Journal of Machine Engineering, Vol. 12, No. 4, 2012

machining, modeling,
numerical simulations, chip

Jaroslaw CHODOR[1]
Leon KUKIELKA[1]

BEHAVIOUR OF ELASTO/VISCO–PLASTIC WORKPIECE MATERIAL DURING MACHINING

Experimental investigations of plastic deformation and uniaxial tension of elasto/visco-plastic (*E/V-P*) material (41*Cr*4) were conducted to characterize the flow behavior of the material. Dynamic effects, constitutive damage law and contact with non-linear friction in simulations were described using updated Lagrangian formulation. That model of the process allows defining advanced simulations of tool's penetration in workpiece and chip formation. The yield stress is taken as a function of the strain and the strain rate in order to reflect realistic behavior in metal machining. In numerical simulations the Cowper-Symonds model of yield stress is used. For properly modeling of unsteady-state process, a material separation criterion based on the failure strain ε_f were determined. Finite element simulations were carried out using ANSYS code. The influence of the chosen process parameters in numerical simulations on the chip's shapes was presented. Results revealed good agreements between *FEM* results and experimental ones.

1. THE INFLUENCE OF CHOSEN CUTTING CONDITIONS ON CHIP SHAPE DURING EXPERIMENTAL RESEARCHES

In metal forming processes, which material formed has more than one degree of freedom, such as cutting, intuition or experience may not be sufficient to predict the mechanics of the process. Visualization of the process is a useful and effective tool in this case.

An essential part of the work of the cutting process modeling is mathematical and physical modeling. Process that were considered as geometrically and physically nonlinear initial-boundary problem, which has non-linear, flexible and variable in space and time boundary conditions. Boundary conditions in the contact zone between the tool and the subject are unknown.

The main aim of this article is confirming the validity of using *FEM* software to analyze and explain e.g. physical phenomena occurring in the contact area between tool and the object. It was very difficult or impossible to analyze the behavior of workpiece in the contact zone, until now. *FEM* allows observing and explaining the distribution e.g. stresses in the chip formation zone without the need creating and carrying out experiments on precious test stand.

---

[1] Koszalin University of Technology, Mechanical Department, Raclawicka 15–17 street, 75–620 Koszalin, Poland

Currently winding and chip breaking processes are simulating using *FEM* programs such as ANSYS, ABAQUS or AdvantEdge, which were used in [5],[6],[7],[15] to simulate the cutting of e.g. steel 25*CrMo*4. The authors modeled the process of creating and breaking chip as a result of achieving the critical bending moment - the maximum tensile stress in the outer layer of the chip.

1.1. PREPARATION OF THE SAMPLES AND USED TOOL

Experimental researches were conducted on *CNC NEF400* machining center and allowed to determinate of influence of feed value on chip shape. 41*Cr*4 steel shafts in the normalized state were prepared for the researches. Shaft's surface were machined using grinding wheel 05/0/8 38*A*80-*LVBE* 500×50×203 with tool speed 1500*rpm* and hydraulic feed. Every shaft hast two working surface witch roughness Ra = 0,6μm (Fig. 1).

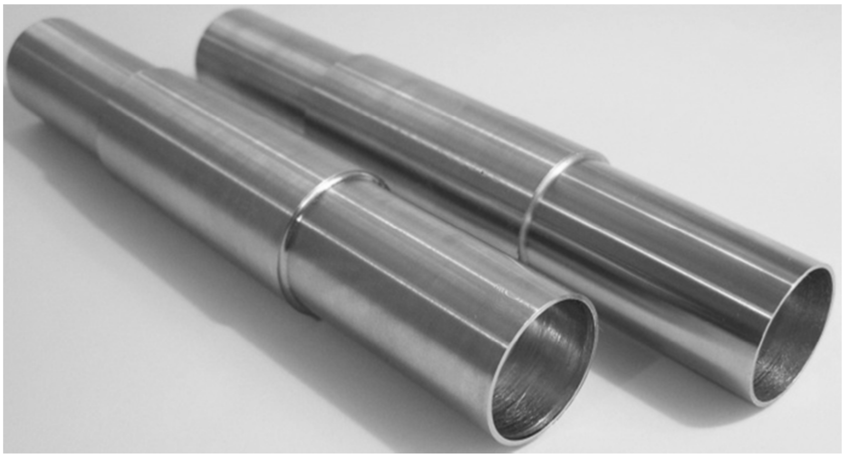

Fig. 1. View of shafts

Tool holder *WALTER* 90^0*STGCL* 2020 *K* 16 with diamond cutting edge *TCMW*16*T*308*FP CD*10 from Sandvik Coromant company was used in researches. After orthogonal machining chip's shape were analyzed.

1.2. REALIZATION OF RESEARCHES

Machining process were analyzed for constant machining velocity $v_c=2{,}9 m\cdot s^{-1}$ but for different value of feed: f =0,025; 0,02; 0,015; 0,01; 0,005 and $0{,}001 mm\cdot r^{-1}$.

For every case, tool distance were similar and was l=5 *mm*. Feed value is value of the thickness layer machined. Measurement of chip's shape and its surface were made on scanning electron microscope Jeol *JSM*-5500*LV*. There are chosen exemplary of chip's shapes on Fig. 2 to Fig. 7.

Fig. 2.View of chips for f=0,025$mm\cdot r^{-1}$

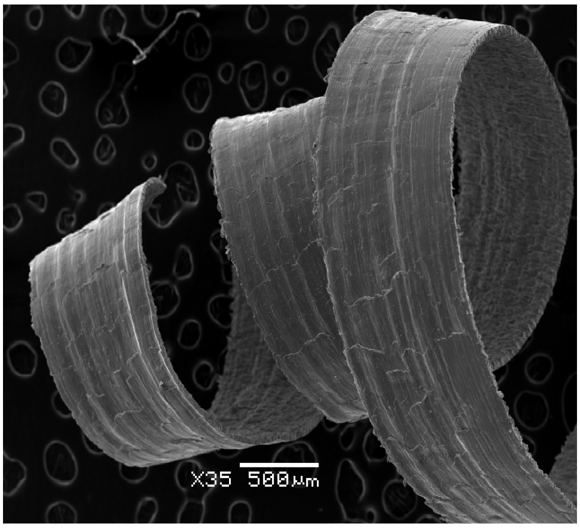

Fig. 3. View of chip for f=0,025$mm\cdot r^{-1}$

Figure 2 shows short compact helical chips. Figure3 shows a view of part of a single compact helical chip at 35× magnification. We can observe internal and external chip's surface and characteristic phenomena when chip is curling. Also is visible a lot of discontinuities on internal surface which are caused by creating a build-up on the cutting edge during machining.

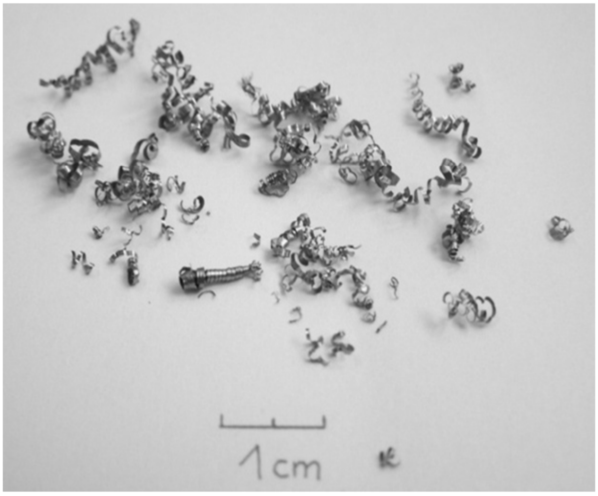

Fig. 4. View of chips for f=0,01$mm\cdot r^{-1}$

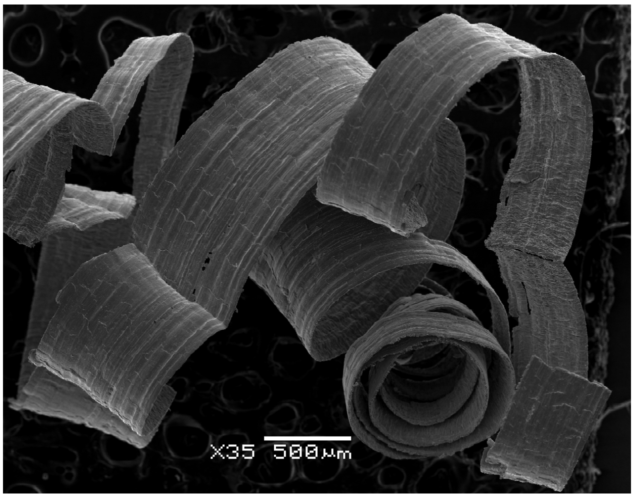

Fig. 5. View of chips for f=0,01$mm\cdot r^{-1}$

For f=0,01$mm\cdot r^{-1}$ received different chip's shapes (Fig. 4). From compact helical chips through open helical chips to arc-related chips.

On figure 5 we can observe in 35×magnification a lot of different kind of chips in one removed element.

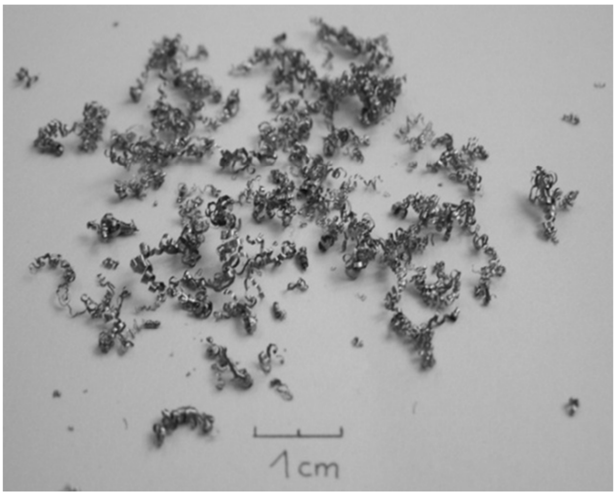

Fig. 6. View of chips for f=0,005 $mm \cdot r^{-1}$

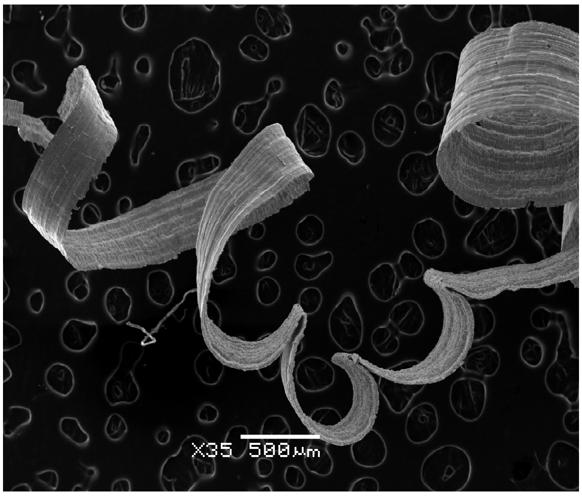

Fig. 7. View of chip for f=0,005$mm \cdot r^{-1}$

For f=0,005 $mm \cdot r^{-1}$ received different chips shapes (Fig. 6). From screw short chips to arc-related chips. Figure 7 shows a view of part of a single arc-related chip at 35× magnification. Numerous collapse chips are visible.

2. MATHEMATICAL MODEL

Qualitative modeling can be used to analyze the process of plastic flow of the material at anytime during the process. Also allows to determining the effect of tool geometry, the conditions of friction in the contact area on the states of displacement and material deformation. In addition, the results of numerical analysis confirm the validity of their use due to the large convergence of simulation results with experimental results. This is due to the development of new, more accurate material model describing the growth components of the stress tensor for the deformation and elastic/visco-plastic (*E/V-P*) bodies, which takes into account the different phases of the cutting process like elasto-plastic, stress, cracking, complete separation, and the iterative methods to solve them. In these models, new models of stress plasticizing were used. This makes possibilities to calculate the state of stress and strain in the different phases of the process, including the time value of strain relief. It is a modern approach requiring continuous development. A detailed description of the mathematical and physical model and its applications in ANSYS programme were described in [8].

While using numerical methods typically two methods of material models [9],[10] are used. The first is Johnson-Cook (*J-C*) model and the second is Zerelli-Armstrong model. In this paper Cowper-Symonds material model of the yield stress is used. There are few works which describes the behavior of the material during processing using this model. After detailed researches, its use on a larger scale initiated by the author and colleagues [11],[12],[13],[14].

For general considerations the material model exhibiting elasto/visco-plastic (*E/V-P*) properties, with a mixed module of empowerment. Accepted the principle of decomposition of stresses and strains can be represented by appropriate rheological schemes. The total strain tensor we can spread on the elastic, viscous and plastic part. Elastic deformation is reversible, while the viscous and plastic does not disappear after removing the load. Sticky and plastic deformation are coupled and can be considered together. It was assumed that for elastic part is valid Hooke's linear relationship, while the visco-plastic part is designated from associated flow rights with nonlinear Huber-Mises-Hencky (*H-M-H*) plastic conditions.

Turning is considered as a geometrical and physical nonlinear initial and boundary problem. The analytic solution of this problem like: determination of states of deformations and stresses in the any moment of duration of the process is impossible. Therefore this problem by finite element method (*FEM*) was solved. Application was developed in the Ansys/LS-Dyna programme, which makes possible a complex time analysis of the states of deformations (displacements and strain) and stress in surface layer of object at/after turning.

For typical time step t→t+Δt, the equation which describes the movement and deformation of the object investigated on the typical step time, in updated Lagrangian formulation, has the following form:

$$\boldsymbol{M} \cdot \Delta\ddot{\boldsymbol{r}} + \boldsymbol{C}_T \cdot \Delta\dot{\boldsymbol{r}} + (\boldsymbol{K}_T + \Delta\boldsymbol{K}_T) \cdot \Delta\boldsymbol{r} = \Delta\boldsymbol{R}_T + \Delta\boldsymbol{F} + \boldsymbol{F}_T \tag{1}$$

where: $\boldsymbol{M}$– global system-mass matrix at time *t*,
$\boldsymbol{C}_T$– global system-damping matrix at time *t*,
$\boldsymbol{K}_T$– global system stiffness matrix at time *t*,
$\Delta\boldsymbol{K}_T$– global system stiffness-increment matrix at the step Δt,
$\boldsymbol{F}_T$– global system internal and external load vector at time *t*,
$\Delta\boldsymbol{F}$– global system internal load increment vector at the step Δt,
$\Delta\boldsymbol{R}_T$– global system external load increment vector at step time Δt,
$\Delta\boldsymbol{r}$– global system displacement increment vector at step time Δt,
$\Delta\dot{\boldsymbol{r}}$–global system velocity increment vector at step time Δt,
$\Delta\ddot{\boldsymbol{r}}$–global system acceleration increment vector at step time Δt.

This equation is not solvable due to number of unknowns exceeding the number of equations.

For the purpose of the solution of the equation (1), the Dynamic Explicit Method (*DEM*), also known as the Method of Central Differences was used. In this method, an approximation by the central–difference method has been applied to express $\dot{\boldsymbol{r}}$ and $\ddot{\boldsymbol{r}}$ vectors using the displacement vectors at moments: $t - \Delta t,\ t,\ t + \Delta t$:

$$\dot{\boldsymbol{r}}^t = \frac{1}{2\Delta t} \cdot (\boldsymbol{r}^{t+\Delta t} - \boldsymbol{r}^{t-\Delta t}) \tag{2}$$

$$\ddot{\boldsymbol{r}}^t = \frac{1}{\Delta t^2} \cdot (\boldsymbol{r}^{t+\Delta t} - 2\boldsymbol{r}^t + \boldsymbol{r}^{t-\Delta t}) \tag{3}$$

It was accepted in the simulations that the cutter is a non–deformable body, but it can be elastic body as well for precise calculations, while the object is an elastic/visco–plastic body, which yield stress is described with the aid of Cowper–Symonds model [1],[2],[11-14].

Specimens were fixed from the bottom while the cutter's edge has moved with specified speed in X-axis. The model takes into consideration the line–isotropic ($\eta = 1$) kinematic ($\eta = 0$) or mixed ($0 < \eta < 1$) plastic hardening as well, as the influence of the intensity of the plastic strain rate, according to the involution dependence:

$$\sigma_Y = \left(\sigma_0 + \eta \cdot E_{tan} \cdot \varepsilon_i^{(p)}\right) \cdot \left[1 + \left(\frac{\dot{\varepsilon}_i^{(p)}}{C}\right)\right]^m \quad [MPa] \tag{4}$$

where: σ_Y– yield stress, σ_0 $[MPa]$– initial yield stress point,

$\varepsilon_i^{(p)}[-], \dot{\varepsilon}_i^{(p)}$ $[s^{-1}]$– intensity of true strain and plastic true strain rate respectively,

C $[s^{-1}]$– material parameter to determine the influence of the intensity of the plastic strain rate,

$m = 1/P$– material constant determining the sensitiveness of material on the plastic strain rate,

$E_{tan} = E_T E/(E - E_T)$– material parameter dependent of the module of plastic hardening,

$E_T = \partial\sigma_Y/\partial\varepsilon_i^{(p)}$and of Young's elasticity module E.

Parameters used in numerical calculations depended from material. For every of them were different. All parameters and coefficients for $41Cr4$ steel were taken from: Ansys User's Guide [3] – (Poisson ratio ν, Young modulus E, material density ρ), specialist's articles, e.g. [4] which describes how to determine the C, P parameters, and own researches e.g. how to determine the value of failure strain ε_f, yield stress R_e from tensile test.

3. NUMERICAL SIMULATIONS

In the case of a correct machining model, different modeling techniques are required [9],[10]. Besides the analytical and mechanistic models van Luttervelt and others [7] described descriptive models, prediction and self-learned. In the numerical solutions of plastic deformation in the machining zone are increasingly used elasto/visco-plastic models [16]. This model was used in simulations in that work.

The biggest problems in modeling of machining processes occurs during analysis of the phenomena in contact area, which are necessary to predict product quality energy consumption and tool life. Physical phenomena occurring during the above processes are very complicated (non-linearity of the process, the complex dynamics of the process, the variability of stress and strain fields, fracture of the material). In the models which are published contains considerable simplification, which in many cases do not cover these issues.

Tensile tests of cylindrical steel samples are necessary to determine characteristic quantities of materials (e.g. value of limiting stress). Limiting stress means that above this value material will be cracking and separating from the body. Material parameters defined below will be used as input data in ANSYS/LS-Dyna programme. Precise determination of these parameters will greatly increase the precision of the results of computer simulations. In numerical simulations was used elasto/visco–plastic (*E/V–P*) material model (Cowper–Symond's model).

1.3. CONDITIONS OF TENSILE TEST AND RESULTS

Tensile tests were carried out on steel shafts (41*Cr*4) which underwent according to *PN-EN*10002-1+*AC*1 standards. Cylindrical and normalized samples were made to determine all material characteristic.

From three-stage samples directly determined all material characteristic (e.g. limiting value of stress and strain) for equation $\sigma_p = K$ (dependence between stress and strain). After tensile test we can designate *n* coefficient (hardening coefficient):

$$n = \frac{ln\left(\frac{b_{C0}}{b_{B0}} \cdot \frac{l_{C0}}{l_{B0}} \cdot \frac{l_B}{l_C}\right)}{ln\left[\frac{ln\left(\frac{l_B}{l_{B0}}\right)}{ln\left(\frac{l_C}{l_{C0}}\right)}\right]} = \frac{ln\left(\frac{19,8}{18,18} \cdot \frac{20}{20} \cdot \frac{22,46}{20,952}\right)}{ln\left[\frac{ln\left(\frac{22,46}{20}\right)}{ln\left(\frac{20,952}{20}\right)}\right]} = 0,1694 \quad (5)$$

and *K* coefficient (strength coefficient):

$$K = \frac{F_{max}}{b_{C0} \cdot g_0 \cdot \frac{l_{C0}}{l_C} \cdot ln\frac{l_C}{l_{C0}}} = \frac{164000}{19,8 \cdot 307,9 \cdot \frac{20}{20,952} \cdot ln\frac{20,952}{20}} = 938\ MPa \quad (6)$$

Received graph's dependency was implemented into ANSYS program in order to create the correct numerical analysis of tensile test.

1.4. NUMERICAL VERIFICATION OF MATERIAL MODEL

In order to verify the material parameters were assigned numerical analysis of the tensile test on standardized cylindrical specimen. As input data to the simulation used data from the experiment.

Figure 8 shows the breaking 41*Cr*4 steel samples during tensile test. Numerical measurement of the length of measurement part after fracture were carried out. Length from the numerical measurement equals 14,95*mm*. Length from the experiment equals 14,98*mm*. Results are consistent with each other at the significance level α=0,05. This demonstrates the correctness of the model and numerical applications.

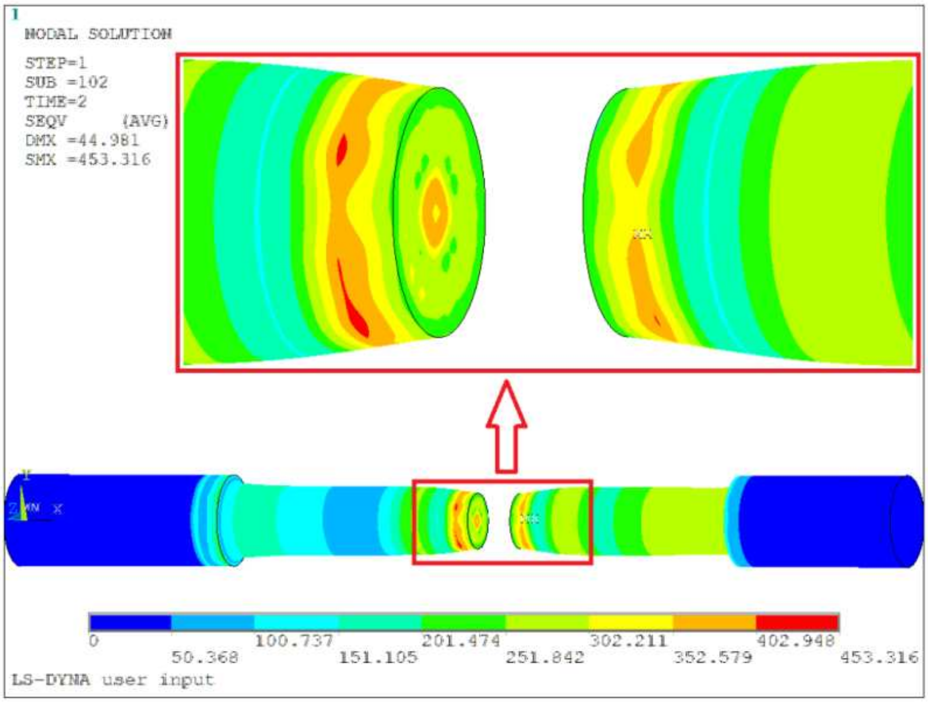

Fig. 8. View of broken sample

1.5. SELECTED RESULTS OF COMPUTER SIMULATIONS OF MACHINING

Computer simulations were performed for identical process parameters that were used in experimental researches. The resulting shapes of chips from computer simulations (*FEM*) were compared to the shape of experimental chips. There was similarity of their shapes and deformation in characteristic areas.

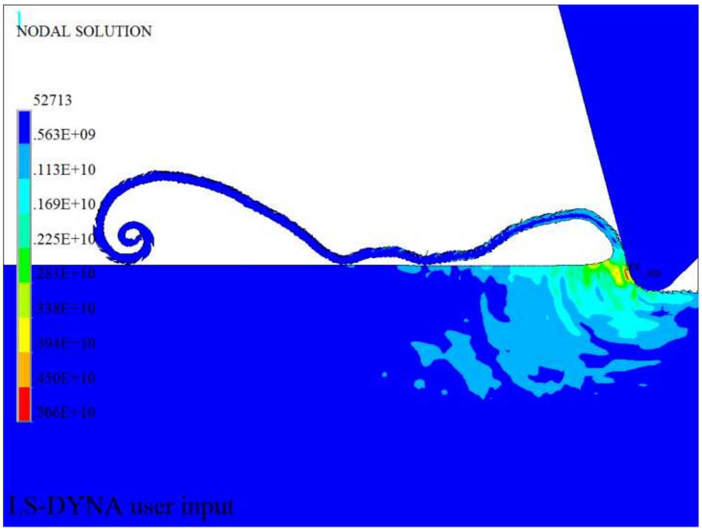

Fig. 9. View of arc-related chip

Figure 9 shows arc-related chip for f=0,005 $mm{\cdot}r^{-1}$. This chip and that from experiment are similar. Similar situation exist in numerical simulation of machining for f=0,01$mm{\cdot}r^{-1}$ (Fig. 10). During simulations observed several kind of chips. From compact helical chips through open helical chips to arc-related chips.

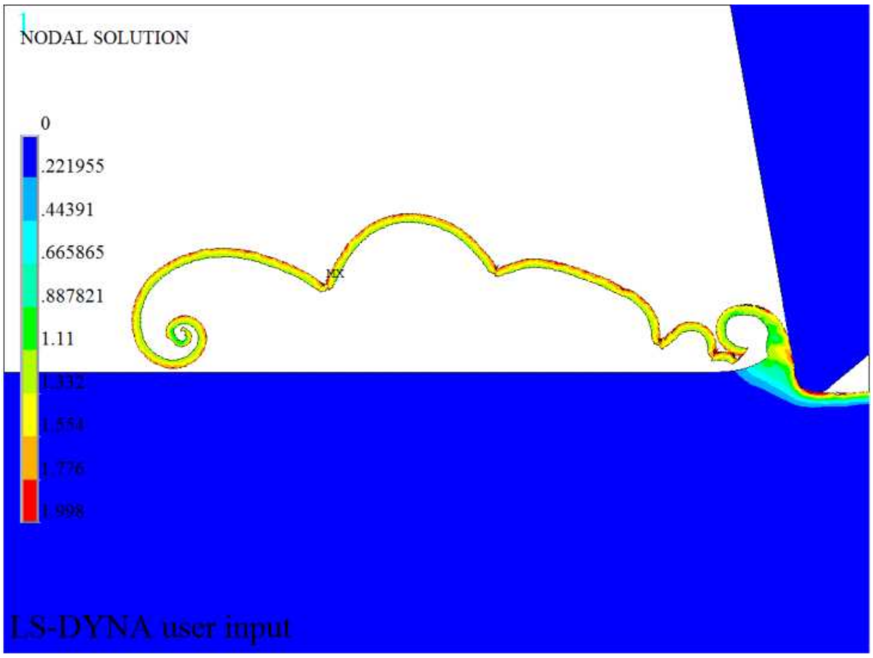

Fig. 10. View of different chip shapes

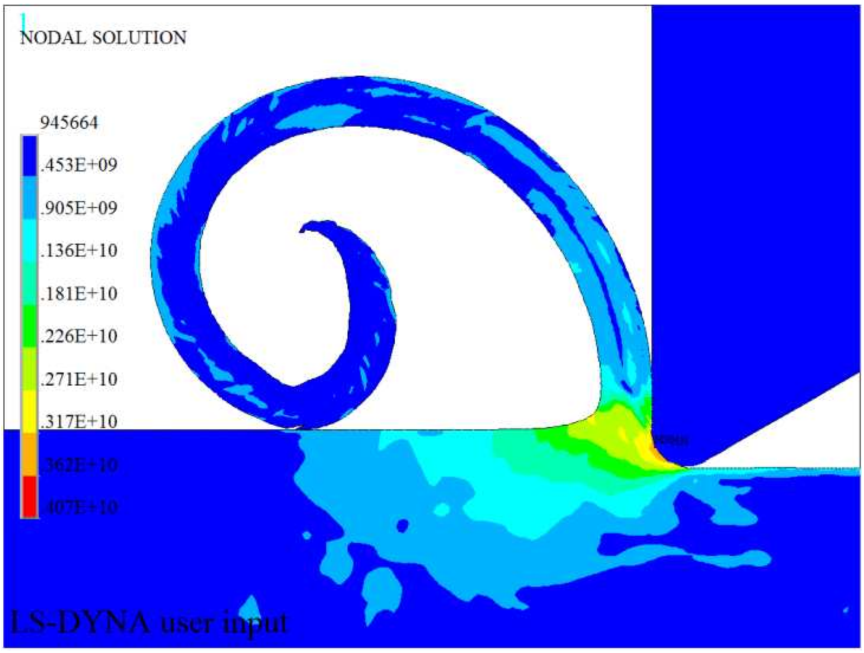

Fig. 11. View of helical chip

Figure 11 shows short compact helical chip. Figure12 shows a lot of segmental chips. It is characteristic for the small value of feed, for example f=0,01$mm \cdot r^{-1}$. Also is visible a lot of discontinuities on internal surface which are caused by creating a build-up on the cutting edge during numerical simulations of machining.

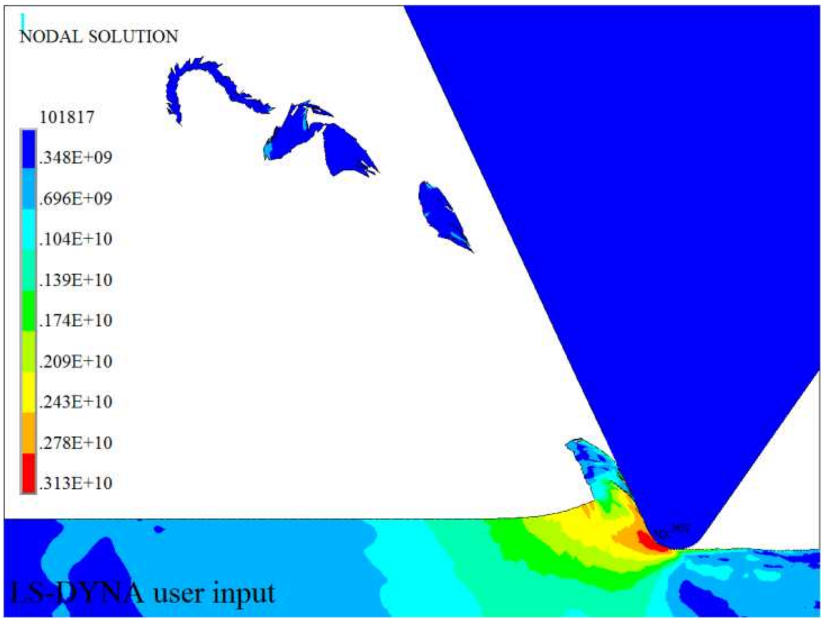

Fig. 12. View of segmental chips

4. CONCLUSIONS

Despite many years of development of numerical analysis methods of elasto-plastic objects with variable loads noted in some studies a significant simplification especially in national papers. Introduces a significant simplification of the applied theoretical model and simulation. The geometrical and physical nonlinearity, and consequently are ignored. It is impossible to analyze physical phenomena with the required accuracy. The influence of the dynamic properties of the material (e.g. plastic strain rate effect) are omitted.

In this paper, process was considered as physical and geometrical non-linear problems, without known the boundary condition in the contact zone. For this case a variational formulation in the updated Lagrangian formulation and adequate description of the measure increments of stress and strain states were used. This approach helps to explain many phenomena in any place and at any time during the machining process. There are still unsolved issues, and their explanation can not only properly designed so complex machining processes, but also to predict the quality of the product.

Simulation studies have shown the possibility of forecasting the shape of chips for defined technological parameters. For example for f=0,005$mm \cdot r^{-1}$ received arc-related chip (Fig. 9) but for f=0,01$mm \cdot r^{-1}$ received a lot of segmental chips (Fig. 12).

The results of numerical calculations have been confirmed experimentally. Shapes of chips obtained were very similar. It therefore seems appropriate to carry out computer simulations to study the physical phenomena existing in the material machined.

REFERENCES

[1] KUKIELKA L., CHODOR J., 2007, *Numerical analysis of the influence of abrasive grain geometry and cutting angle on states of strain and stress in the surface layer of object*, Eighth International Conference On Computer Methods and Experimental Measurements for Surface Effects and Contact Mechanics “Contact and Surface 2007”, Wessex Institute, Ashurst Lodge, Ashurst, Southampton, UK. Editors: J.T.M. De Hosson, C.A. Brebbia, S-I Nishida. WITPRESS, Southampton, Boston, 183–193.

[2] KUKIELKA L., CHODOR J., STORCH B., 2009, *New method of determination of tool rake angle on the basis of crack angle of specimen in tensile test and numerical simulations*, Ninth International Conference on Surface Effects and Contact Mechanics: Computational Methods and Experiments “Contact and Surface 2009", 9–11 June 2009, Algarve, Portugal. Editors: J.T.M. De Hosson, C.A. Brebbia. WITPRESS, Southampton, Boston, 207–216.

[3] ANSYS LS-DYNA User’s Guide.

[4] BOHDAL L., KUKIELKA L., 2006, *The effect of selected material parameters on the stress and strain states in the process of cutting a sheet plate with circular cutters*, TASK QUARTERLY, 10/4, 391–400.

[5] MARUSICH T.D., THIELE J.D., BRAND CH.J., 2002, *A methodology for simulation of chip breakage in turning process using an orthogonal finite element model*, Proceedings of the 5th CIRP International Workshop on Modeling of Machining Operations, West Lafayette, USA, 139–148.

[6] LEGUTKO S., KEDZIERSKI T., PACZOS P., 2005, *Determination of the displacements and tensions distribution in the pull broaches cutting edges by means the Finite Elements Method*, Manufacturing Engineering, IV, 4, Slovakia, ISSN 1335–7972, 15–18.

[7] UMBRELLO D., M’SAOUBI R., OUTEIRO J.C., 2007, *The influence of Johnson-Cook material constants on finite element simulation of machining of AISI 316L steel*, Int. J. Mach. Tools Manuf., 47, 462–470.

[8] CHODOR J., 2011, Modeling and analysis of the movement of the workpiece during mikromachining and sliding burnishing process, taking into account the non-linearity of process, Rozprawa Doktorska, Politechnika Koszalińska, Koszalin, (in Polish).

[9] GRZESIK W., 2008: *Advanced machining processes of metallic materials*, Amsterdam, Elsevier.

[10] NIESLONY P., 2008, *Modeling of heat flow and temperature distribution in the cutting zone for cutting of hard protective coatings*, Studia i Monografie, 221, Politech. Opolska, Opole, ISSN 1429-6063. (in Polish)

[11] CHODOR J., KUKIELKA L., 2006: Influence of geometry of the blade and approach angle on states of stress and strain in the surface layer of cutting part by single abrasive grain, XXIX Naukowa Szkoła Obróbki Ściernej, Gdansk-Jurata, 79-86, (in Polish).

[12] CHODOR J., KUKIELKA L., 2008: *Numerical analysis of chip formation during machining for different value of failure strain*, GAMM 78th Annual Meeting of the Gesellschaft für Angewandte Mathematik und Mechanik, 16 – 20 July, Zürich. Journal PAMM, 7/1, 4030031-4030032, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 12 Dec 2008.

[13] CHODOR J., KUKIELKA L., 2008, *Numerical analysis of micromachining of C45 steel with single abrasive grain*, GAMM79th Annual Meeting of the International Association of Applied Mathematics and Mechanics, 31 March – 4 April, Bremen 2008.

[14] CHODOR J., KUKIELKA L., SZCZEPANSKA M., 2009, *Phenomena occurring on the surface of the chip and tools contact in the process of turning of agricultural vehicle swivel pin* , XII Słupskie Forum Motoryzacji, Słupsk, (in Polish).

[15] PRZYBYLSKI W., DEJA M., 2007, *Computer-aided manufacturing machines, Fundamentals and Application*, WNT Warszawa, ISBN: 978-83-204-3296-1, (in Polish).

[16] LEGUTKO S., KEDZIERSKI T., PACZOS P., 2006:*Usage of Finite Elements Method for Identification of the Displacement and Stresses in Cutting Wedges* – Case Study, in the book Development of Mechanical Engineering as a Tool for the Enterprise Logistics progress, editor St. Legutko, published by Poznan University of Technology, Poznan 2006, pp. 77-84, ISBN 83-89873-28-1.