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The definition of cutting forces in square shoulder milling by 3D numerical Smooth Particle Hydrodynamics methodology

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1. Introduction

Machining is an important material removal process which is widely used in the industry for producing finished components. A better understanding of the physics behind the chip formation process can help to reduce operations cost, tool wear and breakage, improve the surface integrity of the finished products and aid in the development of new alloys with improved machinability [1].

For this purpose, a wide range of different kind of advanced predictive methods for modelling machining processes are proposed. These methods can be broadly clustered as analytical, numerical, experimental, Artificial Intelligence (AI) based, and hybrid modelling techniques [2, 3].

Most of the machining numerical models are developed and based on Finite Element Methods (FEM) [3, 4]. These models are worthy in improving the production efficiency in terms of cutting tool geometry and optimal cutting parameter selection. The complexity of the geometry of cutting tools and time consuming computing numerical techniques had restricted the researchers to limit their models to simplified 2D approaches with plane strain hypothesis. Under the foresaid machining cases, 3D models become inevitable to get the actual physical apprehension of ongoing processes. 3D models are also essential to realize some interesting features of cutting phenomena e.g. oblique machining or 3D cutting tool wear prediction [5].

In recent years many efforts have been put in understanding the cutting processes involved in milling operations in order to achieve more stable cutting conditions, better surface quality, reduced production time, etc [6]. In large area of research topics, cutting forces reveal to be of key importance as they can be seen as a control parameter for many phenomena involved in cutting processes.

According to the peculiarities of milling process, several numerical models can be presented: for example [7] from a non-deformable (but movable) workpiece to a deformable workpiece the dynamic characteristics of which evolve throughout machining (thin partition walls). This assumption is also applied in milling process taking in to account the large range of milling strategies.

According to the milling cutter geometry there are effectively three directional planes which are used to dictate the cutter geometry angles: tool cutting edge angle and the radial and axial planes. By changing the angle of these planes between negative and positive, the cutter geometry is achieved. These angles are called: radial rake angle and axial rake angle. From the combination of these angles, there are principally three basic cutter geometry combinations. The milling tool cutting edge angle is the main angle influencing the type of milling.

For example, the milling cutter with edge angle equal to 90° is generally used for side milling. Consequently, in this milling case, the ratio of width of cut and the diameter of milling tool allow to define the cutting speed factor for specified workpiece material. Milling cutter with edge angle equal to 45° or less is generally applied for high feed milling.

According to the cutting conditions the non-continuous chip of some length is generated in milling process. As it was defined earlier [8] it is very important to understand what is the impact of processed material layer to the cutting edge.

A unified cutting mechanics model developed for the prediction of cutting forces in milling, boring, turning and drilling operations with inserted tools [9] is presented already. In other words to calculate the cutting forces for the single-edge tool (turning) or multi-edge tool (drilling, milling) the simplified tool geometric model must be considered. Milling is a discontinuous cutting process and by each turn the chips are formed depending on the milling width and number of teeth. Then the simplification of complex cutting tools to single-edge tool is not so informative and understandable.

The previous assumptions are comprehensible for researchers of the field, but in the industry it could be also preferable to use 3D numerical tools. For that reason two numerical study branches are in development [3].

This paper focuses on 3D milling modelling using a Smooth Particle Hydrodynamics (SPH) methodology. The SPH method applied to machining modelling involves several advantages compared to classical Finite Element Method (FEM). First, no remeshing is needed when deformations are high. Secondly, SPH method provides simple assumption of friction and failure in non-linear material deformation.

The aim of this paper – to provide cutting force results from simulations according to cutting speed and feed per tooth, which were selected according to the selected milling tool geometry.

A Smooth Particle Hydrodynamics based model was carried out using the LS-Dyna® V9.71.R4 software.

Firstly, for cutting force study, simple "bump" test modelling was provided in order to check the model validity. Finally, the numerical simulations, according the cutting speed with respect to the milling cutter were performed.

2. Milling case study description and numerical model composition

2.1. FE milling cutter creation and generation of SPH particles

3D coupled SPH-FE model was developed in order to study chip formation and cutting forces.

For numerical study of milling process the square shoulder and slot milling cutter with four indexable inserts were selected for numerical study. Comparing to face milling tools, the square shoulder and slot milling cutters works generally with inserts, composing major cutting edge angle of 90°. The latter particularity allows performing the side milling operations or full milling cutter engagement operations.

The conception of milling cutter with four indexable carbide inserts was performed in Catia®V5 R21 environment. The milling cutter (∅50 mm) with four indexable inserts and four screws (for insert fixation) composed in total nine bodies. This conceptual model in Ansys Workbench®V15 environment was created as only one solid body, needed for numerical analysis. Appreciating the position of inserts in milling cutter, the angles are: axial rake angle equal to 6.5°, edge inclination angle equal to 0° and clearance angle equal to 5°.

Hexagonal meshing was performed for milling cutter (set as a rigid "master" body) and also workpiece (set as a "slave" deformable body), using SOLID164 type elements, as they are used in explicit analysis, assuming large deformation speed and nonlinear contact. The SPH particle generation for workpiece was performed in LS-Dyna for further numerical analysis. The milling cutter design with workpiece filled SPH particles is presented in Fig. 1, generated in LS-Dyna environment after CAD model importation.

For numerical analysis the workpiece dimensions were set as follows: $60 \times 30 \times 12$ mm (in the direction of axis X, Y, Z).

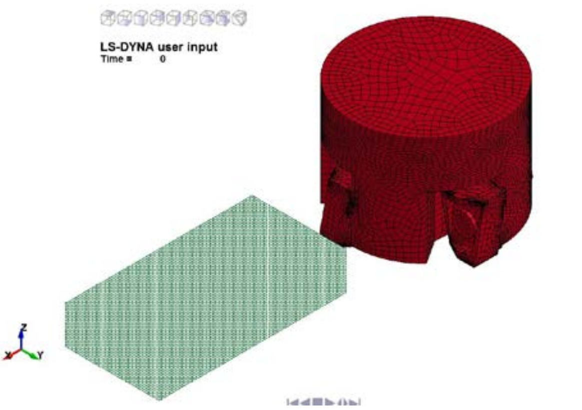


Fig. 1 FE milling cutter model and SPH workpiece model for nonlinear explicit analysis

2.2. Basic principles of SPH method

Created numerical model uses a SPH method in the frame of the LS–DYNA hydrodynamic software.

The method was developed to avoid the limitations of mesh tangling and distortion in extreme deformation problems with FEM [10]. The main difference between FEM and the SPH method is the absence of a grid. In the SPH method the model is defined by a number of particles. The particles are the computational framework on which the governing equations are resolved [10].

The main advantage of "fast" method is the use of Kernel function in particle approximation. The Kernel function W is defined using the function θ by the [11]:

$$W(x,h) = \frac{1}{h(x)^d}\theta(x), \tag{1}$$

where d is the number of space dimensions and h is so-called smoothing length which varies in time and in space. $W(x,y)$ is a centrally peaked function.

The most common smoothing kernel function used with SPH is the cubic B-spline which is defined by choosing θ as:

$$\theta(u) = C_{const} \times \begin{Bmatrix} 1 - \frac{3}{2}u^2 + \frac{3}{4}u^3 \text{for} \left|u\right| \le 1 \\ \frac{1}{4}(2-u)^3 \text{ for } 1 \le \left|u \le 2\right| \\ 0 \text{ for } 2 < \left|u\right| \end{Bmatrix}, \tag{2}$$

where C_{const} is a constant of normalization which depends on the number of spatial dimensions, and $u = r/h$, r is the distance between two particles, h is the smoothing length, as it is presented in the Fig. 2.

The SPH method is based on a quadrature formula for moving particles $(x_i(t))$ $i \in \{1..N\}$, where $x_i(t)$ is the location of particle i, which moves along the field v.

Then, particle approximation of a function can be defined by:

$$\Pi^h f(x) = \sum_{j=1}^{N} w_j f(x_i) W(x_i - x_{j,} h), \tag{3}$$

where $w_j = \frac{m_j}{\rho_j}$ is the "weight" of the particle. The weight of a particle varies proportionally to the divergence of the flow.

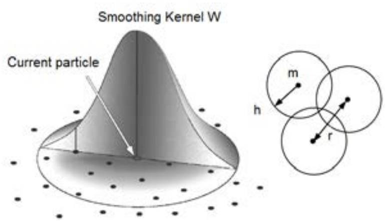


Fig. 2 The representation of smoothing kernel function in the left and typical lengths in the particle model in the right (adopted from [12])

The main advantage induced by the SPH method is the "natural" chip/workpiece separation, i.e. no separation criterion is necessary [12]. Failure strain often is used as separation criterion. During cutting process the material failure strain may be $1.16 \div 1.75$ times larger than its static equivalent [13]. But SPH methodology allows eliminating this artificial criterion, usually used for material failure identification in numerical analysis.

In the same way, the SPH method presents an original aspect concerning contact handling. Indeed, it does not require the definition of surfaces. So, it does not involve a friction parameter. Friction is directly managed via particle interactions [12].

Finally, the main conclusion can be said about the selection of numerical methods for high impact problems.

Nowadays, the hybrid Lagrange-SPH formulation is the best one for impact problems with high deformation of elements and penetration.

2.3. Material behaviour law and material characteristics

The problem as cutting process simulation is classified as high velocity contact–impact interaction problem. The workpiece is set as a deformable body and the elastic – plastic material model with kinematic – isotropic hardening was defined for high strain workpiece material behavior law. Strain rate is accounted for using the Cowper–Symonds model which scales the yield stress by strain rate dependent factor [11]:

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right] \left(\sigma_{Y0} + \beta E_P \varepsilon_{eff}^P \right), \tag{4}$$

where σ_Y, σ_{Y0} - yield stress limits of the material defined with and without the influence of strain rate $\dot{\varepsilon}$; P and C are user defined input constants.

The current radius of the yield surface σ_Y is the sum of the initial yield strength σ_{Y0}, plus the growth $\beta E_P \varepsilon_{eff}^P$, where E_P is the plastic hardening modulus:

$$E_P = \frac{E_t E}{E - E_t}, \tag{5}$$

where E_t - tangential modulus, MPa; ε_{eff}^P - effective plastic strain; β - constant, defining kinematic ($\beta = 0$), isotropic ($\beta = 1$) or kinematic–isotropic hardening ($0 < \beta < 1$).

On the basis of presented relation (4), it is obvious that static and dynamic yield stress ratio depends on deformation speed. Values P and C in relation (4) and the kind of hardening hypothesis (kinematical, isotropic or the combination of two) can be assumed as parameters the values, which need to be determined in order to achieve the adequacy of simulation results to reality [14]. Only the SPH method allows taking in to account the strain rate effect without the definition of these values.

For numerical analysis earlier defined material characteristics of 35 grade steel (0.32–0.4% of GOST) were used. Actual mechanical properties were determined by tensile testing in order to obtain the reliable input data for the developed numerical model. For more details about material characteristics definition the reader is refereed to [15]. Table 1 provides the determined mechanical properties of 35 grade steel and the properties used for SPH modelling. Also, it summarizes the properties needed to define for FEM.

Regarding the material properties in Table 1, it is obvious, that SPH modeling due to particle interaction needs less material properties for numerical analysis. This particularity is also advantageous. Particularly, that the choice of Cowper-Symonds dynamic constants can't be the 'accidental mix' [14].

Table 1

Material properties of 35 grade steel, used for Cowper-Symons law

Characteristics	Value	Used in SPH modelling	Needed to use in FEM
Density, kg/m^3	7800	+	+
Young modulus, GPa	200	+	+
Poisson index	0.29	+	+
Yield stress, MPa	663	+	+
Strength limit, MPa	698	-	-
Failure strain	0.72	-	+
Tangent modulus, MPa	582.6	+	+
Hardening index	0.169	-	-
Cowper-Symonds constants, C, P [11]	40; 5	-	+
Hardening constant	$0 \div 1$	-	+

3. SPH-FE based numerical simulation results

3.1. Numerical sensitivity analysis

This part of chapter focuses on the definition of cutting force with only one translational movement. This simulation test, so called, „bump" test was performed, according to cuting conditions presented in the Table 2.

Table 2

Diameter of milling tool, mm	Width of cutting, mm	Cutting speed, m/min	Cutting depth, mm
50	25	100	1

Generally, the implemented SPH model within the framework of Ls-Dyna reveals some particularities such as artificial viscosity, numerical instabilities. Artificial viscosity is the same term, classically introduced in FEM to preserve the stability of the method when shocks occur. The same approach is used in SPH modelling. The artificial viscosity parameter is introduced into the equation of conservation of momentum and, generally, is selected in order to smooth the physical phenomenon in a coherent way. In the first stage, the numerical simulation test has been performed to check the numerical model adequacy. Model adequacy was tested, according to quantity of SPH particles in the workpiece and the bulk parameter.

In order to test the influence of SPH quantity and viscosity parameter numerical modelling was performed with only one translational movement. So, in this case the analytical expression was applied to calculate the cutting force in the direction of X axis:

$$F_x = S \cdot k_c, \quad (6)$$

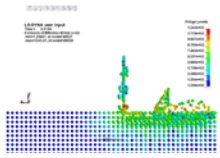
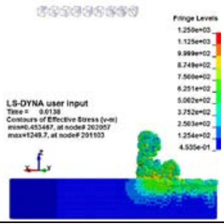
here S is the section to be removed, k_c - specific cutting force (1500 N/mm^2 for 35 grade steel [16]).

The specific cutting coefficients depend on the tool – material couple and the geometry of the tool. Also specific cutting force pressure depends on the section [17] to be removed and the characteristics of material.

Table 3 summarizes the results of performed analysis. For further numerical analysis to identify the cutting forces the numerical model with 2 SPH particles per cutting depth and bulk viscosity parameter of 0.5 were selected.

Table 3

The results of SPH-FE modelling of model validity test, according to the numerical sensitivity study

Quantity of SPH particles in workpiece	Quantity of SPH per cutting depth	Bulk viscosity parameter	Calculated cutting force, F_x, kN	Cutting force estimation by Eq. (6), %	Time of calculation, hours	The shape of removed chip (only translation), according to the quantity of SPH and bulk viscosity parameter = 0.5
11040	1	0.06	30.2	19.4	~3	
		0.5	32.8	12.6	~3	
79534	2	0.06	32.9	12.3	~24	
		0.5	33.2	11.5	~24	

3.2. The definition of cutting forces in 3D milling

For the real 3D milling tool interaction with workpiece the set of cutting conditions was set as presented in Table 4.

Table 4

Cutting conditions for numerical analysis

Cutting speed, m/min	140
Feed speed, mm/min	1783
Milling tool rotation speed, rev/min	892
Depth of cut, mm	1
Feed per tooth, mm/tooth	0.5
Average chip thickness, mm	0.32

Cutting conditions were set according to this assumption, that selected 35 grade steel belongs to P ISO material group and the major cutting edge angle of milling tool is 90°. This allows increasing the recommended cutting speed by the speed factor 1.2.

Several analytical methods [16, 18, 19] also are used to define the main cutting force or tangential cutting force. In our numerical case study, it is the cutting force F_y in Y axis direction. One of these assumptions is based on the definition of average chip thickness in milling and consequently the specific cutting force [18]:

$$F_y = 1.2 \cdot A \cdot k_c \cdot C_{coeff}, \quad (7)$$

where A is the section of chip, mm^2; k_c - specific cutting force (N/mm^2, selected according to average chip thickness in milling); C_{coeff} - the coefficient of correction of cutting speed.

Also in milling the main cutting force can be evaluated by Hulle [19] hypothesis, which takes in account the demand of power in milling:

$$F_y = P_u / V_c, \quad (8)$$

were P_u - power, needed for milling; W, V_c - cutting speed, m/min.

Rigid body motion conditions were applied to milling cutter (characteristics of carbide tool) as set in Table 4. Calculated and averaged cutting forces are presented in Fig. 3. Also tangential cutting force is in comparison with analytical expressions.

4. Conclusions

The 3D SPH-FE based numerical modeling was performed on square shoulder milling case study.

Milling is discontinuous cutting process and by each tool rotation the chips are formed depending on the milling tool width and number or teeth. Then the simplification of complex multi-edge cutting tool to one-point tool is not so informative and understandable.

SPH methodology, used in the presented numerical analysis, allowed to use real cutting tool and to calculate cutting forces for each tooth in rotation, according to workpiece coordinate system.

The numerical model validity tests were performed, according to smooth particle density and bulk viscosity parameter. From these tests the set of combination of numerical sensitivity parameters with error of 11.5% was selected for final numerical modelling.

Calculated tangential cutting force fit the analytically calculated cutting force also, assuming Hulle hypothesis. The results of calculated cutting forces also shows the numerical instabilities, which generally could be eliminated by applying higher cutting speed.

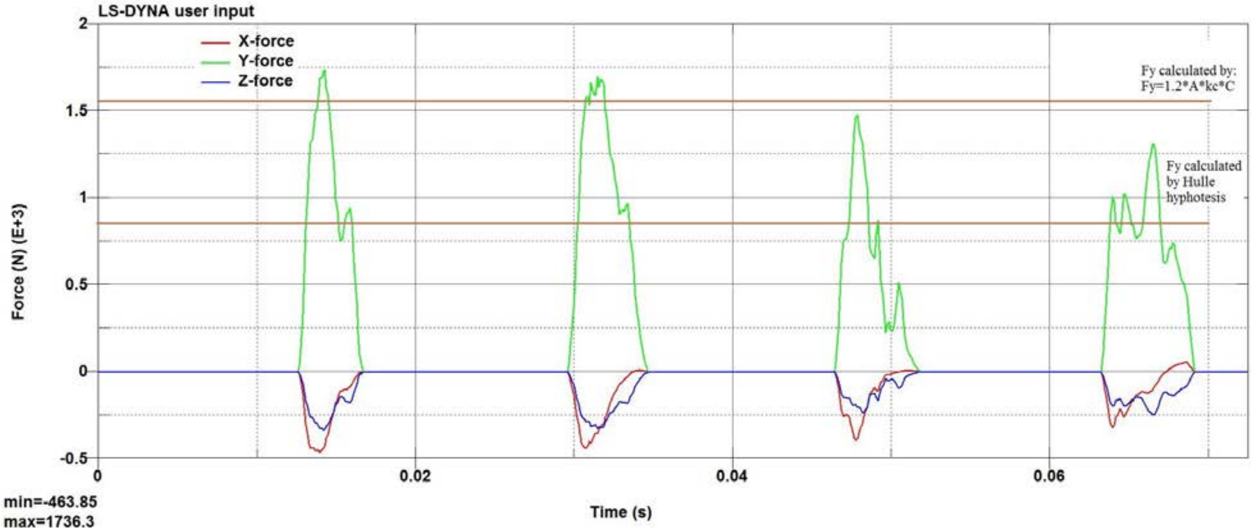


Fig. 3 Calculated cutting forces in 3D square shoulder milling and the comparison of tangential cutting force to analytical expression

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References

1. **Shrot, A.; Bäker, M.** 2012. Determination of Johnson Cook parameters from machining simulations, Journal Comput. Mater. Sci. 52(1): 298-304. http://dx.doi.org/10.1016/j.commatsci.2011.07.035.
2. **Arrazola, P.J.; Özel, T.; Umbrello, D.; Davies, M.; I.S. Jawahir, I.S.** 2013. Recent advances in modelling of metal machining processes, CIRP Ann. - Manuf. Technol. 62(2): 695-718. http://dx.doi.org/10.1016/j.cirp.2013.05.00.
3. **Van Luttervelt, C.A.; Childs, T.H.C.; Jawahir, I.S.; Klocke, F.; Venuvinod, P.K.; Altintas, Y.; Armarego, E.; Dornfeld, D.; Grabec, I.; Leopold, J.; Lindstrom, B.; Lucca, D.; Obikawa, T.; Shirakashi, T.; Sato, H.** 1998. Present situation and future trends in modelling of machining operations progress report of the CIRP working group „modelling of machining operations, CIRP Annals - Manufacturing Technology 47(2): 587-626. http://dx.doi.org/10.1016/S0007-8506(07)63244-2.
4. **Limido, J.; Espinosa, C.; Salaün, M.; Lacome, J.L**. 2007. SPH method applied to high speed cutting modelling, Int. J. Mech. Sci. 49(7): 898-908. http://dx.doi.org/10.1016/j.ijmecsci.2006.11.005.
5. **Asad, M.; Mabrouki, T.** 2013. On the modelling of an aluminium alloy milling: 3D FEM approach, Mechanika 19(5): 588-592. http://dx.doi.org/10.5755/j01.mech.19.5.5538.
6. **Scippa, A.; Sallese, L.; Grossi, N.; Campatelli, G.** 2015. Improved dynamic compensation for accurate cutting force measurements in milling applications, Mech. Syst. Signal Process 54–55: 314-324. http://dx.doi.org/10.1016/j.ymssp.2014.08.019.
7. **Assouline, S.; Beauchesne, E.; Coffignal, G.; Lorong, P.; Marty, A.** 2002. Simulation numérique de l’usinage à l’échelle macroscopique : modèles dynamiques de la pièce, Mécanique Ind. 3(4): 389-402.
8. **Gyliene, V.; Ostasevicius, V.** 2012. Modeling and simulation of a chip load acting on a single milling tool insert, Strojniski Vestn.-J. Mech. Eng. 58(12): 716-723. http://dx.doi.org/10.5545/sv-Jme.2011.356.
9. **Kaymakci, M.; Kilic, Z.M. Altintas, Y.** 2012. Unified cutting force model for turning, boring, drilling and milling operations, Int. J. Mach. Tools Manuf. 54-55: 34-45. http://dx.doi.org/10.1016/j.ijmachtools.2011.12.008.
10. **Villumsen, M.F.; Fauerholdt, T.G.** 2008. Simulation of metal cutting using smooth particle hydrodynamics, Tagungsberichtsband Zum -DYNA Anwenderforum Bamb. 30(10).
11. **Hallquist, J.O.** 1998. LS-DYNA theoretical manual, Livermore Softw. Technol. Corp.
12. **Calamaz, M.; Limido, J.; Nouari, M.; Espinosa, C.; Coupard, D.; Salauen, M.; Girot, F.; Chieragatti, R.** 2009. Toward a better understanding of tool wear effect through a comparison between experiments and SPH numerical modelling of machining hard materials, Int. J. Refract. Met. Hard Mater. 27 (3): 595-604. http://dx.doi.org/10.1016/j.ijrmhm.2008.09.005.
13. **Dey, S.; Børvik, T.; Hopperstad, O.S.; Langseth, M**. 2006. On the influence of fracture criterion in projectile impact of steel plates, Comput. Mater. Sci. 38(1): 176-191. http://dx.doi.org/10.1016/j.commatsci.2006.02.003.
14. **Barauskas, R.; Abraitiene, A.** 2007. Computational analysis of impact of a bullet against the multilayer fabrics in LS-DYNA, Int. J. Impact Eng. 34(7): 1286-1305. http://dx.doi.org/10.1016/j.ijimpeng.2006.06.002.
15. **Gyliene, V.; Ostasevicius, V.** 2013. The validation of FE modeling of orthogonal turning process using Cowper–Symonds material behavior law, Eng. Trans. 61(4): 249-263.

16. http://www.secotools.com/CorpWeb/Downloads/seconews2_2011/MN/milling/Milling_2012_GB_LR_Ny.pdf [revised on 2015 03 02].
17. **Gonzalo, O.; Jauregi, H.; Uriarte, L.G.; Lopez de Lacalle, L.N.** 2009. Prediction of specific force coefficients from a FEM cutting model, Int. J. Adv. Manuf. Technol. 43(3-4): 348-356. http://dx.doi.org/10.1007/s00170-008-1717-9.
18. **Vilkauskas, A.; Juzėnas, K.; Rimašauskas, M.; Eidukynas, V.; Čiuplys, A.; Raudonis, V.; Krasauskas, P.; Griškevičius, P.; Janušas, G.; Jakubčionis, M.** 2014. Mechanikos Inžinieriaus Žinynas, Vilnius: Lietuvos Inžinerinės Pramonės Asociacija LINPRA: 444.
19. **Vergnas J.** 1992. Machining. Technology and practice. –Edition Dunod. 301 p. (in French).

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THE DEFINITION OF CUTTING FORCES IN SQUARE SHOULDER MILLING BY 3D NUMERICAL SMOOTH PARTICLE HYDRODYNAMICS METHODOLOGY

S u m m a r y

The paper presents the 3D square shoulder milling study of modeling, using Smooth Particle Hydrodynamics methodology that also illustrate specific challenges and solutions. The aim of the study – define the cutting forces and to compare them to analytical models.

The milling is a discontinuous cutting process and by each turn the chips are formed depending on the milling tool width and number of teeth. Then the simplification of complex cutting tools to one-point tool is not so informative and understandable for the numerical analysis.

The main advantage of presented SPH methodology – less artificial numerical criterions needed for numerical solution. Also, shorter calculation time comparing to FEM and „natural“ chip removal process due to Kernel function. SPH metodology alloowed to use real 3D milling cutter and to perform the calculation according to feed rate, cutting speed and tool rotation.

In order to provide the numerical simulation the simplified numerical tests were performed, according to the density of smooth particles and artificial bulk viscosity parameter.

The model demonstrated satisfactory coincidence of computed results against the theoretically obtained data. Calculated tangential cutting force is in satisfactory correlation with theoretical Hulle hypothesis. Tne numerical instabilies seen in graphics of results coud be eliminated with SPH metodology, by using higher cutting speed (deformation rate).

Keywords: 3D numerical milling, Smooth Particle Hydrodynamics.

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