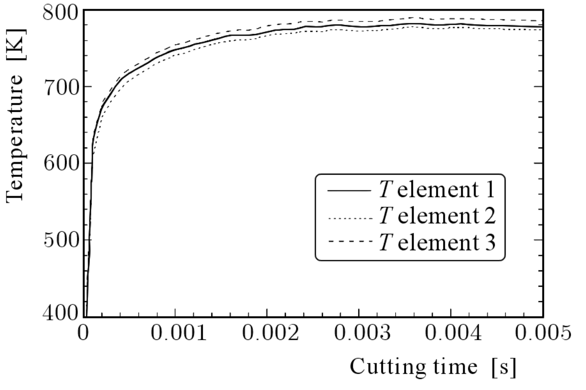

Fig. 8. Evolution of temperature of workpiece elements 1-3 located just beneath the tool tip

On the other hand, it has been experimentally shown (Shaw *et al.*, 1960) that during cutting operation very high levels of pressures are reached at the interface, leading us to consider that the hypothesis of temperature continuity at the interface, should be verified. The evolution of temperature in the interface in both tool and chip is shown in Fig. 9. The contact length and chip morphology during cutting is presented in Fig. 7b, showing the path of nodes where the temperature in the interface has been obtained.

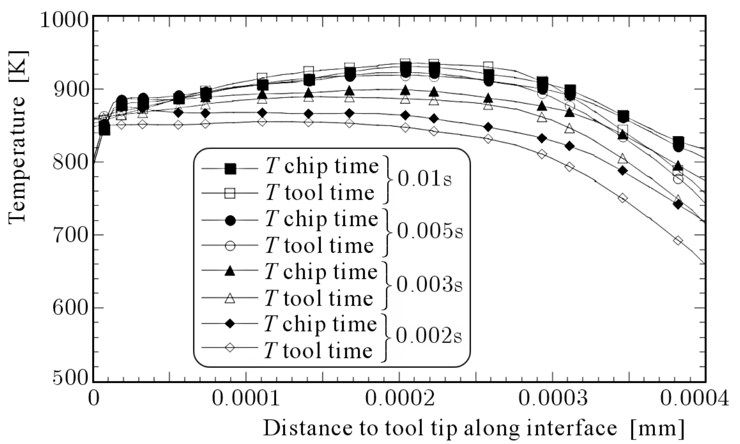

Fig. 9. Evolution of temperature distribution at the interface

It should be noted that temperature continuity in the interface is reached around the cutting time of 5 ms. As the calculation advances, up to the value of cutting time equal to 10 ms (corresponding to a length of machined surface of 20 mm), the differences in the temperature distribution in both chip and tool at the interface are negligible. Although the level of temperature in the interface does not directly influence the residual stresses, it is very important when studying tool wear evolution. The new configuration of the model allowed simulation of large cutting times, thus reaching steady state conditions, also from the point of view of the analysis of temperature continuity in the interface.

3.2. Experimental validation

The model was validated comparing the predicted residual stresses obtained with the model through simulation and experimentally measured. The predicted residual stress distribution was obtained in depth in the workpiece, in a section corresponding with steady state conditions.

Orthogonal dry cutting tests with air cooling were carried out in a lathe (PINACHO model Smart-Turn 6/165) with the following parameters: cutting speed 120 m/min, feed rate 0.1 mm/rev, cutting width 2 mm (corresponding with those used in simulations). The workpiece material was a tube of AISI 316L steel with wall thickness 2 mm. The tool geometry was generated by electro-discharge machining in a hard metal. The cutting edge radius was 20 μm. The distribution of residual stress in the circumferential direction was measured in the Technological Centre IDEKO (see http://www.ideko.es/) in a specimen previously machined in the same conditions as those imposed in simulations.

Figure 10 shows reasonable accuracy of the model when predicting residual stresses. Experimental tensile values in the machined surface are larger than the predicted ones. This behaviour could be related with the uncertainty of the measurement which value is around 120 MPa.

4. Concluding remarks

In this work, a finite element model for calculation of the machinning-induced residual stresses has been presented. The model was developed in the commercial code ABAQUS using the ALE approach and both explicit and implicit integration schemes. The model was developed from the basis of well known

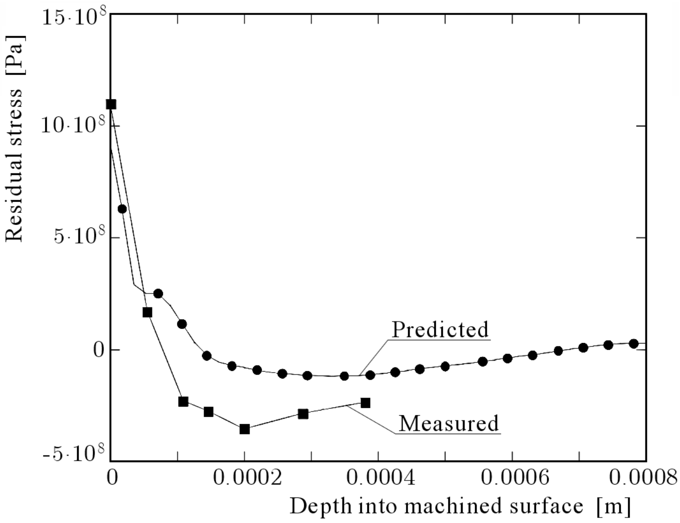

Fig. 10. Experimental and numerical residual stresses in the circumferential direction, cutting speed equal to 120 m/min

models used in the scientific literature and also by the authors. Boundary conditions in the entrance of the work piece and in the upper border of the chip were modified from Lagrangian boundaries in the previous model to Eulerian boundaries in the new model. This change significantly diminishes the preparation time of the model that is usually extremely time consuming, although this fact is not commonly referred in the literature. This approach, not only decreases the work time, it also allows simulation of longer machined surfaces and thus increased cutting times. The simulation of a large cutting time is necessary when a study of thermal issues should be performed due to the long cutting time corresponding to steady state conditions of temperature. The model has been satisfactorily applied to calculation of residual stresses when machining AISI 316L steel. Orthogonal cutting tests were performed in similar conditions with those imposed in the simulations. Resultant residual stresses predicted by the numerical simulation have been compared with experimental measurements showing reasonable accuracy of the model.

Acknowledgements

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Efektywne sformułowanie warunków brzegowych w modelowaniu procesu skrawania we współrzędnych Lagrange-Eulera (ALE)

Streszczenie

Przewidywanie szczątkowych naprężeń wywoływanych obróbką skrawaniem w materiale próbki stanowi interesujące zagadnienie modelowania tego typu technologii wytwarzania. Mimo, że analiza oparta na elementach skończonych znalazła szerokie zastosowanie w tej dziedzinie, jej skuteczność jest problematyczna na poziomie budowy modelu numerycznego. Koszt symulacji i kłopoty obliczeniowe związane z ogromnym zniekształceniem siatki elementów skończonych czynią ten rodzaj analizy wyjątkowo czasochłonnym. Celem tej pracy jest opis metody określania naprężeń szczątkowych indukowanych obróbką skrawaniem za pomocą modelu z elementami skończonymi w opisie eulerowsko-lagrange'owskim ALE (ang. *Arbitrary Lagrangian Eulerian*). W obliczeniach zastosowano wielozadaniowy pakiet ABAQUS, który pozwolił na modyfikację dotychczas stosowanego modelu, opisanego w literaturze. Warunki brzegowe w obszarze wejścia noża w obrabiany materiał i górnej strefie wióra zmodyfikowano z typu Lagrange'a na Eulera w nowej wersji. Zaletą tego rozwiązania okazało się małe zniekształcenie siatki elementów skończonych, możliwość symulacji długich powierzchni obróbczych i znacznie krótszy czas obliczeń. Model wykorzystano do określenia naprężeń szczątkowych w stali AISI 316L podczas skrawania. Potwierdzono satysfakcjonującą zgodność symulacji z wynikami pomiarów doświadczalnych.

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