Dynamics modeling of surface treatment with end spherical cylindrical milling cutters

B B Ponomarev¹, E V Gabanov², Sh Kh Nguyen¹

¹Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia
²Irkutsk Aviation Plant (IAP), an affiliate of Irkut Corporation, Department of mechanical processing, 3, Novatorov St., Irkutsk, 664020, Russia

E-mail: pusw@ex.istu.edu

Abstract. The designs of modern vehicles and aviation can be traced to a constant increase in the range of parts that have complexly shaped free-form surfaces. Production of such quality parts requires new methods of automated mechanical engineering and particularly program operated multi-purpose five-coordinate machine processing. The paper is dedicated to dynamical modelling of surface treatment of materials by spherical cylindrical milling cutter. The simulation results are the basis for the formation of optimal conditions for machining free-form surfaces and determining combinations of tilt and advance angles and their optimization for positioning the tool for end milling of surfaces on five-axis CNC machines.

1. Introduction
The designs of modern aircrafts, ships, automobiles, high-speed trains and other engineering vehicles can be traced to a constant increase in the range of parts that have complexly shaped free-form surfaces. To produce such parts by the methods of machining, multi-purpose five-coordinate machines with numerical program control are widely used. Technological equipment used in the blank, stamping and foundry industries for parts manufacture that determine aerodynamic and hydrodynamics of the main production items has complex surfaces.

Spherocylinder end milling cutters are most often used for a finishing process of complex surfaces. These cutters minimize the residual scallop and avoid local and global cuttings in the workpiece. However, at axial tool rotation, the velocity of the points located on the cutting edge of a spherical part of the milling cutter in the area of the tool tip is close to zero. During chip formation, it leads to the load increase in the area of the cutter tip and a decrease in the quality of the surface to be treated. This can be eliminated by orientation of the tool at the angles of inclination and tool advancement in relation to the normal to the surface to be machined. In this case, the kinematics and dynamics of the cutting process change during its processing, since the very concept of a complex surface is associated with a significant change in curvature values in each direction in the vicinity of all its points.

Cutting forces are one of the most important parameters that require tracking during the cutting process, as they directly affect product quality and process efficiency. The characteristic of cutting forces is important for research and development in modeling, optimization, monitoring and control of milling processes. Cutting forces are close to optimal values during machining. Excessive cutting forces cause large deflections of the system involved in the end milling process and result in poor product quality, while low cutting forces often indicate low machining efficiency. Therefore, reliable quantitative...
predictions of cutting forces and optimization of cutting forces in machining operations are necessary to select the optimal machining conditions and determine the level of geometric errors of the workpiece.

The research in the field of machining began in the XIX century in several aspects of metal cutting, such as chip formation, cutting mechanics, thermal phenomena, residual stresses, tool dynamics, etc. [1]. Some studies served to predict and measure cutting forces. Due to the complex configuration of the tool, cutting conditions in metalworking operations and some other factors, theoretical calculations of the cutting force did not give accurate results. Experimental measurement of cutting forces requires a large amount of work and significant costs. Therefore, numerical modeling has become necessary and relevant in the process of researching mechanical processing processes. Virtual modeling of technological processes enables to optimize processing modes and conditions at the preproduction stage, analyzing the process for compliance with productivity requirements and processing quality. At the same time, it is possible to minimize material costs, machine time for processing workpieces when debugging control programs for CNC machines, as well as wage costs for machine operators and achieve a reduction of finishing work after machining.

In world practice, there are many researches on modeling machining processes to study cutting forces, distribution of temperature fields in the cutting zone during chip formation, predicting the quality of the surface layer after machining and determining tool durability at end milling. The most part of the work was based on orthogonal models and in the form of micro-processing. In this case, only a contact between the part of the cutting edge and the surface to be treated is considered. To reproduce the actual cutting process, we need a three-dimensional spatial model of finite elements.

An orthogonal finite element method (FEM) approach was used to investigate the cutting mechanism in papers by Jin and Altintas [2], Feng and Menq [3], Budak and Altintas [4], Hinds [5], Lai [6], Chen [7], Lekkala [8].

Feng and Menq successfully applied a mechanistic approach to model the process of finishing spherocylinder milling using orthogonal processing data. In their work, the spherocylinder tool model is represented as an absolutely rigid body with a small ratio of length to diameter. Budak and Altintas modeled cutting forces using a unified approach based on a specific experimental database for orthogonal cutting. This approach helped them to conduct experimental studies of geometry of each tooth cutter, which was required in the mechanistic approach to determine cutting forces.

The stress analysis in the process of micromilling using the finite element method was presented in the work by Hinds, who studied the correlation between stress and tool life (service life). Lai considered the FEM model and the analytical model of micromilling, taking into account the radius of the cutter's edge and the minimum chip thickness.

Chen and Lekkala worked on modeling and analyzing the characteristics of the chip formation process during micromilling. Chen observed the effect of the cut depth, the speed of rotation of the spindle and the feed per tooth on the size and shape of the chips, and concluded that among the three factors, the cut depth has the greatest influence on the chip formation process. In the work by Lekkala, it was found that the depth of cut and the diameter of the tool are the main parameters that significantly affect the thickness of the chip, and the speed of rotation of the spindle and feed per tooth have little effect.

The orthogonal approach to processing modeling and shaping microprocesses is not sufficient to study the dynamics for obtaining parts of complex shape. Therefore, some researchers have moved to the creation of a 3D model to analyze the process of metalworking. Pantal created 3D models to study the cutting process of 42CrMo4 steel [9]. Maurel-Pantel used a three-dimensional model of finite elements to model the milling process of AISI304L stainless steel [10]. However, the simulation was simplified and idealized.

When milling, we use a spherical cylinder tool, many researchers considered modeling cutting forces using various methods. Lamikiz [11] developed an empirical model to calculate cutting forces on inclined surfaces with three-coordinate machining. In this work, cutting forces are calculated based on the advance factors, which depend on the workpiece material, geometric parameters of the workpiece, and cutting parameters. On the other hand, based on the thermomechanical modeling of three-
dimensional cutting, Fontaine [12] developed an analytical model to calculate cutting forces when machining using modern mills. In his work, the tool geometry is decomposed into a series of axial elementary cutting edges. For any element of the cutting edge, elementary cutting forces are calculated based on the relative movement of the edge element to the workpiece at an angle of cutting according to the Johnson-Cook law.

Fussell [13] modeled five-axis milling of sculptural surfaces using discrete geometric models select the optimal feed per tooth by mechanistic modeling of cutting forces. Bailey [14] proposed a general mechanistic model of cutting force to model multi-axis processing of sculptural surfaces. A generalized approach has been developed to represent arbitrary cutting edge design and the local surface topology of a complex sculptural surface. The NURBS curve is used to represent the cutting edge profile. This approach realizes the advantages of representing any arbitrary shape of the cutting edge in general, and provides standardized methods to control the location and orientation of the cutting edge of the tool.

Ozturk and Budak [15] presented an analytical process modeling of five-axis machining with a spherical end mill cutter, and the tool orientation relative to the workpiece at an angle of inclination. The obtained simulation data determine the cutting forces and select the optimal process parameters to improve performance. Erdim [16, 17] presented a mechanistic simulation of five-axis spherical milling. A method to plan the tool feed rate has been developed, taking into account the strength and speed of material removal. This method determines the performance and service life of the tool.

The main objective of the paper is to create a model of a spatial end milling process using spherical cylindrical milling cutters, and analyze the influence of machining conditions and tool orientation on tilt and advance angles relative to the normal to the workpiece on cutting forces.

There are many software engineering tools for finite-element analysis, both specialized in the field of machining simulation, such as DEFORM, ADVENTEDGE, and universal - ABAQUS, LSDYNA, ANSYS, AUTODYN, and others. The Abaqus/CAE software package is selected as the main one. Abaqus/CAE software is focused on solving problems taking into account various types of non-linearities and on performing complex static and dynamic analysis within a single approach, while combining the advantages of an explicit and implicit method of finite element analysis.

2. Model peculiarities in Abaqus environment

2.1 Material, tool and workpiece

The model for spatial milling dynamics includes 3D models of tools and workpieces. A spherocylinder end mill from high-speed steel P18, considered as an absolutely rigid body, with two cutting edges was chosen as a tool. The diameter of the tools equals to 2 mm. In this case, the workpiece is a plate of steel 45. Figure 1 shows the tool and the workpiece in the process of milling with reference to the coordinate system of the machine.

Figure 1. Position of tool and workpiece during milling
In Abaqus program, tool materials and workpieces are linearly elastic materials, where tool properties are according to GOST 19265-73. When modeling the chip removal process, Johnson-Cook models [18] are used to set the mechanical properties of the workpiece material. Linear-elastic properties of the material of the tool and the workpiece are presented in Table 1.

| Material properties | Steel 45 | Steel P18 |
|---------------------|----------|-----------|
| Density (kg/m³)     | 7800     | 8800      |
| Modulus of longitudinal elasticity (Young - HPa) | 200 | 255 |
| Poisson's ratio     | 0.3      | 0.27      |
| Melting temperature (°C) | 1460 | - |
| Room temperature (°C) | 25    | 25       |

The properties of the constitutive Johnson-Cook model are most often represented by the expression for equivalent stress [19, 21]:

\[
\tilde{\sigma} = \left[ A + B(\tilde{\varepsilon}^p)^n \right]^{1+ C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)} \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right],
\]

(1)

where \( \tilde{\sigma} \) - dynamic yield strength, \( A \) - static yield strength, \( B \) - strain hardening modulus, \( C \) - strain rate ratio, \( n \) - exponent in strain hardening law, \( m \) - exponent in the law of thermal softening, \( T \) - absolute instantaneous temperature, \( T_m \) - material melting temperature, \( T_r \) - room temperature, \( \tilde{\varepsilon}^p \) - plastic strain, \( \dot{\varepsilon}_0 \) - plastic strain rate threshold (1 e⁻¹).

| A(MPa) | B(MPa) | C | m | \( \varepsilon^{pl} \) |
|--------|--------|---|---|----------------|
| 553    | 600.8  | 0.0134 | 0.234 | 1 | 0.001 |

Table 2. Parameters of workpiece material from steel 45 [14]

Simulation of chip formation during milling is based on the theory of destruction of the finite element mesh. The Johnson-Cook model of dynamic destruction used in the work suggests that the removal of the material (removal of the finite element mesh) occurs at the parameter value \( D_{\omega} \), which exceeds 1. Destruction parameter \( D_{\omega} \) is defined in the following way [22]:

\[
D_{\omega} = \sum \left( \frac{\Delta \varepsilon^{pl}}{\varepsilon_f} \right),
\]

(2)

where \( \Delta \varepsilon^{pl} \) - increment of effective plastic strain, \( \varepsilon_f \) - fracture deformation. Summation is performed over all increments.

The Johnson-Cook model of dynamic destruction suggests that the equivalent deformation during grid failure is [19, 22]:

\[
\varepsilon_f = \left[ D_1 + D_2 \exp \left( \frac{D_3}{q} \right) \right] \left[ 1 + D_4 \ln \left( \frac{\tilde{\varepsilon}^{pl}}{\dot{\varepsilon}_0} \right) \right] \cdot \left[ 1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right],
\]

(3)

where \( D_1...D_5 \) Johnson-Cook destruction parameters, \( p \) - pressure in considered final element, \( q \) - effective stress. Johnson-Cook destruction parameter values for steel 45 are presented in Table 3.
Table 3. Johnson-Cook destruction parameters for steel 45 ([20])

|   |   |   |   |   |
|---|---|---|---|---|
| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
| 0.06 | 3.31 | -1.96 | 0.0018 | 0.58 |

2.2 The task of contact interactions

When modeling the material removal process in Abaqus, you can use the surface-to-surface contact type. In this case, the “leading surface” defines all the surfaces of the tool, and the “driven surface” defines the workpiece. The friction coefficient is assumed to be 0.2.

Abaqus does not enable to set the speed of movement "around you" for deformable bodies, therefore, to specify the speed of rotation of the tool in the Contact Restrictions module; the Regid Body connection type is used. We can determine the projections of the component forces acting on the entire surface of the tool during the milling process. To do this, we associate all the surfaces of the tool with a virtual point created on the line of the tool axis. In this case, the virtual point is a control point (Fig. 2).

![Figure 2. Task of contact interaction between tool and workpiece](image)

During the calculation, the tool can rotate around the axes passing through the virtual point parallel to the axes of the coordinate system.

2.3 Grid construction

For the most accurate calculations, you should select a specific type of elements. In connection with the chips removal in the workpiece model, the type of 8-node hexahedral elements of the first order C3D8R was selected for it; and for a model of complex shape, as a tool, the type of 10-node tetrahedra C3D10M is also chosen.
2.4 Calculation step design

Abaqus enables to implement several analysis steps. Each step of the analysis is associated with a specific procedure that determines its type and must be performed during the step execution. To solve the problem related to the simulation of the process of chip removal, Dynamic analysis step is chosen, Explicit is a dynamic explicit step. At the same time, in the Field Output Request tab, the output variable STATUS is included, which belongs to the user subprogram VUMAT.

3. 2D modeling of milling process

For a preliminary analysis of cutting force changes, confirmation of the working capacity of ABAQUS program and the accuracy of research results, the milling process was first simulated in a two-dimensional formulation. Figure 3 shows a diagram of the component cutting forces in the form of 2D processes of on-off and side milling. In the coordinate system corresponding to the nature of the workpiece touching the tool, the tangential force is the component force $F_o$ and radial force $F_p$, and in the coordinate system of the machine force projection $F_x$ and $F_y$. $P_{res}$ – resultant cutting force, $v$ – cutting speed, $S$ – table feed, $\psi$ – tool rotation angle, $f_z$ – tooth feed and $a_z$ – instant chip thickness.

Thus, we have:

$$P_{res} = F_p + F_o = F_x + F_y$$  \hspace{0.5cm} (4)

$$a_z = f_z \cdot \sin \psi$$  \hspace{0.5cm} (5)

![Component cutting forces in 2D](image)

**Figure 3.** Component cutting forces in 2D a) with counter milling b) with passing milling

$F_p$ and $F_o$ are defined as functions of variables $F_{cmax}$, $F_{omax}$ (maximum cutting force at maximum chip thickness ($f_z$) and $a_z$).

$$F_p = f(F_{cmax}, a_z) = f(F_{cmax}, f_z \cdot \sin \psi)$$

$$F_o = f(F_{omax}, a_z) = f(F_{omax}, f_z \cdot \sin \psi)$$  \hspace{0.5cm} (6)

From figure 3 it follows that:

$$
\begin{align*}
F_x &= F_o \cdot \cos \psi + F_p \cdot \sin \psi \\
F_y &= F_o \cdot \sin \psi - F_p \cdot \cos \psi
\end{align*}
$$

Taking into account (5) and (6), we have:

$$
\begin{align*}
F_x &= f(F_{cmax}, f_z \cdot \sin \psi) \cdot \cos \psi + f(F_{cmax}, f_z \cdot \sin \psi) \cdot \sin \psi \\
F_y &= f(F_{omax}, f_z \cdot \sin \psi) \cdot \sin \psi - f(F_{omax}, f_z \cdot \sin \psi) \cdot \cos \psi
\end{align*}
$$

(8)

Graphically projected cutting force $F_x$ and $F_y$ are given in Figure 4.
Figure 4. Force charts $F_x$ and $F_y$ depending on the angle of tool rotation

To confirm the working capacity of ABAQUS program when modeling the process of finishing milling, a 2D model was developed, which is a model of the dynamics of tool interaction with the workpiece in one of the sections of the spherical part of the cutter (Fig. 5).

Figure 5. Finite element mesh milling process model

To obtain numerical results, it was assumed that the tool in the section under consideration has a diameter of 2 mm and is made of high-speed steel R18, a spindle speed of 12,500 rev/min, feed per tooth is 0.02 mm, steel 45 is used as the material. Figure 6 presents the results of calculating the projections of the cutting forces $F_x$ and $F_y$ when the tool has one turn.

Figure 6. Projection dependence of cutting force $F_x$ on the angle of tool rotation in 2D modeling
Simulation results and theoretical definitions are similar from charts 4 and 6. It confirms the efficiency of ABAQUS program as applied to the process of finishing milling. Next, we will analyze the results of milling process modeling in a three-dimensional formulation.

4. The effect of machining conditions on cutting forces
To study the effect of cutting conditions on the magnitude of the cutting force, we chose the feed rates and cutting depths recommended by tool manufacturers. Cutting force projection $F_x$, $F_y$, $F_z$ are determined by the values of the reaction acting on the tool in projections on the three coordinate axes $OX$, $OY$ and $OZ$ associated with the machine.

Figures 7, 8, 9 show the results of cutting forces projections $F_x$, $F_y$ and $F_z$ that were obtained with ABAQUS program for different values of tooth feeds with end milling with a two-edged spherocylinder mill with a diameter of 2 mm and a cutting depth of 0.22 mm.
The cutting force values increase with a constant spindle speed, and increasing feed per tooth. The modeling results in ABAQUS are similar to the results of experiment and simulation presented in [23].

Figure 10 shows projection dependences of the cutting force $F_x$, $F_y$, $F_z$ on the angle of tool rotation during milling at different values of the cut depth at $f_z = 0.02$ mm. The projections of the cutting force $F_x$, $F_y$ and $F_z$ increase with increasing the cut depth.

5. The influence of tool orientation on cutting forces

5.1 The influence of the cutter angle on cutting forces

Figure 11 shows simulation results of workpiece milling and the definition of the projections for cutting forces $F_x$, $F_y$ and $F_z$ in the workpiece coordinate system (RMS) at different tool tilt angles. A positive angle is the tilt angle of the instrument, counted counterclockwise from the normal. The angle values are in the intervals of $0 \ldots 90^\circ$ and $270^\circ \ldots 360^\circ$. 
Figure 11. Dependencies of cutting force projections $F_x$, $F_y$ and $F_z$ on the angle of tool rotation when milling with a tilt angle $\alpha = 30^\circ$ (a), $60^\circ$ (b), $300^\circ$ (c) и $330^\circ$ (d)

At the inclination angle $\alpha = 30^\circ$ and $330^\circ$, the point located on the axis of tool rotation, which has zero cutting speed, the spherical cylindrical milling cutter with diameter $D = 2$ mm and $t = 0.22$ mm is still in the contact zone with the workpiece. At the same time, a tool with an even number of teeth simultaneously participates both in passing and counter milling. When the angle of inclination is $60^\circ$ ($300^\circ$ at the opposite direction of inclination), the zero point leaves the cutting zone, and the process of chip removal occurs either in the opposite direction or in the tailwind.

Figure 11 demonstrates that when counter-milling, the cutting forces acting on a tooth gradually increase and sharply decrease in value, while with associated milling they sharply increase and then decrease, which corresponds to theoretical conclusions made in [24, 25].

When the angle of inclination changes from $30^\circ$ to $60^\circ$, the projection of the cutting force $F_x$ increases almost 2 times, $F_y$ remains constant, and $F_z$ changes both in value and in direction.

5.2 Influence of lead angle on cutting forces
The simulation results of the milling process and magnitude determination of the projections of the cutting forces with a change in the tool advance angle in the RMS are shown in Fig. 12. In this case, the values of the lead angle were assigned in the intervals of $0...90^\circ$ and $270^\circ...360^\circ$. 
With advance angles of 270°… 360°, the point on the tool edge with zero cutting speed is outside the touch zone with the workpiece being machined. Chip removal occurs with an interruption, which has an adverse effect on the cutting process and on the tool, each tooth of the spherical part of which in a short period of time participates both in the counter and in the milling.

For a complete tool turn, the sign of the projections of the cutting force $F_x$ and $F_z$ is reversed. When changing the lead angle from 330° to 300°, the projection of the cutting force $F_x$ decreases, and $F_z$ increases dramatically. When the tool advance angle is $\beta = 0$ and 90°, the values of the projections of the cutting force $F_x$, $F_y$ and $F_z$ are less than in the previous case (see Fig. 12). When the advance angle is 60°, the projection of the cutting force $F_y$ increases significantly.

5.3 Experimental studies
To confirm the results compliance of dynamic processing modeling with the theoretical data and actual values of the cutting force, both in magnitude and the nature of its change, a series of experiments was performed on a CNC machine HSC 75 linear. Cutting forces were measured with a stationary dynamometer type 9129AA. At the same time, a spherocylinder end mill of MISUBISHI company with a diameter of 8 mm and a billet of steel 3 were used as a tool.
The signals from dynamometer sensors are transmitted through an amplifier and the data processing board to transform them into digital values. This data was processed with DynoWare software module,
whose interface determines the maximum, minimum and average values of cutting forces over any period of time, for example from \( t_1 \) to \( t_2 \).

Charts 13, 14, 15 demonstrate that cutting forces vary with time according to sinusoidal laws. Since during the machining of the workpiece, each tooth of the spherocylinder mill per one turn of the tool alternately participates in the counter and side milling projection of the force \( F_z \) changes its sign (Figures 4, 6). Therefore, its average value cannot be used to assess the dynamic characteristics of the process. When comparing the minimum and maximum values, it can be seen (Fig. 13, 14, 15) that the absolute value of the projection of the cutting force \( F_x \) increases with increasing feed per tooth.

When we compare the average value for the components of the cutting force \( F_y \) and \( F_z \), we found that their values also increase with increasing feed per tool. \( F_y \) av. = 26.89\( \text{N} \) and \( F_z \) av. = 28.23\( \text{N} \) with feed for tooth \( f_z = 0.02 \text{ mm} \); \( F_y \) av. = 31.24\( \text{N} \) and \( F_z \) av. = 31.91\( \text{N} \) when \( f_z = 0.02 \text{ mm} \); \( F_y \) av. = 35.46\( \text{N} \) and \( F_z \) av. = 35.72\( \text{N} \) with feed for tooth \( f_z = 0.02 \text{ mm} \).

To study the effect of cutting depth on cutting forces, the workpiece was machined with a spherocylinder mill at depths of 0.2 mm; 0.25 mm and 0.3 mm. Figure 16 shows the charts based on the test results. Obviously, as the cutting depth increases, the cutting force components \( F_x \), \( F_y \) and \( F_z \) increase.

Thus, the measurement results of components for cutting force in the process of experimental research fully correspond to the results obtained using the vertical model of the dynamics of the milling process.

6. Conclusion
In NX 10 program, models were created for geometrical analysis of the tool position relatively to the workpiece normal and the surface construction of the conditional cutter tangency in the contact zone of the workpiece with the shaping part of the tool during five-axis milling. According to the analysis results, conditions were determined under which contact with the workpiece of a tool point, which has zero cutting speed during machining, is excluded, which allows improving the quality of the machined surface.

It is theoretically and practically justified that ABAQUS software package models the process dynamics of finishing milling parts with end mills, including spherocylinder mills. The results of numerical calculation are close to the results of theoretical and practical research. They evaluate the influence of machining conditions and tool orientation on cutting forces and conclude that to improve the performance of the end milling process, it is necessary to optimize not only the tool path, but also the cutting conditions and the relative position of the tool to billet.

The simulation results are the basis for the formation of optimal conditions for machining free-form surfaces and determining combinations of tilt and advance angles and their optimization for positioning the tool for end milling of surfaces on five-axis CNC machines.
References
[1] Parihar V, Saloda M A, Nandwana B P and Khidiya M S 2015 Effects of Cutting Parameters on Cutting Forces: An Experimental Study and Numerical Modeling of Turning Operation by Finite Element Analysis J. of Environmental Science Computer Science and Engineering & Technology Sept–Nov C 4(4) 532–44
[2] Jin X and Altintas Y 2012 Prediction of micro-milling forces with finite element method J. of Materials Processing Technology 212(3) 542–52
[3] Feng H-Y and Menq C-H 1994 The prediction of cutting forces in the ball-end milling process– I. Model formulation and model building procedure Int. J. of Machine Tools and Manufacture 34(5) 697–710
[4] Budak E, Altintaş Y and Armarego E J A 1996 Prediction of Milling Force Coefficients From Orthogonal Cutting Data J. of Manufacturing Science and Engineering 118(2) 216
[5] Hinds B and Treanor G 2000) Analysis of stresses in micro-drills using the finite element method International J. of Machine Tools and Manufacture 40(10) 1443–56
[6] Lai X, Li H, Li C, Lin Z and Ni J 2008 Modelling and analysis of micro scale milling considering size effect, micro cutter edge radius and minimum chip thickness Int. J. of Machine Tools and Manufacture 48(1) 1–14
[7] Chen M J, Ni H B, Wang Z J and Jiang Y 2012 Research on the modeling of burr formation process in micro-ball end milling operation on Ti–6Al–4V Int. J. of Advanced Manufacturing Technology 62(9–12) 901–12
[8] Lekkala R, Bajpai V, Singh R K and Joshi S S 2011 Characterization and modeling of burr formation in micro-end milling Precision Engineering 35(4) 625–37
[9] Pantalé O, Bacaria J-L, Dalverny O, Rakotomalala R and Caperaa S 2004) 2D and 3D numerical models of metal cutting with damage effects Computer Methods in Applied Mechanics and Engineering 193(39–41) 4383–99
[10] Maurel-Pantel A, Fontaine M, Thibaud S and Gelin J C 2012 3D FEM simulations of shoulder milling operations on a 304 L stainless steel Simul Model Pract Theory 22 13–27
[11] Lamikiz A, López de Lacalle L N, Sánchez J A and Salgado M A 2004 Cutting force estimation in sculptured surface milling Int. J. of Machine Tools and Manufacture 44(14) 1511–26
[12] Fontaine M, Devillez A, Moufki A and Dudzinski D 2006) Predictive force model for ball-end milling and experimental validation with a wavelike form machining test Int. J. of Machine Tools and Manufacture 46(3–4) 367–80
[13] Fussell B K, Jerard R B and Hemmett J G 2003 Modeling of cutting geometry and forces for 5-axis sculptured surface machining Computer-Aided Design 35(4) 333–46
[14] Bailey T, Elbestawi M A, El-Wardany T I and Fitzpatrick P 2002 Generic Simulation Approach for Multi-Axis Machining, Part 1: Modeling Methodology J. of Manufacturing Science and Engineering 124(3) 624
[15] Budak E, Ozturk E and Tunc L T 2009 Modeling and simulation of 5-axis milling processes CIRP Annals 58(1) 347–50
[16] Erdim H, Lazoglu I and Ozturk B 2006 Feedrate scheduling strategies for free-form surfaces Int. J. of Machine Tools and Manufacture 46(7–8) 747–57
[17] Erdim H, Lazoglu I and Kaymakci M 2007 Free-form surface machining and comparing feedrate scheduling strategies Machining Sci. and Technol. 11(1) 117–33
[18] Johnson G R and Cook W H 1985 Fracture Characteristics of Three Metals Subjected to Various Strains, Strain rates, Temperatures and Pressures Engineering Fracture Mechanics 21(1) 31–48
[19] ABAQUS 2016 Retrieved from: http://abaqus.software.polimi.it/v2016/
[20] Duan C Z, Dou T, Cai Y J and Li Y Y 2009 Finite element simulation & experiment of chip formation process during high speed machining of AISI 1045 hardened steel Int. J. Recent Trend Eng. 1(5) 46–50
[21] Khodko A A 2014 Features for model choice of metal plasticity for a deformable workpiece in the numerical study in hydrodynamic stamping *Aerospace Engineering and Technology* 5 11–24

[22] Kuzkin V A and Mikhaluk D S 2010 The use of numerical simulation to identify the parameters of johnson-Cook model for high-speed deformation of aluminum *Computational Continuum Mechanics* 3(1) 32–43

[23] Altintas Y and Lee P 1998 Mechanics and Dynamics of Ball End Milling *ASME J. Manufact. Sci. and Eng.* 120 684–91

[24] Reznikov N I 1947 *Theory of metal cutting* (Moscow: Mashgiz) 588 p

[25] Wulf A M 1973 *Metal cutting* (Leningrad: Mechanical Engineering) 496 p