Cowper-Symonds material deformation law application in material cutting process using LS-DYNA FE code:

turning and milling

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ABSTRACT:

Finite element modeling becomes the huge support in understanding technological process. Besides, there are no so much milling process studies, or these studies are simplified to, as orthogonal cutting process. This paper presents experiences results from orthogonal turning and face milling process. These results were taken for FE model validation and material deformation law constants prediction. In both cases some cutting process simplifications were taken, in order to define contact interaction - to execute meso-scale FE analysis.

Concerning FE modeling, calculation scheme is presented in order to evaluate removing material load to cutting tool. Secondly, material behaviour characteristics were evaluated, assuming high speed deformation and material failure. Thirdly, cutting tool path is modeled in order to evaluate his influence on chip formation.

KEYWORDS:
Cutting process, Milling, Cowper-Symonds function

INTRODUCTION

Considering all cutting process studies, like turning or milling, the chip removing process is considered as cutting edge interaction to workpiece, which is submitted to large deformation rate. Well, workpiece material is submitted to impact, penetration and material failure and erosion (in finite element calculation scheme). But there is no attention to real cutting tool movement, as tool's rotation or linear feed rate. Some authors [1] take in account non constant chip section; witch is the particularity of milling process, of cause by non–constant load acting to cutting tool.

Some studies have been made to prove material characteristics determination methods. These studies focused on correct material parameters selection of material constitutive behaviour law. Umbrello with authors showed that a reasonable prediction of cutting forces, chip morphology, temperature distribution and residual stress is obtained when using material constants set, found from orthogonal cutting tests [2]. Considering these assumption material behaviour parameters firstly was tested on orthogonal cutting tests.

As it will be presented here, the most interesting moment cutting forces, in this work were average stabilized cutting forces, which are the most important. The idea of cutting force measurements experiments is to apply experiments output when simulating by FE-method real physical cutting process. Although cutting force is the main parameter used for specification of Cowper–Symonds constants, it will be further demonstrated that during modeling of a cutting process these constants have to be adjusted by taking into account additional parameters such as chip shape, tool motion law and others.

EXPERIMENTS

Experimental set-up:

This article presents FEM applications, using LS–DYNA software package of two technological processes: orthogonal turning and face milling.

Fig. 1 a) presents technological set-up of orthogonal turning experiment. Respectively, Fig. 1 b) presents technological set-up of face milling set-up.

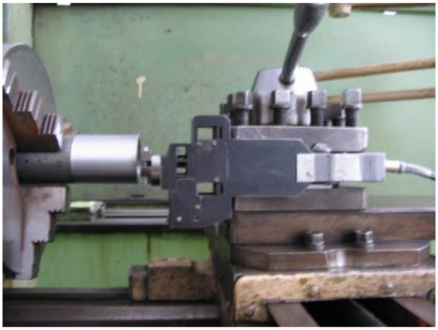


Fig. 1 a) Orthogonal turning set–up: workpiece (CT35–Gost) mounted in spindle, tool mounted on cutting force measurement system (tenzo–sensors).

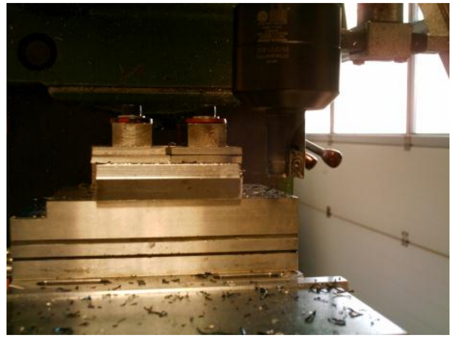


Fig. 2 b) Face milling set–up: workpiece (XC38–Afnor) mounted on Kistler dynamometer, mill tool with two indexable insets.

For orthogonal turning experiments a special "tube" type workpiece (outer diameter: 54.75 mm, inner diameter: 47.75 mm) was produced. Cutting tests also provided the distribution of cutting forces in the range of cutting speeds of (0,42÷3,6 m/s) and feed/ cutting depth (0.05 ÷ 0.1 mm/rev).

Tool (carbure: 85% of WC, 6% of TiC, 9% of Co) parameters used in turning experiments: rake angle: 0°, clearance angle 20°, edge sharpness – 13µm.

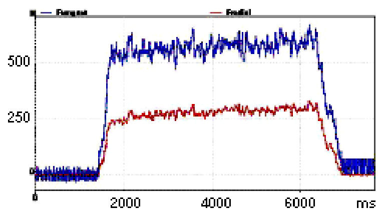
Face milling experiments were performed using these cutting conditions with two non-coated indexable inserts (carbure: APKT 16 04 PD ER–43 from Stellram): width of cut –10 mm, depth of cut – 0.5, 0.75, 1.0 mm, spindle speed – 1500 r/min, cutting speed – 2m/s.

Output from cutting experiments:

Turning experiments were performed in the large zone of cutting speed and feed. And according to the nature of forces change cutting mode zones were extinguished where built–up edge develops, arise resonance vibrations and other processes. These experiments were performed in the aim to define the cutting range of "ideal plastic deformation". After every test (each test was repeated three times) chips were collected.

Cutting force measurement estimated tangential and radial cutting force measurement. This measurement was plotted directly by Picolog software, as it is presented in
Fig. 2 a).

Contrary to these turning force measurements, milling force estimation was non direct from Kistler dynamometer system. Firstly, cutting force was estimated by force action signals registration (tension variation according to Kistler dynamometer coordinate system). Secondly, Kistler dynamometer linearity tests were executed. Thirdly, using coordinate system (from dynamometer to tool coordinate system) transformation matrix, force action to one mill indexable insert was defined.
This calculated cutting force repartition according to tool rotation is presented in
Fig. 2 b).



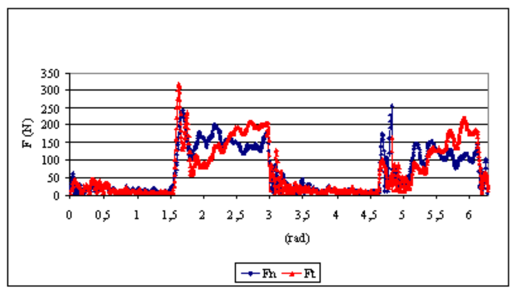


Fig. 2 a) Cutting force measurement in orthogonal turning (cutting speed: 2.88 m/s; feed rate: 0.05 mm/rot)

Fig. 2 b) Calculated cutting force repartition according to tool rotation in milling process (cutting speed: 2 m/s; depth: 0.5 mm)

After the orthogonal turning experiments, the microsections were prepared and used to determine chip form. Fig. 3 present chips form change according to cutting depth (pictures were taken with microscope LMA10). In Fig. 3 a) and b) the chip form presented then cutting conditions: feed 0.05 mm/rot and 0.1 mm/rot respectively (in both cases cutting speed: 2.88 m/s).

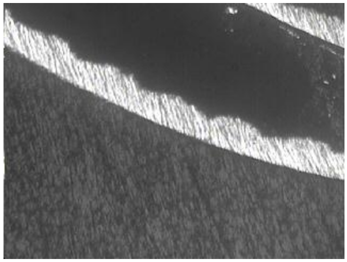


Fig. 3 a) Chip form from orthogonal turning experiment, when V_c=2.88 m/s, p=0.05 mm/rot

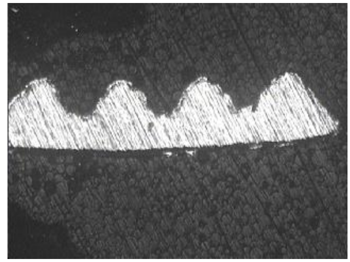
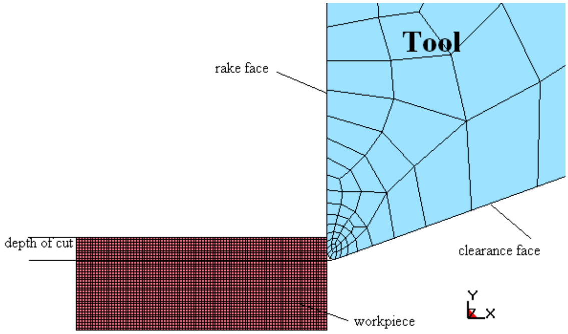


Fig. 3 b) Chip form from orthogonal turning experiment, when V_c=2.88 m/s, p=0.1 mm/rot

For futher FE analysis „ideal plastic" chip formation zone was taken. Concerning cutting dynamics, in both technological processes cutting speed is defined from spindle frequency, and workpiece diameter (in turning process) or tool diameter (in milling process).

FINITE ELEMENT MODELING

In order to estimate workpiece and tool interaction, in both cutting process cases, geometrical FE models were composed. Assuming cutting tool geometry, generally, rake and clearance angles are taken in account, respectively with edge roundness. LS-DYNA finite element program was employed for modeling purposes. For 3D modeling and nonlinear dynamic simulations a solid element SOLID164 was used, which consists of 8 nodes with three degrees of freedom at each node in X, Y, Z directions. Both coarse and fine meshing was used in the finite element model depending on deformation intensity in the considered zone. Fig. 4 illustrates the general view of the developed computational model. In orthogonal cutting process width of cutting 0.5 mm was taken. Because, the simulation of contact interaction usually requires extremely fine mesh resulting in huge computational efforts. Reasonable selection of mesh size allowed reduction of required CPU time without compromising solution accuracy (mesh size was estimated assuming the influence of this parameter to cutting force).



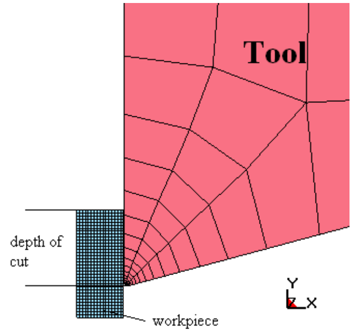


Fig. 4 a) Turning FE model:
Depth of cut=0.05mm
PartID 1Solid (Workpiece) – 28980 elements, 16392 nodes
PartID 2Solid (Tool) – 2375 elements, 2460 nodes

Fig. 4 b) Milling FE model:
Depth of cut=0.5mm
PartID 1Solid (Tool) – 441 elements, 672 nodes
Part ID 2Solid (Workpiece) – 7280 elements, 4408 nodes

In order to define contact interaction the width of cut and depth of cut are taken in account.
In the same way, milling process FE model was composed taking in account Hulle theory [3]. According to Hulle hypothesis [3]:

- the tool cuts by single cutting point, which removes the straight cross-section;
- the direction of cutting force is perpendicular to cutting edge.

Regarding to cut cross–section assumption, the FE model was composed as it is shown in Fig. 4 b). To define the contact interaction the feed per tooth and depth of cut were taken.
Boundary conditions of the finite element model were as follows. The workpiece was constrained in all 6 DOFs. Load of type $U = f(t)$ was imposed on the tool with the purpose to simulate cutting motion with respect to cutting velocity.
Modeling dynamics of cutting tool, keywords in LS–DYNA were used:
1) *DEFINE_CURVE, 2) *BOUNDARY_PRESCRIBED_MOTION_RIGID

Contact interaction was described as follows. Numerical FE model of cutting process was formed evaluating contact between interacting bodies (deformable body – rigid body). In LS–DYNA package contact interaction between two bodies was formulated using "master-slave" methodology and penalty method.
Modeling chip formation, keyword in LS–DYNA was used:
*CONTACT_ERODING_SURFACE_TO_SURFACE
To define element deletion keyword *CONTROL_TIMESTEP with ERODE=1 was adjusted.

MATERIAL MODEL DEFINITION

Since material in cutting is subjected to impact, they are highly affected by large strains and high strain rates, temperature softening, which finally leads to failure. Nevertheless, elastic plastic material law with kinematic isotropic hardening was chosen.

The choice of fracture criterion in LS–DYNA is emphasized and the choice of failure strain as material failure criterion is the most suitable of the simplicity. It is known that failure strain besides can vary in the large zone [3] assuming thermal and high deformation rate effect.

To define material–workpiece in high impact deformation Elastic – plastic material model with kinematic – isotropic hardening was chosen (model#3). Dynamic effects of strain rates are taken into account by scaling static yield stress with the factor, assumed by Cowper – Symonds relation [4]:

$$\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \qquad (1)$$

here: σ_d – dynamic yield stress, σ_s – static yield stress, $\dot{\varepsilon}$ – strain rate, C,P – constants of Cowper – Symonds relation.

Isotropic, kinematic, or a combination of isotropic and kinematic hardening may be obtained by varying a parameter, called β between 0 and 1 [4].

On the basis of presented relation (1), it is obvious that static and dynamic yield stress ratio depends on deformation speed.

Workpiece material properties definition in LS–DYNA FE package was executed, using keyword: *MAT_PLASTIC_KINEMATIC.
Respectively, cutting tool material properties were introduced with keyword: *MAT_RIGID. Arbitrary Lagrangian Eulerian calculation scheme was introduced with adjustment *SECTION_SOLID.
Workpiece material properties defined from tensile test were introduced, as presented in Table 1.

Table 1.

Density (kg/m^3)	Young modulus (GPa)	Poisson index	Yield stress (Mpa)	Strength limit (Mpa) (Non in#3)	Failure strain	Tangential modulus (MPa)	Hardening index (Non in#3)
7800	200	0.29	663	698	0.72	582.6	0.169

In Table 1 properties, found from tensile tests but not used in LS-DYNA material model are mentioned too.

FE MODELING RESULTS

At the initial stage of modeling, the failure strain was set to 0.8 (similar to the static value obtained from tensile tests). Some researchers claim that the magnitude of the fracture deformation does not affect simulation results [5]. It was demonstrated that when neglecting deformation rate (i.e. without artificial enlarging of yield limit), the maximal achieved value of cutting force is equal to 170 N, which is 3.4 times smaller that the experimental value.

Thus, taking into consideration that in the course of cutting process the material was subjected both to temperature effect and influences arising from high deformation rate, the actual failure strain value maybe be 1.16 ÷1.75 times larger than its static equivalent [3]. Fig. 5 a) presents the FE modeling results of calculated cutting force, assuming failure strain.

The influence of isotropic, kinematic or both effect were tested on cutting force in orthogonal cutting process.

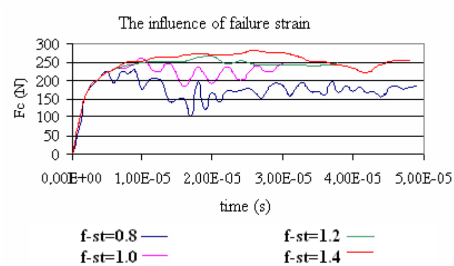


Fig. 5 a) The influence of failure strain

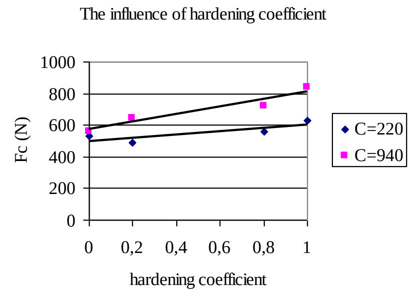


Fig. 5 b) The influence of hardening coefficient

In Fig. 5 b) it is presented cutting force variation according to Cowper-Symonds constants and material hardening coefficients (C=220 s^{-1}, P=5 and C=940 s^{-1}, P=3.5). Both series of simulations the combination with hardening coefficient which corresponds correctly (2.1%) with experimental results (F_t=572 N). Consequently, it's here another precision of chip formation is needed. The chip form, specifically the chip segmentation frequency, defined from chip geometrical elements, was introduced to precise FE model. As it is presented, in Fig. 3, chips, taken from orthogonal turning experiments have repeated segments, characterized by segmentation frequency 6~7 kHz.

Another set of Cowper-Symonds constants was taken to introduce the chip formation with segmentation frequency.

Fig. 6 presents chip formation from orthogonal cutting process simulation.

To model milling process by FE method, the same LS–DYNA model (model#3) was taken and properties too, as mentioned in Table 1. Material hardening law with constant $\beta = 0.5$ was chosen. FE modeling, of face milling process, assuming average chip assumption (0.0485defined from [6]) for depth of cut 0.5 mm was performed.

Calculated cutting force differs about 23% according to experimental results (assuming material deformation rate constants from LS–DYNA library: C=40 s^{-1}, P=5). Cutting force calculated without estimation of material deformation rate is smaller 4.1 times.

Fig. 7 presents milling modeling results according to average chip cross–section estimation.

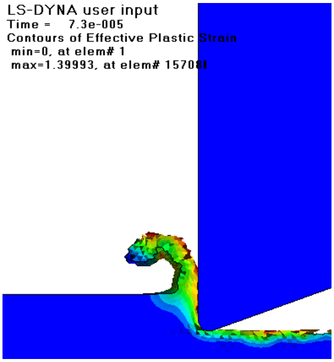


Fig. 6 a) Chip formation in orthogonal turning modeling:
C=220 s^{-1}, P=5, β=0, f-st=1.4;
Fc calc=562N, fsegm~38kHz

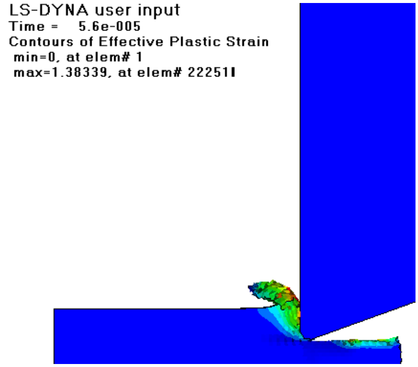


Fig. 6 a) Chip formation in orthogonal turning modeling:
C=220 s^{-1}, P=5, β=1, f-st=1.4;
Fc calc=640N, Failure of chip

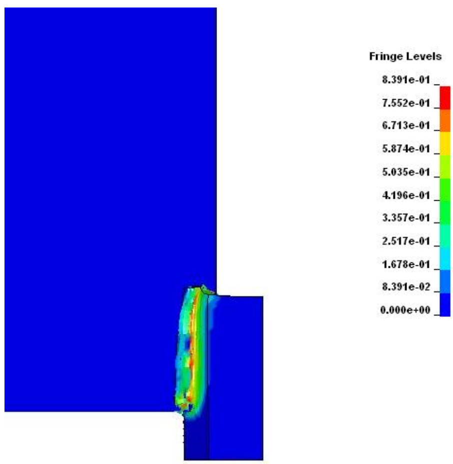


Fig. 7 a) plastic strain distribution, modeling chip removing in milling process

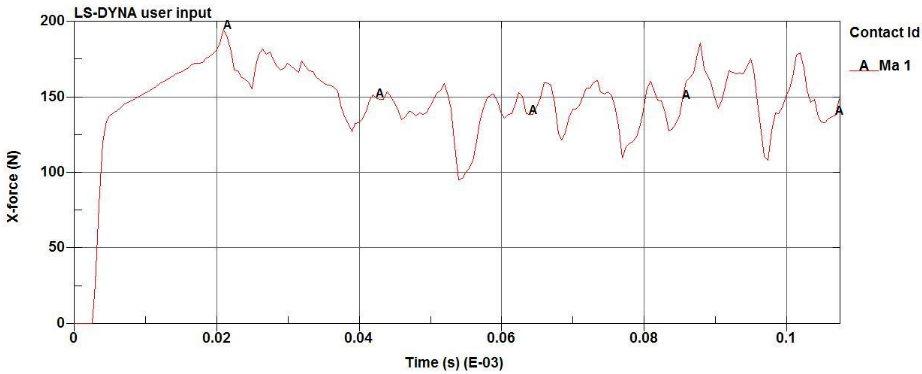


Fig. 7 b) Cutting force distribution in milling process with characteristics:
C=802 s^{-1}, P=3.585 [7], f-st=0.84, β=0.5, μ=0.5 (friction coefficient)

According to results, presented Fig. 7 it is seen, that calculated cutting force is less 10% comparing with experimental results.

But results in Fig. 6 show that cutting force in cutting process can't be only parameter to validate FE modeling results. Material deformation constants and other parameters as friction coefficient, material hardening coefficient are to precise, according to chip form at least.

CONCLUSIONS

The paper proposes finite element computational models for both turning and milling processes by simplifying these models to the case which evaluates the associated contact interaction. Results of the conducted analysis indicate that this simplification is qualitatively justifiable since the developed FE models enable preliminary determination of the cutting forces. In addition, it was demonstrated that without implementation of additional criteria for model validation with respect to the actual process, the researcher without proper knowledge of the technological aspects may produce erroneous simulation results.

In the presented study validation of the FE model for orthogonal turning is accomplished through application of segmentation frequency, a parameter that defines the shape of the chip. The following parameters were considered and adjusted during modeling of the material removal process: material hardening coefficient, failure strain, Cowper-Symonds constants.

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REFERENCES

[1] K.-D. Bouzakis et al., "Optimisation of the cutting edge roundness and its manufacturing procedures of cemented carbide inserts, to improve their milling performance after a PVD coating deposition," *Surface and Coatings Technology*, vol. 163-164, pp. 625-630, Jan. 2003.

[2] D. Umbrello, R. M'Saoubi, and J. C. Outeiro, "The influence of Johnson-Cook material constants on finite element simulation of machining of AISI 316L steel," *International Journal of Machine Tools and Manufacture*, vol. 47, no. 3-4, pp. 462-470, Mar. 2007.

[3] S. Dey, T. Børvik, O. S. Hopperstad, and M. Langseth, "On the influence of fracture criterion in projectile impact of steel plates," *Computational Materials Science*, vol. 38, no. 1, pp. 176-191, Nov. 2006.

[4] J. O. Hallquist, "LS-DYNA theoretical manual. 1998," *Livermore Software Technology Corporation*.

[5] J. C. Hamann, V. Grolleau, and F. Le Maītre, "Machinability improvement of steels at high cutting speeds-study of tool/work material interaction," *CIRP Annals-Manufacturing Technology*, vol. 45, no. 1, p. 87–92, 1996.

[6] F. Koenigsberger and A. J. P. Sabberwal, "An investigation into the cutting force pulsations during milling operations," *International Journal of Machine Tool Design and Research*, vol. 1, no. 1-2, p. 15–33, 1961.

[7] Ł. Bohdal and L. Kukiełka, "The effect of selected material parameters on the stress and strain states in the process of cutting a sheet plate with circular cutters," *TASK Quarterly*, vol. 10, no. 4, p. 391–400, 2006.