Denis Chemezov
Master of Engineering and Technology,
Corresponding Member of International Academy of
Theoretical and Applied Sciences, Lecturer of Vladimir
Industrial College, Russian Federation
chemezov-da@yandex.ru

Nikita Palev
Student of Vladimir Industrial College,
Russian Federation
nik-palev@yandex.ru

SECTION 7. Mechanics and machine construction.

THE SIMULATION OF CUTTING PROCESS OF THE CYLINDRICAL MILLING CUTTER

Abstract: The article is presented the structure cards of the conditions of processing of flat surface of the milling in the software package LS-DYNA. The analysis of cutting process of the cylindrical milling cutter with helical cutting teeth was made.
Key words: a milling, a milling cutter, a billet, a card, a variable, a key word.
Language: English
Citation: Chemezov D, Palev N (2016) THE SIMULATION OF CUTTING PROCESS OF THE CYLINDRICAL MILLING CUTTER. ISJ Theoretical & Applied Science, 06 (38): 57-67.
Soi: http://s-o-i.org/1.1/TAS-06-38-13   Doi: cross http://dx.doi.org/10.15863/TAS.2016.06.38.13

Introduction

Cylindrical milling is used in cases when it is necessary to mechanically process flat surface of a billet of substantial width of the cutting tool. The cylindrical milling cutter is a multiblade cutting tool, the perceiver variable load during the work. Improve the process of milling flat surfaces on the production is achieved by using a cylindrical milling cutters with the helical cutting teeth. Cylindrical milling cutters with the straight cutting teeth are used less, mainly for the milling of narrow surfaces [1, 2].

During the cylindrical milling (in this work it is considered conventional milling) in the cutting zone acts tangential and radial forces, the force of friction, leading to wear and the thermal deformations of the cutting edges of the tool. All of these factors can lead to processing errors (deviation from specified dimensions, geometric shapes or the correct positioning of the surfaces).

This problem has been considered in the various scientific research works. In the work [3] the results by the computer simulation of milling process the ledge of the end milling cutter are presented. It was made the optimization of cutting feed of the cutting tool on the basis of the contours of distribution of the plastic deformations, stresses and shear strains of the material in the cutting zone. The article [4] is described the mechanism of formation the systematic errors of forming when the processing the outer cylindrical surfaces of cylindrical milling cutters with axial and radial feeds, and the analytical dependence is derived for definition of errors that

allowing you to control of the process parameters. The comparison of the geometric roughness of the processed flat and contoured surfaces during climb milling and conventional milling is presented in work [5]. It was determined that the trajectory of the cutting tooth during the conventional milling is an inverted trajectory of climb milling. The milling of convex geometric profile provides a lower surface roughness by the compare of the milling concave surfaces. The influence of the rounding radius of the cutting edge on the stress-strain state of the zone of the chip formation and on the surface quality when milling was investigated in the research work [6]. During the roughing it is recommended to use a cutting tool with a rounding radius in the range of 0.01 – 0.03 mm, and when finishing with optimum rounding radius 0.03 – 0.04 mm provides the smallest cumulative deformation and roughness of the processed surface.

The research of the process of milling of the cylindrical milling cutter with the helical cutting teeth by the approach of computer modeling will allow to receive the authentic results of the stress-strain state of the material of the billet. The changing of cutting modes during the simulation enables for the engineer to correct of the technological process of milling on the machines with the numerical control (CNC), which it is an actual task for automated machinery production.

Materials and methods

The research of subject was the contact interaction of cutting edges of the milling cutter with the processed surface of the billet in conditions of conventional milling.

The creation and subsequent orientation in the global coordinate system solid of models of the billet and the cylindrical milling cutter with helical cutting teeth can be performed in any CAD system.

The parameters of the models of billet and cylindrical milling cutter are presented in table 1.

Table 1

The parameters of the billet and the cylindrical milling cutter.

Name of the parameter	Reference designation	Unit of the measurement	Magnitude
A billet			
Length	L_b	mm	50
Width	B	mm	50
Height	H	mm	20
The cylindrical milling cutter			
The outside diameter of the milling cutter	d_m	mm	70
The length of the cutting part of the milling cutter	l_m	mm	52
The total length of the milling cutter	L_m	mm	60
Rake angle	γ	deg.	10
Clearance angle	α	deg.	10
Helix angle	ω	deg.	36
Width of cylindrical facet	f	mm	1
The outside diameter of the flanges of the milling cutter	d_f	mm	54
Hole diameter	D	mm	28
Keyway width	b_k	mm	7
Keyway depth	t_k	mm	3

The magnitude γ of the cylindrical milling cutter is selected in depending on processed material and the character of processing. For this type of milling with constant cutting depth γ is performed positive. In order to increase resistance of cutting tools α was taken to be the magnitude of not more than 10 degrees.

The helix angle of the cutting blade is used to increase the smoothness of work of the cylindrical milling cutter and for creating the direction of the descending chip on the tooth face [7].

The orientation of solid models of the billet and the cylindrical milling cutter with helical cutting teeth in three-dimensional formulation is presented in Fig. 1.
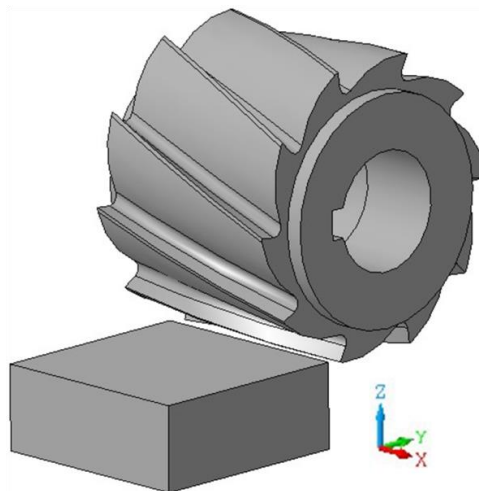
Figure 1 – The orientation of the models of billet and cylindrical milling cutter.

To reduce the size of the file the model of the fixture for clamping of billet (vice) was not created. The billet was fixed for the bearing flat surface and didn't move around the coordinate axes. The milling process was carried out at the combination of two motions: a rectilinear translational motion of *s* with

velocity of 1000 mm/s and the rotational motion n around its axis with a frequency 2865 min^{-1} of the cylindrical milling cutter. The translational motion of the cutting tool directed toward to the billet. The cutting depth t was accepted magnitude of 2 mm. The cylindrical milling cutter has 10 cutting teeth.

The models of the billet and the milling cutter are split into finite elements in Explicit Dynamics module of Ansys program (Fig. 2).
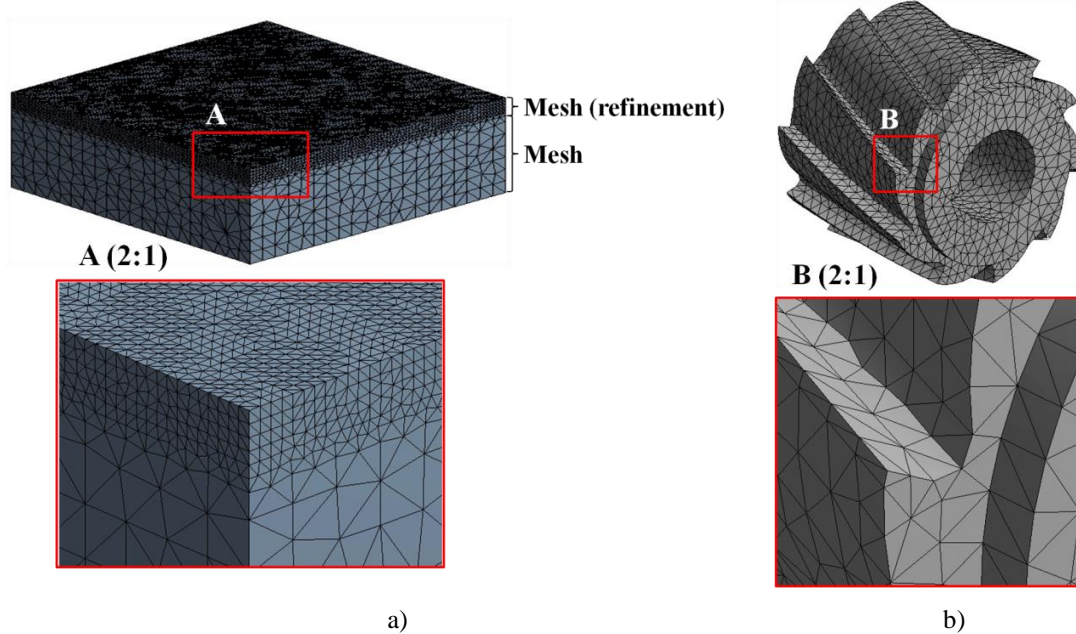

Figure 2 – Split solid models into finite elements: a – billet, b – cylindrical milling cutter.

The model of the billet was split into 70286 elements (16873 nodes), the model of the cylindrical milling cutter was split into 27660 elements (6066 nodes).

The removable layer of material (allowance) from the model of billet had the smaller size of the finite elements (refinement) than the other layers. It should be noted that the reducing of the size the finite element allows to obtain the more accurate results of the research. However, it leads to an increase the amount of data and, consequently, for to implement the calculation will require the significant computing resources.

The setting of processing conditions and simulation of milling process was implemented in the program LS-DYNA [8]. The choice of the type of finite element, material properties, type of contact, the character of the motion models of the billet and the cylindrical milling cutter were performed by the special cards [9].

The identification of the models of the billet (2) and the cutting tool (1) are executed with the help of the card of the key word *PART (table 2).

Table 2

The cards of the setting of the parameters of the structural unit of the models.

*PART							
pid	secid	mid	eosid	hgid	grav	adpopt	tmid
1	1	1					
*PART							
pid	secid	mid	eosid	hgid	grav	adpopt	tmid
2	2	2					

The assignment of material parameters and the types of elements was performed by three variables: *pid* (model number), *secid* (section identification defined in the *SECTION section), and *mid* (material identification defined in the *MAT section).

The solid elements are set for models. The completed card is presented in table 3.

Table 3

The cards of the setting of the properties of the elements of the solid type.

```
*SECTION_SOLID
secid   elform   aet
  1        1
*SECTION_SOLID
secid   elform   aet
  2        1
```

Section ID (*secid*) and element formulation options (*elform*) are selected in the card. The constant stress solid element (defaults) is used in accordance with equation 1.

As a processed material it was selected by the structural steel. The milling cutter made of the tool steel. The milling cutter is adopted of perfectly rigid

body (card of the key word *MAT_RIGID), don't subject to deformations, billet – plastic material (card of the key word *MAT_PLASTIC_KINEMATIC) with the properties of isotropic and kinematic hardening. The material models for the billet and the cylindrical milling cutter are recorded in table 4.

Table 4

The cards are given models of material and their characteristics.

```
                    *MAT_RIGID
mid       ro        e       pr     n     couple    m     alias
 1      7.85e-9    2e+5    0.3     0       0        0
cmo      con1      con2
 1        6         5
lco or a1  a2       a3      v1     v2      v3
 0        0         0       0      0

               *MAT_PLASTIC_KINEMATIC
mid       ro        e       pr    sigy    etan    beta
 2      7.85e-9    2e+5    0.3    250     960
src      srp       fs      vp
 0        0        0.78    0
```

The identification of the materials of models is implemented by the variable *mid* 1 or 2 (see cards of the key words *PART).

For the material of the cylindrical milling cutter it was taken by following physico-mechanical properties: mass density (*ro*), Young's modulus (*e*), Poisson's ratio (*pr*). The variables *sigy* (yield strength) and *etan* (tangent modulus) are added for the material of the billet. The variables *n*, *couple* and *m* are defined the relationship of the options with module MADYMO3D/CAL3D (rigid body in the local coordinate system).

For the model milling cutter the center of mass constraint (in global directions) sets of the variable *cmo* (EQ.1). The constraints of the displacement of the milling cutter along the coordinate axes X and Z are recorded in *con1* (EQ.6). The choice of rotation milling cutter (around the coordinate axis X) runs variable *con2* (EQ.5). The number of local coordinate system (*lco or a1*) and the parameters of the vectors (*a1 – v3*) were not taken for the calculation.

The ratio of failure strain for eroding elements for steel (variable *fs*) is 0.78.

The contact between the billet and the cylindrical milling cutter was asked by the key word *CONTACT_ERODING_NODES_TO_SURFACE_ THERMAL_ID. This key word takes into account elastic-plastic properties of the contacting materials, and when overcoming the resistance of the material of cutting occurs the removal of elements from the surface of the model. Also it provides for the assignment of thermal parameters of the material during processing. The structure of this card of the key word is presented in table 5.

The contact interface ID is defined of the variable *cid*. The cutting teeth of the model cylindrical milling cutter and free from the fixing flat surface of model of the billet (variables *ssid*, *msid*, *sstyp* and *mstyp*) contact.

The magnitudes of static coefficient of friction and viscous damping coefficient in percentage are set, respectively, the variables *fs* and *vdc*. The birth time and the death time of the contact surface are setting of the variables *bt* and *dt*.

Table 5

The card of the setting of the parameters solid contact models with the failure of material.

```
*CONTACT_ERODING_NODES_TO_SURFACE_THERMAL_ID
cid
 1
ssid   msid   sstyp   mstyp   sboxid   mboxid   spr    mpr
 1      2      3       3
 fs     fd     dc      vc      vdc      penchk   bt     dt
0.2     0      0       0       20       0        0      1e+20
sfs    sfm    sst     mst     sfst     sfmt     fsf    vsf
 1      1      0       0       1        1        1      1
isym   erosop  iadj
 1      1       1
 cf    frad   htc     gcrit   gmax     cd_fact  bc_flg  algo
 0      0     4.7e-5   2       10000    1
```

In the fourth line of the card there are recorded parameters of scale factors for the two models.

The parameters of the direct contact of the models are given in the fifth line of the card:

isym – symmetry plane option (EQ.1 – do not include faces with normal boundary constraints);

erosop – erosion/interior node option (EQ.1 – storage is allocated so that eroding contact can occur);

iadj – adjacent material treatment for solid elements (EQ.1 – solid element faces are included if they are on the boundary of the material subset).

The magnitudes of thermal conductance for the closed gaps, the critical gap, the gap, in which there is no thermal contact, and the multiplier which is used on the element characteristic distance for the search routine are selected by using variables *htc*, *gcrit*, *gmax* and *cd_fact*, recorded in the sixth line of the card.

The motion of the models is carried out by the five cards. The key words *BOUNDARY_PRESCRIBED_MOTION_SET_ID, for cylindrical milling cutter – *BOUNDARY_PRESCRIBED_MOTION_RIGID are used for the billet (table 6).

Table 6

The cards define the desired law of motion of the models.

```
*BOUNDARY_PRESCRIBED_MOTION_SET_ID
        $ 1Displacement
              $ Billet
 id    dof   vad   lcid   sf   vid   death   birth
  2     1     2     3     1    0      0       0
*BOUNDARY_PRESCRIBED_MOTION_SET_ID
        $ 2Displacement
              $ Billet
 id    dof   vad   lcid   sf   vid   death   birth
  2     2     2     4     1    0      0       0
*BOUNDARY_PRESCRIBED_MOTION_SET_ID
        $ 3Displacement
              $ Billet
 id    dof   vad   lcid   sf   vid   death   birth
  2     3     2     5     1    0      0       0
*BOUNDARY_PRESCRIBED_MOTION_RIGID
           $ Displacement
        $ Cylindrical milling cutter
 pid   dof   vad   lcid   sf   vid   death   birth
  1     2     0     6     1    0    1e+28
*BOUNDARY_PRESCRIBED_MOTION_RIGID
             $ Rotation
        $ Cylindrical milling cutter
 pid   dof   vad   lcid   sf   vid   death   birth
  1     5     0     7     1    0    1e+28
```

The variables *id* and *pid* is the identification of the models. For billet the constraint of motion along the coordinate axes is defined of the variable *dof* (EQ. 1, 2, 3). The cylindrical milling cutter is moved along the Y-axis (*dof* 2) and has a degree of freedom of the rotational motion around the X-axis (*dof* 5).

The flags-signs of *vad* set the parameters of the motion of the model: 2 – displacement and 0 – velocity. By each movement there is assigned an ID

for the description of the dependence of the velocity models from time (*lcid* 3 – 7). The load curve scale factor *sf* defaults equal 1. The time imposed motion/constraint (activated *death*) was taken by default.

The choice of the velocity motion at time intervals of simulation of the milling process (0 – 0.005 s, 0.005 – 0.02 s, 0.02 – 0.06 s) is presented in cards of the key word *DEFINE_CURVE (table 7).

Table 7

The cards of the setting of the table relationship between two variables.

			*DEFINE_CURVE			
lcid	sidr	sfa	sfo	offa	offo	dattyp
3						
	a1		o1			
	0		0			
	0.005		0			
	0.02		0			
	0.06		0			

			*DEFINE_CURVE			
lcid	sidr	sfa	sfo	offa	offo	dattyp
4						
	a1		o1			
	0		0			
	0.005		0			
	0.02		0			
	0.06		0			

			*DEFINE_CURVE			
lcid	sidr	sfa	sfo	offa	offo	dattyp
5						
	a1		o1			
	0		0			
	0.005		0			
	0.02		0			
	0.06		0			

			*DEFINE_CURVE			
lcid	sidr	sfa	sfo	offa	offo	dattyp
6		1	1			
	a1		o1			
	0		0			
	0.005		-1000			
	0.02		-1000			
	0.06		-1000			

			*DEFINE_CURVE			
lcid	sidr	sfa	sfo	offa	offo	dattyp
7		1	1			
	a1		o1			
	0		0			
	0.005		-300			
	0.02		-300			
	0.06		-300			

The key word *DEFINE provides a way of defining boxes, the coordinate systems, the load curves, the tables, and the orientation vectors for various uses.

Recorded in the card of the key word *BOUNDARY_PRESCRIBED_MOTION variable *lcid* is specified and in the card of the key word

*DEFINE_CURVE. The scale factors for abscissas and ordinates (*sfa* and *sfo*) were taken by default 1.

The variables *a1* and *o1* set magnitudes of the abscissas and ordinates. The magnitudes of the abscissa – time for milling, the magnitudes of the ordinates – velocities motion of models. Zero in the ordinate corresponds that the model of the billet does not move. The minus sign on the ordinate characterizes the displacement of the cylindrical milling cutter to the billet at a velocity of 1000 mm/s and rotation of the cylindrical milling cutter clockwise with a velocity of 300 rad/s. The displacement velocities of cylindrical milling cutter are not change on throughout the time range of the milling process.

The termination time of simulation of the milling process is recorded by the card, presented in the table 8.

Table 8

The card of the assignment the condition of termination time of the calculation.

*CONTROL_TERMINATION

endtim	endcyc	dtmin	endeng	endmas
0.06				

The key word control cards are optional and can be used to change defaults to activate such solution of options as a mass scaling, the adaptive remeshing, and an implicit solution.

The saving of the results was carried out every 0.001 s solutions. Reducing the time step of the calculation allows to get on output more detailed view of the cutting process of the material of the cylindrical milling cutter. The card is presented in table 9.

Table 9

The card of the assignment of time interval between outputs.

*DATABASE_BINARY_D3PLOT

dt	lcdt	beam	npltc
0.001			

In the card it was recorded one variable *dt*, defining the time interval between outputs.

Output format for D3PLOT file recorded by the card of the key word *DATABASE_FORMAT (table 10). In the card *iform* (EQ.0) – LS-DYNA database format, *ibinary* (EQ.0) – word size of the binary output files (64 bit).

Table 10

The card of the assignment of the format writable databases.

*DATABASE_FORMAT

iform	ibinary
0	0

By using this option one can reduce the size of the binary output files which are created by 64 bits computer such as CRAY and NEC [10].

The size of the created keyword file was 9 MB.

Results and discussion

The cutting of the material of the cylindrical milling cutter on the 0.006, 0.02, 0.04 and 0.06 seconds of the process are presented in Fig. 3 – 6. Coloured contours on the model of the billet show a degree of maximum shear stress of the material.
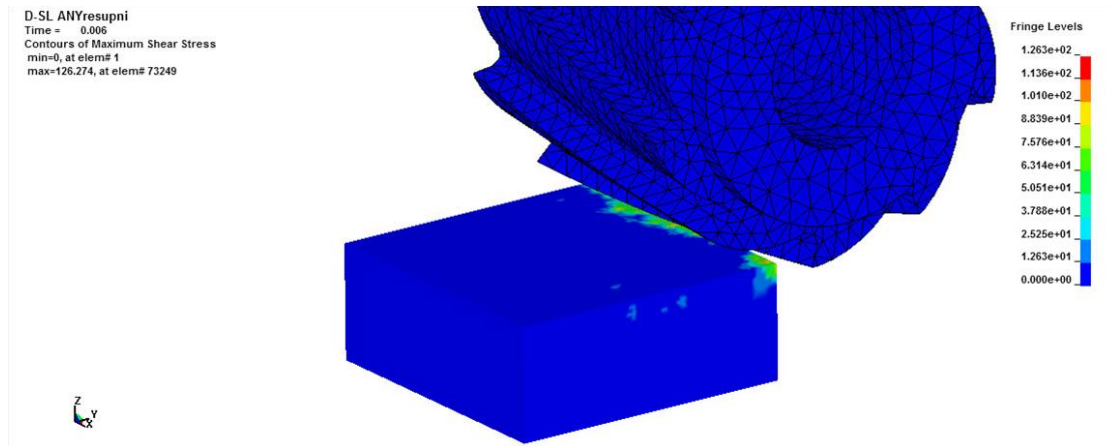
Figure 3 – The maximum shear stress of the billet material during milling cylindrical milling cutter to 0.006 s of the calculation process. The unit of stress is N/mm².
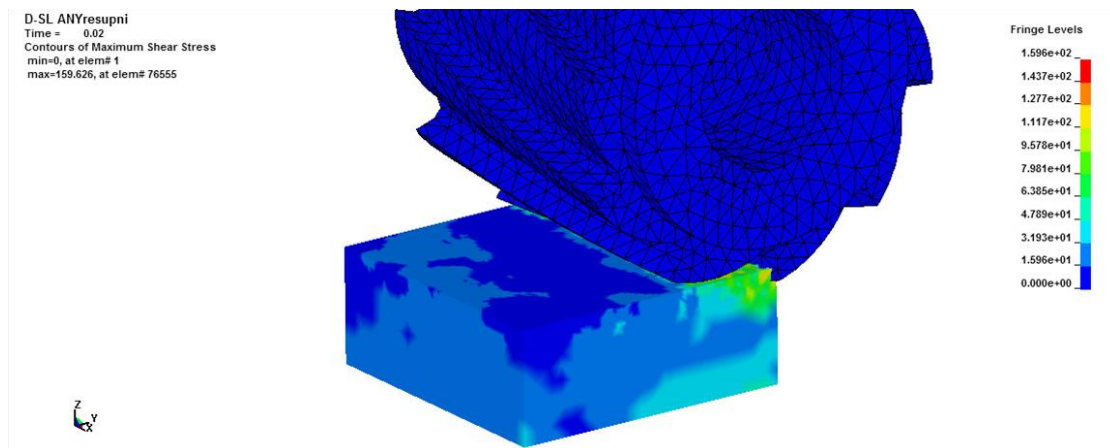

Figure 4 – The maximum shear stress of the billet material during milling cylindrical milling cutter to 0.02 s of the calculation process. The unit of stress is N/mm².
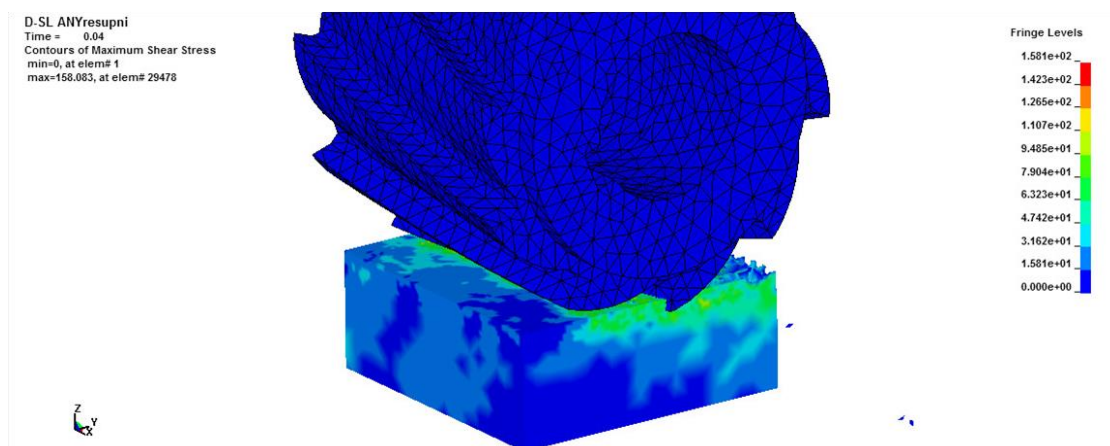

Figure 5 – The maximum shear stress of the billet material during milling cylindrical milling cutter to 0.04 s of the calculation process. The unit of stress is N/mm².
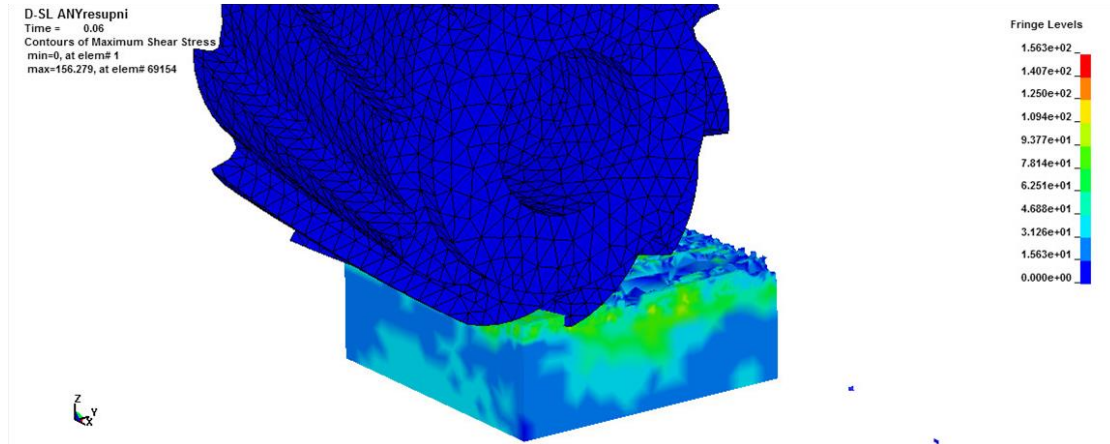
Figure 6 – The maximum shear stress of the billet material during milling cylindrical milling cutter to 0.06 s of the calculation process. The unit of stress is N/mm².

Shear stress in the cutting zone reaches of magnitude 125 – 160 N/mm². Finite elements of the model of the billet, on which the cutting edges of cylindrical milling cutter are act, is deformed (to damage), and is separated with the processed surface (formation of chips). At full cutting depth of milling and in the different positions of the teeth of the milling cutter, the cutting process is carried out by one or simultaneously (partially) three of cutting edges. There is observed don't uniform the cutting of the layer of material of the billet of the cutting edge of the cylindrical milling cutter. In the central part of the billet, the thickness of a removed layer of the

material is reduced. This is due to the withdrawal of the cutting tool from the processed surface of the billet, as a result of the action is of the radial component of the cutting force. The intensity of maximum shear stress of the material of billet constantly is increasing as is passing of the cutting tool to a predetermined length of milling. A complete picture of the stress-strain state of the billet can be obtained by choosing the operations displaying of the fields of strains and stresses on the toolbar of the program LS-DYNA.

Table 11

The control of the parameters of the milling process on one of the cycles of the calculation.

dt of cycle 5821500 is controlled by solid	Element 36768
Parameter	Magnitude
Time	5.98888e-2
Time step	1.00258e-8
Kinetic energy	3.22453e6
Internal energy	1.93678e5
Spring and damper energy	1e-20
System damping energy	0
Sliding interface energy	5.47795e4
External work	3.45732e6
Eroded kinetic energy	2.51909e4
Eroded internal energy	1.08185e5
Eroded hourglass energy	-8.11405e4
Total energy	3.39185e6
Total energy/Initial energy	9.81064e-1
Energy ratio w/o eroded energy	9.65955e-1
Global x velocity	-1.79275e1
Global y velocity	-7.18865e2
Global z velocity	-6.15721e-1
CPU time per zone cycle	0 nanoseconds
Average CPU time per zone cycle	107 nanoseconds
Average clock time per zone cycle	109 nanoseconds
Node number 10718 deleted at time 5.98888e-2	
Solid element 42462 failed at time 5.98888e-2	

The termination of the calculation occurred on 5832316 cycle. The report on the implementation of the solution is created in a text files "messag", "d3dump" and "d3hsp".

The control of energy and other process parameters of cylindrical milling at 5821500 cycle, the calculation are presented in table 11.

Perform a comparison of parameters of the milling process at the beginning and at the end of the processing. At the end of the milling process are increased to 10^4 times values of the kinetic energy, internal energy, sliding interface energy, external work, eroded kinetic energy and eroded internal energy, total energy. Does not change the value of spring and damper energy, the ratio of total/initial energies and energy ratio w/o eroded energy. The control of the contact is carried out by the quantity and serial numbers of the deformed or deleted elements from the processed surface of the billet.

The information about calculation time (in seconds and in percentage) is presented in table 12.

Table 12

The information about the calculation of time of milling process.

Parameter	CPU (seconds) Magnitude	CPU (%)
Initialization	0	0
Element processing	4.0123e4	65.33
Binary databases	4	0.01
ASCII database	2	0
Contact algorithm	2.1154e4	34.44
Contact entities	0	0
Rigid bodies	1.37e2	0.22
Implicit nonlinear	0	0
Implicit lin. alg.	0	0
Totals	6.1420e4	100

The time of total calculation of the milling process is spent on the control work of the element processing and the contact algorithm.

Conclusion

The quality of the finished product will depend on rationally selected the cutting tool geometry and defined the cutting conditions. The control of the mechanical processing of the billet, on the design stage of the technological process, it is necessary to implement virtually by the programs for the calculating of the nonlinear dynamics. Given a sequence of the computer simulation of milling process with some modifications can be used for the continuous processing of billet with a large number of passages of the cutting tool.

References:

1. (2016) Klassifikatsiya frez. Available: http://machinetools.aggress.ru/index.php/frezernyj-stanok/osnovy-rezanija-metallov/268-klassifikatsija-frez (Accessed: 16.06.2016).
2. (2016) Naznachenie i tipy frez. Available: http://www.info.instrumentmr.ru/freza.shtml (Accessed: 16.06.2016).
3. Medvedev FV, Ponomarev BB, Cheremnyh EA (2009) Modeling of the dynamics of end milling. International Collection of Scientific Papers «Progressive technologies and systems of mechanical engineering», №2 (38), 2009. Pp. 139 – 142.
4. Gryazev MV, Stepanenko AV (2010) Milling the outer cylindrical surface of the cylindrical cutter. "Izvestija Tulskogo gosudarstvennogo universiteta", № 2-1 / 2010. Pp. 137 -140.
5. Tihonova AA, Vinogradov DV (2011) Geometrical surface roughness in cylindrical conventional milling and climb milling. Proceedings of Higher Educational Institutions. Machine Building. № 11 / 2011. Pp. 68 – 71.

6. Breev SV (2011) Improving the quality of surface finish in cylindrical milling on the basis of studies of the stress-strain state of the chip formation zone. The dissertation on competition of a scientific degree of candidate of technical sciences, Komsomolsk-on-Amur, 2011. P. 151.

7. (2016) Geometriya tortsovoy i tsilindricheskoy frezy. Available: http://dlja-mashinostroitelja.info/2010/05/geometriya_frezy/ (Accessed: 16.06.2016).

8. Rapovets VV, Grishkevich AA, Medvedev SV, Ivanets GG (2015) The methodology of modeling during machining of wood materials by milling in the soft LS-DYNA. XI International Eurasian Symposium "Woodworking: technologies, equipment, management of the XXI century". Pp. 1 – 6.

9. LS-DYNA. KEYWORD USER`S MANUAL (VOLUME I, II). – Livermore Software Technology Corporation, 2001.

10. (2016) Cray-1. Available: https://en.wikipedia.org/wiki/Cray-1 (Accessed: 16.06.2016).