Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 46 (2016) 436 – 439

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

The numerical analysis of cutting forces in High Feed face milling, assuming the milling tool geometry

Virginija Gylienė[a,]*, Valdas Eidukynas[b]

[a]Production Engineering Department, Faculty of Mechanical Engineering and Design, Kaunas University of Technology, Studentų st. 56, Kaunas, LT-51424, Lithuania

[b]Mechanical Engineering Department, Faculty of Mechanical Engineering and Design, Kaunas University of Technology, Studentų st. 56, Kaunas, LT-51424, Lithuania

* Corresponding author. Tel.: +37061469342; fax: +370-37-324-144. *E-mail address:* virginija.gyliene@ktu.lt

Abstract

This paper presents the research study of cutting forces assuming the geometry of the milling cutter. The particularity of the milling process is the discontinuity of chip removal assuming the chip cross-section as well as the complexity of milling tool geometry. Usually, the simplification of milling tool (or other multi-edge cutting tools) and kinematics are considered for the purpose of defining the output parameters of cutting process. However, the simplification of complex cutting tools to single-edge tool is not that informative and understandable or limited to the definition of output parameters, considering the really physical milling process. For this purpose, the paper focuses on the definition of cutting forces considering the geometry of the milling cutter. Three main geometries for face milling are known, and they are called double negative, double positive and positive/negative. Considering these geometries, the 3D different milling cutters were composed. Smooth Particles Hydrodynamics (SPH) numerical method was used to perform the simulation of full (without geometry and kinematics simplification) face milling. SPH method is the effective numerical technique to solve the problems of high deformation. For high impact deformation problem, the elastic-plastic material model with kinematic isotropic hardening was chosen. Finally, the results of calculated cutting forces are presented for face milling assuming double negative, double positive and negative/positive face milling.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz

Keywords: Milling; Cutting tool; Modelling

1. Introduction

The huge number of researches focuses on the topic of evaluation of cutting forces during the cutting process. However, the sweeping majority of them focus on the orthogonal machining [1]. The authors Mackerle [2] and Arrazola [1] performed large overview concerning the recent cutting process research techniques. Moreover, it can be noticed that all the analytical and numerical methods focus on the mesoscale machining research. Empirical and hybrid modelling approaches focus generally on the macroscale of machining research.

Earlier Van Luttervelt [3] mentioned that the main difficulties in modelling machining processes are largely attributed to two main factors, i.e., the lack of fundamental understanding of the basic mechanisms of cutting processes and the great variety and complexity of the real machining operations. For this reason, such complicated cutting processes as milling or drilling are simplified to the orthogonal machining. Finally, a unified cutting mechanics model had a demand and was developed for the prediction of cutting forces in milling, boring, turning and drilling operations with the inserted tools [4].

However, the particularity of discontinuous chip removal process in milling tends to predict the variable chip cross-section [5], [6]. The majority of cutting processes modelling use the Finite Element (FE) techniques. Due to the particularities of FE techniques (mostly the huge time of

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz
doi:10.1016/j.procir.2016.03.132

calculation), the meshless or meshfree methods are already in application in the field of machining. The Smooth Particle Hydrodynamics (SPH) method involves several advantages compared to the classical Finite Element Method (FEM). Firstly, no remeshing, no artificial FE deletion methods are needed. Secondly, the SPH method provides a simple assumption of friction and failure in non-linear material deformation. The last mentioned aspect follows to perform the interaction of contacting bodies of complex geometries when high deformations are achieved.

Finally, this paper focus on the study of cutting forces, according to the so-called double positive, double negative and positive/negative face milling. Considering the main types of the face milling geometries, the set of 3D simulations was performed by using the SPH based model and using the LS-Dyna®V9.71.R4 software. The use of SPH method allowed us to perform full 3D milling simulation without milling tool and milling process kinematics simplification.

2. Face milling simulation

In FEM, different numerical approaches are used, i.e., Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE). In the Lagrangian approach, the numerical mesh moves and distorts with the physical material. The Lagrangian approach applies artificial numerical tools to destroy the material, but the FE distortion and deletion is not "natural" for the cutting process.

On the contrary, the Eulerian FE approach eliminates the element distortion problems, but requires the knowledge of the chip geometry in advance. ALE technique combines the best features of the pure Lagrangian and Eulerian analysis. Due to these particularities of FE techniques, the meshless or meshfree methods have been recently applied for the cutting processes [7-9].

2.1. Smooth particle hydrodynamics formulation in Ls-Dyna

SPH is one of several particle methods (Meshfree Galerkin RKPM, EFG and others) in continuum mechanics. Like FE modelling method, SPH uses conservation equations for the continuum mechanics to solve velocity, pressure and energy. In SPH method, it is needed to define the interpolation function and derivation function for solving the conservative equations. The use of Kernel function in particle approximation provides fast solution. The Kernel function *W* is defined using the function θ by the [10]:

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

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

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

$$\Pi^h f(x) = \sum_{j=1}^{N} w_j f(x_i) W(x_i - x_j, h) \tag{2}$$

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. In the Fig. 1, r is the distance between two particles, h is the smoothing length.

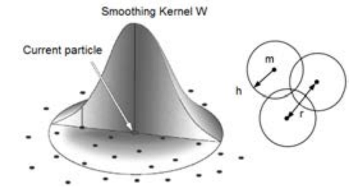

Fig. 1. The representation of smoothing kernel function and typical lengths in the particle model (adopted from [9]).

2.2. Geometrical conception of face milling cutter

The three main types of the milling cutter geometries exist for face milling: double negative, double positive and positive/negative [11]. There are effective three directional planes which are used to define the cutter geometry angles: tool cutting edge angle plane, the radial and axial planes. By changing the angle of these planes between negative and positive, the milling cutter geometry is achieved. These angles are called radial rake angle and axial rake angle. Cutting edge inclination angle and effective rake angle (after the fixing insert on the cutter) are functional angles which influence the tangential cutting forces and mainly the chip path after the milling [11].

From the previous assumptions, the milling insert geometry was created. The milling insert geometry was created with rake angle of 9° and clearance angle of 5°. The corner radius was set 0.4mm for avoiding scale effect. And the cutting edge radius was set 0.025mm to eliminate the effect of edge bluntness on machined surface. Four inserts were oriented on the milling cutter of diameter of 50 mm. The orientation and fixation of the inserts allowed creating three milling cutter geometries: double negative, double positive and positive/negative (Fig. 2, 3, 4).

After the fixing insert on milling cutter, the clearance angle was left 5°.The conceptual models of milling cutter with four specially oriented inserts were finally meshed as only one solid body in Ansys Workbench®V16.2 environment.

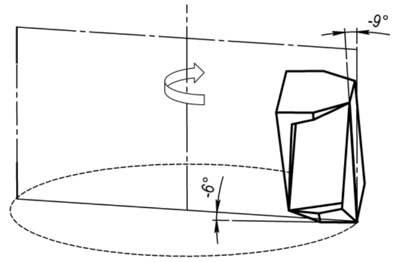

Fig.2. Fixation and orientation of the insert on double negative milling tool (axial rake angle of -9° and radial rake angle of -6°).

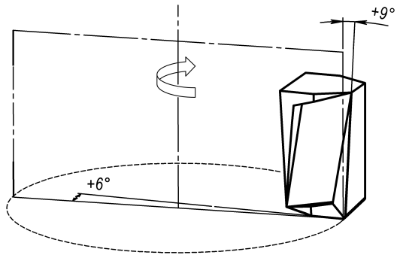

Fig.3. Fixation and orientation of the insert on double positive milling tool (axial rake angle of 9° and radial rake angle of 6°).

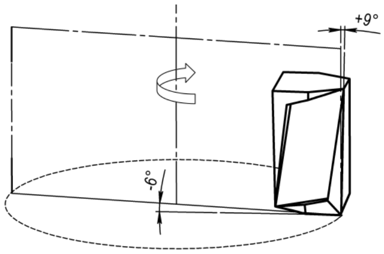

Fig.4. Fixation and orientation of the insert on positive/negative milling tool (axial rake angle of 9° and radial rake angle of -6°).

The milling cutter design (double negative) with workpiece filled SPH particles is presented in Fig. 5. For numerical analysis the workpiece dimensions were set as follows: 10×30×10 mm (respectively in the direction of axis X, Y, Z). The density of SPH particles was generated as regular as possible: two particles per cutting depth of 1 mm. Also for numerical modeling as numerical sensitivity parameters, from previously received "bump" test results were used [12].

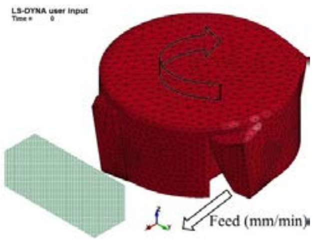

Fig.5. FE milling cutter (double negative geometry) model and SPH workpiece model for nonlinear explicit analysis.

For the 3D face milling tool interaction with workpiece the set of cutting conditions was set as presented in the Table 1.

Table 1. Cutting conditions for numerical analysis.

Cutting parameter	Units	Value
Cutting speed	m/min	140
Feed speed	mm/min	3566
Milling tool rotation speed	rev/min	892
Depth of cut	mm	1
Feed per tooth	mm/tooth	1
Width of cutting	mm	25

2.3. Material behavior law and workpiece material characteristics

For numerical analysis 35 grade steel (0.32-0.4% of GOST) was used. Actual mechanical properties were determined by tensile testing [13]. Table 2 provides the mechanical and physical properties of 35 grade steel.

Table 2. Material properties of 35 grade steel.

Characteristics	Value	Use in SPH modelling
Density, kg/m^3	7800	idem
Young modulus, GPa	200	idem
Poisson index	0.29	idem
Yield stress, MPa	663	idem
Strength limit, MPa	698	-
Failure strain	0.72	1
Tangent modulus, MPa	582.6	idem
Hardening index	0.169	-
Cowper-Symonds constants [10]	C=40, P=5	-
Hardening constants	0÷1	-

Also, in previous work [12] we summarized the material properties needed for SPH and FE modelling, when using Cowper–Symonds behavior law. SPH modelling due to particle interaction needs less material properties for numerical analysis. For example, Cowper-Symonds constants are not setting in SPH modelling. The workpiece is set as a deformable body and strain rate is accounted for using the Cowper–Symonds model which scales the yield stress by strain rate dependent factor [10]:

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right]\left(\sigma_{Y0} + \beta E_P \varepsilon_{eff}^P\right) \tag{3}$$

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 milling cutter was set as rigid non deformable body with the characteristics of carbide.

3. The results of numerical simulations

The Fig. 6 presents the calculated cutting forces and respectively the received chip shape after the cutting of each insert of milling tools so-called: double negative, double positive, positive/negative. The tangential cutting force (F_T) of double negative milling tool is higher 40%, comparing with milling with tool geometry double positive. Also, the tangential cutting force (F_T) of double negative milling tool is higher 30%, comparing with milling with tool geometry positive/negative.

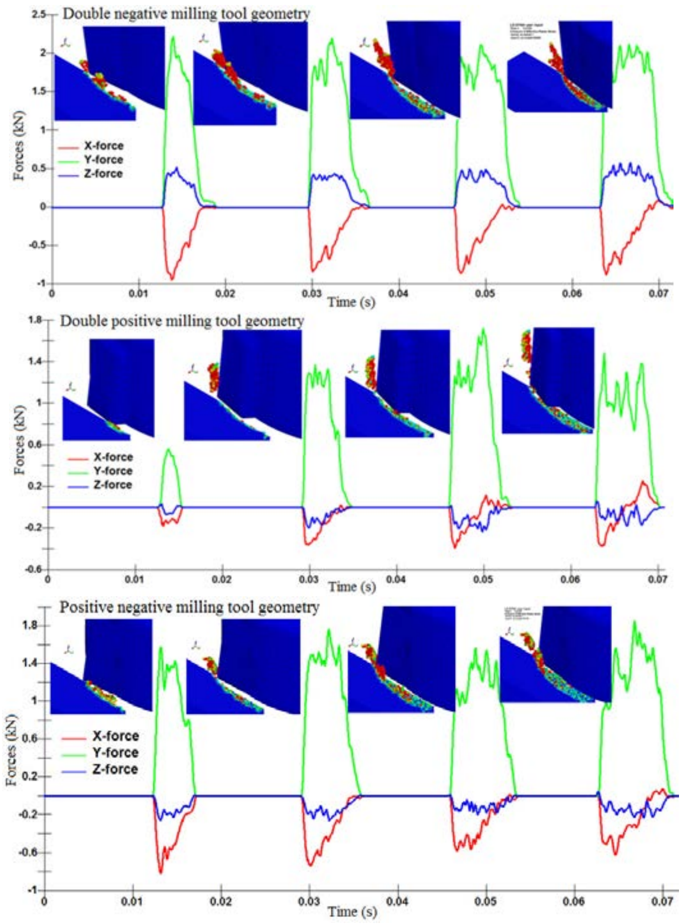

Fig.6. Results of numerical simulation according the geometry of milling tool: cutting forces and chip removal path.

4. Conclusions

SPH methodology, used in the presented numerical analysis, allowed using real milling tool without geometrical simplification to one cutting edge tool. Performing face milling simulation cutting forces for steel 35 grade steel were calculated for each tooth in rotation, according workpiece coordinate system.

The main result was achieved – the definition of cutting forces, assuming the milling tool geometry. For example of presented case study, the tangential cutting force of milling tool of double negative geometry increase about 40% comparing the same cutting force with double positive milling tool geometry. Also the chip removal path was defined for each milling cutter tooth.

References

[1] Arrazola PJ, Özel T, et al. Recent advances in modelling of metal machining processes. CIRP Ann - Manuf Technol 2013; 62(2):695-718.

[2] Mackerle J. Finite element analysis and simulation of machining: an addendum - A bibliography (1996-2002). Int J Mach Tools Manuf 2003; 43(1):103-114.

[3] Van Luttervelt CA, Childs THC, Jawahir IS, Klocke F, et al. Present Situation and Future Trends in Modelling of Machining Operations Progress Report of the CIRP Working Group 'Modelling of Machining Operations'. CIRP Ann - Manuf Technol 1998; 47(2):587-626.

[4] Kaymakci M, Kilic ZM, Altintas Y. Unified cutting force model for turning, boring, drilling and milling operations. Int J Mach Tools Manuf 2012; 54-55:34-45.

[5] Sartkulvanich P, Sahlan H, Altan T. A finite element analysis of burr formation in face milling of a cast aluminum alloy. Mach Sci Technol 2007; 11(2):157-181.

[6] Asad M, Mabrouki T. On the modelling of an aluminium alloy milling: 3D FEM approach. Mechanika 2013; 5:588-592.

[7] Xi Y, Bermingham M, Wang G, Dargusch M. SPH/FE modeling of cutting force and chip formation during thermally assisted machining of Ti6Al4V alloy. Comput Mater Sci 2014; 84:188-197.

[8] Limido J, Espinosa C, Salauen M, Lacome JL. SPH method applied to high speed cutting modelling. Int J Mech Sci 2007; 49(7):898-908.

[9] Calamaz M, Limido J, Nouari M, Espinosa C, Coupard D, et al. 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 2009; 27(3):595-604.

[10] Hallquist JO. LS-Dyna manual 1998. Livermore Softw Technol Corp.

[11]http://www.techniques-ingenieur.fr/base-documentaire/mecanique-th7/procedes-d-usinage-42190210/fraisage-bm7082/[in French].

[12] Gyliene V, Eidukynas V, Fehr G. The definition of cutting forces in square shoulder milling by 3D numerical Smooth Particle Hydrodynamics methodology. Mechanika 2015;(3):234-239.

[13] Gyliene V, Ostasevicius V. The Validation of FE Modeling of Orthogonal Turning Process Using Cowper-Symonds Material Behavior Law. Eng Trans 2013; 61(4):249-263.