MODELLING THE ORTHOGONAL MACHINING PROCESS USING CUTTING TOOLS WITH DIFFERENT GEOMETRY

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This paper deals with modelling of the orthogonal machining process using tools with different geometries. The finite element method (FEM) is used for a simulation based on the Lagrangian formulation including ANSYS/LS-DYNA software. The constitutive Johnson – Cook material model regarding strain, strain rate and temperature to predict material plasticity and chip separation is used. Chip morphology, stress, strain, strain rate, residual stress and temperature have been obtained for a range of tool rake angles, cutting edge radii and friction coefficient values. Results are compared with experimental results and other references.

Keywords
FEM, orthogonal cutting, LS-DYNA, Johnson – Cook

1. Introduction

One of the most common operations in manufacturing is metal cutting. There is a wide range of cutting operations such as turning, milling, drilling, grinding, etc. Many studies and experiments were performed since beginning of the 20th century. First analytical models of orthogonal cutting were create on the base of experiments and empirically based research. There are some important historically models: Piispanen's and his "card model" (1930s), Merchant's orthogonal force model (1945) and Oxley's parallel sided shear zone theory (1960) [Oxley 1960]. Many researchers have presented other theories and models. The problem of analytically models is to express wide range of materials, their properties and cutting conditions.

Machining and chip separation is a specific computational problem. Its importance reflects in the design of new tools and specification of conditions for their use. With application of numerical simulations only limited number of experiments needs to be carried out which results in time, financial and material cost saving.

Development of the Finite Element Method (FEM) in early 1970s first pioneered simulations of orthogonal machining process. First research work used as self-developed finite element code. From 1990s massive use of commercial software starts, which is capable of modelling the machining process, as a NIKE2, ABAQUS/Standard, MARC, DEFORM 2D, FORGE 2D, ALGOR, FLUENT, ABAQUS/Explicit, LS DYNA. History and major research work presents [Soo 2007, Mackerle 1999, Mackerle 2003].

FEM simulation of the machining is a typical dynamic non/linear problem for use of the explicit method. In FEM continuum modelling there are four formulations, which can be used for simulations: Lagrangian, Eulerian, Arbitrary Lagrangian Eulerian (ALE) and Smooth Particle Hydrodynamics (SPH). Most common formulation based on the early works, and with simplest code, is the Lagrangian one, which was also used in this research. A separation criterion is important to describe the chip separation in the Lagrangian formulation. Several of them have been implemented into a commercial FE software [Hallquist 2006]. Another method called as a remeshing (Adaptive meshing) or contact break criteria can be used for the chip separation. One of the best results has been showed by the remeshing method [Özel 2005, Yen 2004, MacGinley 2001, Guo 2004], but this method is characterised by long computational times. Therefore it is useful for small and quick simulations only.

At the earliest works the cutting tool was represented by a simple shape [Watanabe 1995, Movahhedy 2000, Shet 2000, McClain 2002, Soo 2004]. That was necessary due to predefined criterion for chip separation from the workpiece along the separation area. In the recent years the developments in codes, especially remeshing and higher computer power allowed advanced analysis for a round or chamfered edge. Özel and Zeren [Özel 2005] used for such simulations commercial software Abaqus/Explicit. The ALE formulation and remeshing scheme with friction control was also used. Yen et al. [Yen 2004] studied by means of the module Conti-Cut an influence of the rounded and honed edge on the cutting forces and temperatures.

In this study a simulation model of orthogonal machining process based on the Lagrangian formulation using commercial software LS_DYNA is presented. Material model is Johnson-Cook plasticity model and for chip separation criteria is used Johnson – Cook damage law. Cutting tool is created with a different geometries for the rake angle and for the tool edge radius. The values are chosen with regards to the mesh density and used method for chip separation. Cutting conditions are chosen for continuous chip formation. The effect of radius and rake angle on the cutting force, stress, strain and temperature has been studied.

2. Modelling of cutting using FEA

2.1. Explicit solution

For simulations of fast dynamic processes calculation of an integration step using implicit integration methods is too slow. For this reason such processes (explosions, penetration simulations, crash tests, etc.) are calculated using explicit integration methods [Petruska 2003]. Difference of the implicit and explicit methods is in the way of calculating of each time step from equation (1). Implicit method uses e.g. Newmark – method and the explicit method uses a central difference scheme.

$$M \cdot \ddot{U} + C \cdot \dot{U} + K \cdot U = F(t) \tag{1}$$

At the equation 1, ***M*** is the mass matrix, ***C*** is the damping matrix, ***K*** is the stiffness matrix, ***U*** is the displacement matrix and ***F*** is the force matrix.

Principle of explicit FEM consists in the use of the Second Newton's Law that is rewritten into the matrix form and defined in the time of the beginning of each time step. Dynamic balance appears when the next equation is fulfilled:

$$\{a_t\} = [M]^{-1}\left(\{F_t^{ext}\} - \{F_t^{int}\}\right) \tag{2}$$

where $\{a_t\}$ is the vector of acceleration in time ***t***, ***[M]*** is the mass matrix, $\{F_t^{ext}\}$ is the vector of external forces applied in time ***t*** and $\{F_t^{int}\}$ is the vector of internal forces in the time ***t***. These methods are more described in [Petruska 2003, Borkovec 2008] in detail.

Most important advantages of explicit FEM are:

- simple code;
- building of stiffness matrix [K] is not required;
- nonlinearities included into the vector of internal forces (simple setup of contact);
- inversion of matrices is not necessary;
- less memory required.

Among the most used explicit FEM programs are: LS-DYNA, ABAQUS Explicit, PAM-CRASH, Deform, MSC-Dytran.

2.2. Model formulation

For a problem solution right formulation must be chosen to describe FE mesh associated with the workpiece material. There are four main formulations: Lagrangian, Eulerian, arbitrary Lagrangian-Eulerian (ALE) and the SPH method.

Lagrangian formulation

In the Lagrangian formulation FE mesh is attached to the workpiece and deformed together. This case is useful for relatively low distortions and possibly large deformations. The history of state of the material in each element is known completely. Compared to the Eulerian method the Lagrange method tends to be faster in calculations as no transport of material through the mesh needs to be calculated. For metal cutting simulations, the Lagrangian formulation is preferable due to the more convenient modelling of the evolution of the chip from the incipient stage to a steady form [Yen 2004, Watanabe 1995, Shet 2000, McClain 2002, Soo 2004, Umbrello 2007, Barge 2005]. The geometry of the material boundaries (or chip shape) does not have to be predetermined, but is developed during the course of the analysis entirely as a function of the physical deformation process, machining parameters, and material properties. Disadvantage of Lagrangian mesh is increasing time step or a stability loss when the distortion of elements is too high.

Eulerian formulation

In the Eulerian formulation the material flows through the finite element (FE) mesh. The unknown material variables are calculated at preset locations as the material flows through the FE mesh. Eulerian mesh is free from distortion problems and remeshing algorithms are not necessary. Other advantage is that a mix of material through cell is allowed. Large deformation is possible in the simulation. A disadvantage of the Eulerian mesh can be seen in higher time consumption as a fine mesh is needed. For machining simulation chip shape must be known before the simulation. Other separation criteria are not necessary. This formulation is often used for hydrodynamic and aerodynamic problems [Kim 1997].

Arbitrary Lagrangian-Eulerian (ALE) formulation

The ALE formulation is an extension of the Lagrangian formulation that, with additional computational steps, moves the grid and remaps the solution onto a new grid. One advantage of this technique is that the freedom in dynamically defining the mesh configuration so allows a combination of the best features of Lagrange and Eulerian. For metal cutting simulations, the Eulerian approach is convenient for modelling of the area around the tool tip, while the Lagrangian approach can be used for modelling the unconstrained material flow at the free boundaries [Özel 2005, Guo 2004, Movahhedy 2000, Pantalé 2004].

Smoothed Particle Hydrodynamics (SPH) formulation

The SPH technique uses no grid, it is pure Lagrangian formulation. The absence of a mesh and the calculation of interactions main particles based on their separation alone means that large deformation can be computed. This method is primarily used in fluid mechanics [Limido 2007].

2.3. Material model

During solving the problem of material separation the explicit algorithm has to be specified; the condition when damage/fracture of each element occurs. Commercially used programs have several models of damage described in [Soo 2007, Borkovec 2008, Liang 1999]. For simulations of machining Johnson – Cook criterion [Johnson 1983, Johnson 1985] appears to be the best one, the criterion of equivalent strain similarly.

Johnson-Cook – this material model was developed in the 80's to study impacts, penetrations and explosives. It is favoured as well in studies of problems of fast deformations, large strain, e. g. simulations of machining [Johnson 1983].

The Johnson-Cook formulation – equation (3) – Involves the the equivalent plastic strain rate σ_y, equivalent plastic strain $\bar{\varepsilon}^p$, strain hardening index *n*, equivalent plastic strain rate $\dot{\bar{\varepsilon}}^p$, initial dimensionless plastic strain rate $\dot{\varepsilon}^0$, the melting temperature of the workpiece T_{melt}, workpiece transitive temperature T_{room}, and strain rate sensitive exponent m as shown at Eq. 3. A, B and C are constants. The parameters for J – C model identified by [Borkovec 2008] are used in this study. A review of the available material parameters is in Table 1 A.

$$\sigma_y = \left[A + B\left(\bar{\varepsilon}^p\right)^n\right]\left[1 + c\,ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}^0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (3)$$

A study of Umbrello [Umbrello 2007] deals with an influence of single constants used in the J-C model. This model has some disadvantages, as a failure to describe the material softening [Calamaz 2008].

Table 1. J-C parameters used in simulation of AISI 1045 steel

Author	Ref.	A (MPa)	B (MPa)	n	C	m
Borkovec	[16]	375.0	552.0	0.457	0.020	1.400
Forejt	[26]	375.0	580.0	0.500	0.020	1.040
Jaspers	[27]	553.1	600.8	0.234	0.013	1.000
Özel	[6]	451.6	819.5	0.173	0.9e-6	1.095

A dilatation of the element is based on the value of equivalent plastic strain at element integration points. Failure is done when damage parameter ***D*** exceeds one element. The damage parameter follows a cumulative damage law and is given by equation (4).

$$D = \sum \frac{\Delta\bar{\varepsilon}^p}{\varepsilon^f} \quad (4)$$

$\Delta\bar{\varepsilon}^p$ is the increment of the equivalent plastic strain during an integration cycle and ε^f the equivalent strain to fracture under current conditions of strain rate, temperature, pressure and equivalent stress, see equation (5) [Johnson 1985].

$$\varepsilon^f = \left[D_1 + D_2\,exp\left(D_3\frac{p}{q}\right)\right]\left[1 + D_4\,ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}^0}\right)\right]\left[1 + D_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right] \quad (5)$$

Where ***p*** is the pressure stress, ***q*** is the Von Mises stress and other parameters were defined earlier. The failure constants ***D1–D5*** were determined experimentally – see Table 2.

Table 2. Parameters of the J-C damage law for AISI 1045 steel

Parameters	D1	D2	D3	D4	D5
Bořkovec [16]	0,250	4,38	2,68	0,002	0,61

It is necessary to do some independent experimental tests (tensile tests) in parallel with computational simulation [Borkovec 2008, Liang 1999] to get a good verification of results.

Criterion of the equivalent strain – it means that a failure occurs when equivalent strain reached the critical value in a corresponding element, see equation (6).

$$\bar{\varepsilon} = \bar{\varepsilon}_{krit} \quad (6)$$

Criteria are easy for calibration and understanding. But these criteria are not quite optimal, because failure equivalent strain is based on state of stress.

2.4. Models of chip formation

There are several possibilities how this state of material can be implemented into the FEM algorithm. Three most often used methods are presented below:

Adaptive meshing – during crack propagation a new mesh is created around the moving crack tip. All parameters have to be obtained for the new mesh and it leads to long computation time [Özel 2005, Yen 2004, MacGinley 2001, Guo 2004].

Element deletion – after achieving the criterion of fracture the element is removed from the calculation. Disadvantage of this method is disappearing of mass during solution. With large losses of material obtained results are suspicious. In this work, the selected fracture criteria were J-C law and the criterion of equivalent strain [Guo 2004, Barge 2005, Pantalé 2004, Ng 2002].

Damage of contact link at the elements – in this approach area of developing chip has to be known before the solutions. For this area and rest of the workpiece contact link with condition of failure has to be created. This condition is based on normal and shear forces applied on the contact elements or using normal and shear stresses between elements [Hallquist 2006]. This approach is published in [Watanabe 1995, McClain 2002].

3. Finite element model

ANSYS 11.0 was used to prepare finite element mesh; other modifications were done in software Lsprepost2_1. Type of element is Solid 164, which is 3D hexahedral element. The mapped mesh with various densities for chip and for workpiece was generated. Workpiece dimensions were: length 10 mm, height 3,25 mm and width 0,1 mm. Depth of cut was 1 mm. Resulting mesh was built from 7406 nodes and 3580 elements. The tool was meshed with mapped mesh for edge radius 0,0 mm and with sweep mesh for radius 0,1 and 0,2. Tool contains about 70 – 100 elements, depending on radius value. Boundary conditions were applied on the bottom and right side nodes of the workpiece. The total time of simulated machining process was 3,5 ms for cutting speed 180 m.min^{-1}. The computational time for each model was 10 –15 hours on the HP 9300 workstation

3.1. *Cutting tool*

Cutting tool was modelled with a variable geometry in order to study its influence on the numerical results. Four values of rake angles (–5; 0; 5; 10 degrees) have been used for the simulation. Each model of rake angle was modelled for three tip tool radii (0; 0,1, and 0,2). These values were chosen with regard to the mesh density and method of chip separation. For using lower radius than 0,1 it is necessary remeshing model of chip separation otherwise the effect of the radius is inconsiderable.

4. Results and discussion

The simulation showed that the chip formation was in the conditions suitable for a continuous chip morphology. Energy state of the simulation was stable. Hourglass energy was lower than 1,5 % of the internal energy. Number of the deleted elements was equal to the number of the elements along parting line for 5° and 10° of the rake angle and for 0 and –5° was value lower than 3 % for all workpiece elements.

In the simulation chip parameters (width and shear angle), were highly influenced by the deleted element. With deleted elements a decrease of chip width and contact areas in the secondary shear zone was predicted.

Values of the cutting forces are shown at the Figure 1, increasing with the both parameters (rake angle, edge radius). The main effect for an increase of cutting force was related to the rake angle. An increase of the tool edge radius resulted in a lesser force increase.

The higher rake angle caused higher chip thickness and higher shear angle. Modification of the tool edge radius caused increase of the contact area between tool and workpiece elements and that lead to an increase of the internal contact energy (as well as the cutting force). Figure 2 shows the increase of the resultant plastic strain at the machined surface influenced by edge radii. This increase was locally higher than 150 %.

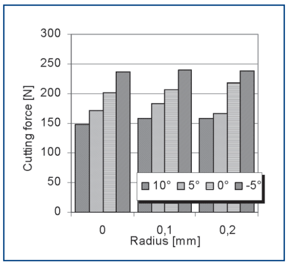

Figure 1. *An influence of the rake angles and cutting edge radii on the cutting force.*

A calculated Von Mises stress at the chip in time 1,85 ms is showed in Figure 3. Maximum values of the stress were concentrated in the vicinity of the tool edge. The increased rake angle increased also the width of the primary shear zone and chip width consequently. Larger edge radius increased stress around tool edge and decreased the stress at the primary shear zone. Secondary shear zone was caused by severe friction between tool and rake face.

Temperature of the chip for different tool edge radius is shown in the Figure 4. The temperature value is about 750 °C at the tool tip and at the area of the secondary shear zone. Locally, at the high distorted elements, the temperatures reached 1405 °C. At the machined surface of the workpiece is temperature about 50 °C for zero radii. For radius 0,1 and 0,2 the temperature reached to the 250 – 300 °C, that is caused by plastic deformation which can be observed in Figure 2.

5. Summary

In this paper, a primary study and calculations based on FEM for the orthogonal machining of the ASIS1045 steel has been done. Cutting tool used for the simulation was modelled with a different ra-

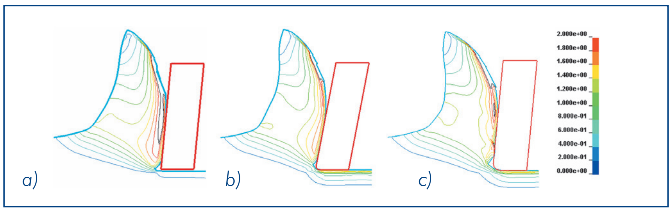

Figure 2. *Contour plot of plastic strain for three tool edge radii a) 0; b) 0,1; c) 0 mm. Results of the simulations were very close to other references [Ozel 2005], [Yen 2004], [Pantalé 2004]. Some differences can be explained different cutting parameters and material data.*

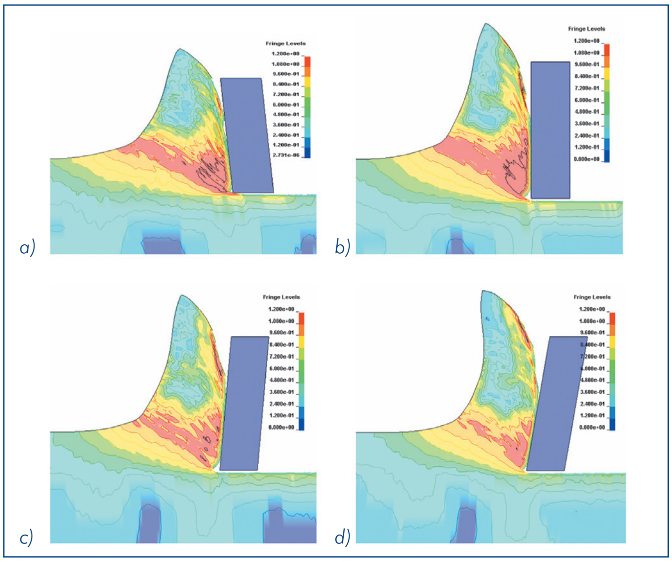

Figure 3. *Von Mises stress fields (MPa) for tool with different rake angle a) -5°; b) 0°; c) 5°; d) 10°.*

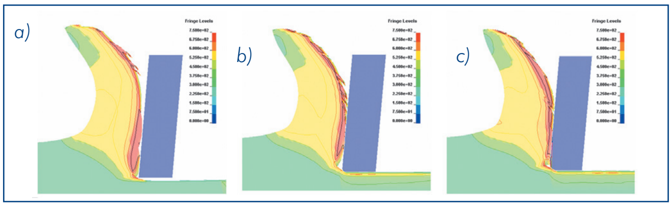

Figure 4. Temperature fields at the chip for tool edge radii a) 0; b) 0,1; c) 0,2 mm.

ke/edge geometry. FE mesh used the Lagrangian formulation with Johnson-Cook plasticity model and Johnson Cook damage law for the chip separation criteria. Cutting force, stress, temperature and chip formation were calculated also. The computer simulation confirmed previous experimental works and will be worked out for conventional turning operations and milling consequently.

Acknowledgements
This research was supported by Fond of Scientific Board of FME 2008 at the Brno University of Technology, and the help was gratefully acknowledged.

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