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NUMERICAL ANALYSIS AND COMPUTER SIMULATIONS OF BURNISHING ROLLING PROCESS OF ROUGH SURFACE

Abstract

In this study the process of burnishing rolling is considered as a geometrical and physical boundary and initial value problem, with unknown boundary conditions in the contact area. 3D dynamic explicit method for burnishing rolling process with taking into account surface roughness after turning (as previous treatment) under ANSYS environment were established. The analysis covered surfaces characterized by vertical angle of the asperities equal: 75°. The simulation results (i.e. surface deformation, states of strain and stresses, material behavior) were evaluated. Numerical algorithms can be used for an assessment of the influence of the surface after previous treatment on the burnished product.

INTRODUCTION

Nowadays, automotive technology at a very high level is developed. Big companies try to outdo each other by introducing newer, better and innovative projects. More and more companies increasing engine power, improving traction properties, consumables and others. One must keep in mind that the quality of the manufactured products and the cost of their production are among the most important problems of modern manufacturing techniques. The increasing performance requirements in relation to modern machine parts are put. For reliability, durability and life of the properties decisive influence have the properties of surface layer, which are achieved depending on the type and the course of finishing treatment. Also, the diversity of the destination and working conditions result in the need to find treatment methods that allow for the formation of different and yet optimal due to the adopted criteria of product quality.

Technological quality of the product depends mainly on the type of finishing treatment and conditions of its realization, mainly on the technological parameters. One of the methods of finishing treatment, which allows obtaining the surface layer characterized by advantageous utility properties, is burnishing rolling treatment [1÷4]. It is used to improve the surface state and/or the state of the surface layer, to increase the smoothness of the surface, strengthening and increase its dimensionally and shaping accuracy [5, 6, 14÷19, 21].

The surface quality after previous treatment has significant influence on its quality after burnishing rolling [23÷25]. It is recommended that outline of the surface roughness under burnishing was regular, determined and periodical. After burnishing rolling of such profile, one receives also regular, determined and periodical profile. Figure 1 shows the scheme of determined surface profiles after previous treatment and after burnishing rolling.

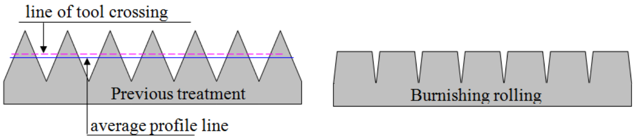

Fig. 1. *Determined surface profile after previous treatment and after burnishing rolling*

Burnishing rolling of the surface with a stochastic roughness profile (e.g. after grinding) causes that the achieved burnished surface is also with stochastic surface roughness profile. On the surface the secondary cavities are formed and material overflows, resulting in deterioration of the burnished surface quality [1÷4, 24]. Outline of asperities may have a decisive influence on the deformation process (displacement, strain) and the state of stresses and smoothing the surface after burnishing process.

Previous studies have shown that the surface roughness after the process of burnishing the regular, triangular asperities depends on the material type of asperities (yield stress Re, Young's modulus E), the geometrical parameters (vertical angle θ of asperities, the distance f, the volume V (or surface outline area S), rounding of asperities volleys and the peaks.

Authors [1÷4], with the assumption that the asperity of the surface after previous treatment is regular, symmetrical, and triangular and that it is symmetrical deformity, single out three qualitatively different cases of the material flowing in the product's Surface Layer (SL) during burnishing rolling process depending only on the vertical angle θ of the asperity (Fig. 2):

1. for the vertical angles $\theta \leq 80°$ a strain of the material occurs only in the area of asperities. The valleys of asperities do not rise. The core of the material remains unstrained. With a total strain, deformed asperities are visible and are separated from one to another with gaps (discontinuity planes) with the depth 0.5Rt. The levelling of the surface occurs as a result of the flow of the material of asperities to sides,
2. for the vertical angle $80° < \theta < 145°$ there occurs an increase of the zone of plastic strains, which cover the core of the material, as well. The asperity valleys rise, while with a total strain, in the contact zone of neighbouring material overflows, gaps are visible, yet with a smaller depth than previously,
3. for the vertical angle $\theta \geq 145°$ the levelling of the surface occurs as a result of a strain of asperities and the core of the material, and not at the cost of the material overflows, in the direction of the sides of asperities. The value of the lowering of the vertex of asperities equals the value by which its valley rises. In the surface layer, there are no planes of the material's discontinuity.

So it is important to receive after previous treatment not only regular outline, but also adequate vertical angle θ of the shaping asperities. The values of the vertical angle θ of the asperity and the feed during previous treatment should be taken every time for the part and it's inappropriate.

However, currently there is no explanation of the impact of determined profile parameters on the physical phenomena in the burnishing process, which have a direct impact on the quality of the formed product's surface layer, and therefore on the tribological properties and fatigue of the product after the process. Moreover, in the process of burnishing there are many physical phenomena whose observation or measurement is very difficult or impossible. These include for example: phenomena in the contact zone of the tool with the object - the pressure, the friction forces, the slip and contact zones, states of displacement, strain and stresses. The aim of the paper is to provide an effective numerical model based on the finite element method, which allow for the analysis of phenomena (i.e. surface deformation, states of strain and stresses, depth of stress deposition, normal force, material behavior) at any point of the object and at any time during the process, taking into account the physical and geometric nonlinearity.

The specific aim is to vivificate the impact of the vertical angle θ=75º of symmetrical triangular asperity on the process of deformation and strain and stresses in object's SL in the burnishing rolling process. The vertical angle θ=75º is in the group which is characterized by an increase of the zone of plastic strains, which cover the core of the material, as well. The asperity valleys rise, while with a total strain, in the contact zone of neighbouring material overflows, gaps are visible, yet with a smaller depth than previously. The asperities with the vertical angle θ=75º after previous treatment but under burnishing are used during forming secondary micro cavities. It is useful in attrition pairs, where micro cavities are necessary because of the gathering of the lubricant.

1. METHOD OF PROBLEM SOLUTION

The process of burnishing rolling was considered as a geometrical and physical boundary and initial value problem, with unknown boundary conditions in the contact area. An updated Lagrange's description was used for the description of non-linear phenomena on a typical incremental step. The increments of strains and stresses were described respectively with an increment of a non-linear strain tensor of green – Lagrange and an increment of the second symmetric stress tensor of Pioli – Kirchhoff respectively. For the purpose of a variational formulation of the incremental equation of the object's movement for the case of stress rolling burnishing, a variational functional was used, in which there occurs only one independent field, namely the field of an increment of displacements. Moreover, it was accepted that compatibility equations are satisfied and the initial and boundary conditions are fulfilled. Such assumptions lead to the so-called compatible model for the problems of non-linear dynamics, which is expressed in the increments of displacements.

While writing particular equations of motion for all the finite elements separated from the tool and the object, after their expansion and totalising, after all the finite elements of the object, an equation of motion of the object's deformation in the burnishing process is obtained. While not resigning from the general nature of the discussion, it was accepted that the burnishing process of the rotating section is described. A general equation of the object's motion has then the following form:

where:

$$\begin{aligned}&[{}^{t}_{t}\mathbf{M}]\{{}^{\tau}_{t}\Delta\ddot{\mathbf{r}}\}+[{}^{t}_{t}\mathbf{C}_{\mathrm{T}}(\cdot)]\{{}^{\tau}_{t}\Delta\dot{\mathbf{r}}\}+([{}^{t}_{t}\mathbf{K}_{\mathrm{T}}(\cdot)]+\\&[{}^{\tau}_{t}\Delta\mathbf{K}_{\mathrm{T}}(\cdot)])\{{}^{\tau}_{t}\Delta\mathbf{r}\}=\{{}^{\tau}_{t}\Delta\mathbf{R}_{\mathrm{T}}(\cdot)\}+\{{}^{\tau}_{t}\Delta\mathbf{F}(\cdot)\}+\{{}^{t}_{t}\mathbf{F}_{\mathrm{T}}(\cdot)\}\end{aligned} \qquad (1)$$

$[{}^{t}_{t}\mathbf{M}]$ – global matrix of the mass of the system in moment *t*,

$[{}^{t}_{t}\mathbf{C}_{\mathrm{T}}]$ – global matrix of the damping of the system in moment *t*,

$[{}^{t}_{t}\mathbf{K}_{\mathrm{T}}]$ – global matrix of the rigidity of the system in moment *t*,

$[{}^{\tau}_{t}\Delta\mathbf{K}_{\mathrm{T}}]$ – global matrix of an increment of the object's rigidity on a step,

$\{{}^{t}_{t}\mathbf{F}_{\mathrm{T}}\}$ – global vector of the object's internal loads in moment *t*,

$\{{}^{\tau}_{t}\Delta\mathbf{F}\}$ – vector of an increment of the object's internal loads,

$\{{}^{\tau}_{t}\Delta\mathbf{R}_{\mathrm{T}}\}$ – global vector of an increment of the object's internal loads,

$\{{}^{\tau}_{t}\Delta\mathbf{r}\}$ – vector of an increment of the displacements of the object's nodes,

$\{{}^{\tau}_{t}\Delta\dot{\mathbf{r}}\}$ – vector of an increment of the velocity of the object's nodes,

$\{{}^{\tau}_{t}\Delta\ddot{\mathbf{r}}\}$ – vector of an increment of the accelerations of the object's nodes

2. COMPUTER MODEL

Geometrical model (3D) (tool and object) and cross section of the object in zoom, with the mesh grid in figure 2 is presented.

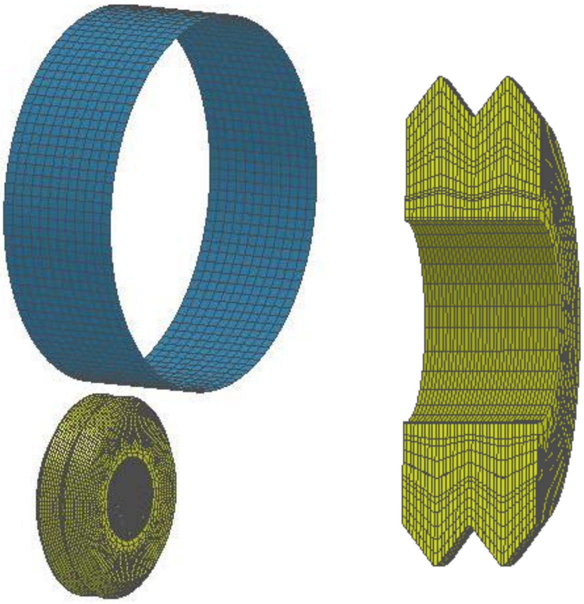

Fig. 2. *Determined surface profile after previous treatment and after burnishing rolling*

Computer model (3D) of the process in real scale in ANSYS/LS-DYNA was prepared performing following operation:

- geometrical computer modeling: creation of tool geometry (roller) and object (shaft) with marked regular asperities of the outer surface. There is a possibility to input different geometry of asperity e.g. varying the vertical angle θ and asperities distance f and technological parameters of the process. For example, calculations performed for θ = 75° and f=2,7 mm.
- adoption of material models for individual bodies. In the present case the subject was treated as an elastic body (in the range of reversible strains) and visco-plastic (in the range of irreversible strains), while the tool (roller) was treated as a perfectly rigid body. Moreover, the incremental material models, assumes that the object is made of C45 steel. Other, necessary material parameters: Young's modulus E=210 GPa and Poisson's ratio ν=0.29.
- discretisation of the object with finite elements type Solid164 (with a linear function of the shape), finite element type Shell 163 and contact elements. Model contains 374388 finite ele-

ments, and 385214 nodes. The number of degrees of freedom, assuming only translational components, is: N=810 024.

- modeling of variable body contact with the adoption of a model of friction - nonlinear anisotropic Coulomb friction, and the coefficient of static friction μ=0,1.
- reference relevant boundary conditions - mainly applying to displacement: references cavity tool and received degrees of freedom for the subject, as well as set rotational speed providing the required burnishing speed. In this case burnished shaft with surfaces asperities rotates, then the burnishing element (roller) reach to the object's surface. Contact of the roller with the surface also causes the rotation of the roll.
- establishing methods of discrete solution of motion equations. For this purpose, according to a sensible solution algorithm (explicit), in every step of the analysis approximations of column vector of acceleration and velocity increment as a function of displacement column vector. Subsequently, bordering time increment Δt_{kr} was defined. Total analysis time t=3,5 s.

3. RECEIVED RESULTS OF DISPLACEMENTS AND DEFORMATION OF THE ROUGH SURFACE

Exemplary results of model displacement and deformation of the finite element mesh grid in subsequent time steps are shown in Figure 3. In the first picture there is an example of the object that is prepared in previous treatment (for example in turning process) under burnishing. The model consists of two triangular, regular asperities on the surface of the shaft, which constitute the actual details of the surface prepared to be treated. Then the moment, when the tool moves to the rotating part of shaft is visible as well as its immersion and then the deformation of asperities vertexes. Further immersion of the burnishing tool (until a value equal a half of the asperity height) and rotation of the shaft causes increasing asperities squeeze until it is completely smooth out.

The subsequent time steps of asperities burnishing rolling process in relation to the shaft cut-Y plane were analyzed. (Fig. 3). This allowed observation of the surface deformation of triangular asperities, in cross section. At the beginning of the process, it can be clear seen, that the tool caused asperities deformation as well as finite element mesh grids. However, only in the area of the asperities in the upper area of the shaft, the bottom remain intact (no contact between the tool and the object in this subsequent time step), which is consistent with the real course of the process of the burnishing rolling. In the following steps, the increasing deformation of the mesh grid is visible. Initially it covers only the area of asperities, however, with successive time steps there are also visible changes in the core area. This analysis also reveals how during time changes the distance between asperities, and thus as the material fills this area. In the initial phases the formed cavity between the asperities vertices is large, and in subsequent phases of the burnishing becomes increasingly filled with material and it is getting narrower. The width of the gap from the second to the last considered time step changed by taking the values: 2,7, 0,47, 0,25, 0,19 mm. In the case of burnished asperities, it can be seen how in subsequent time steps increases the width of the deformed asperity, and their value in subsequent time steps are: 0, 1,97, 2,33, 2,42 mm. The result is determined profile with the asperities flat vertex outline (plateau outline used in tribological pairs).

4. MAPS OF REDUCED STRAINS AND STRESSES AFTER BURNISHING ROLLING PROCESS

Maps of reduced strains in the fragment of the shaft and cross section, for vertical angles of asperity θ=75° and the spacing of

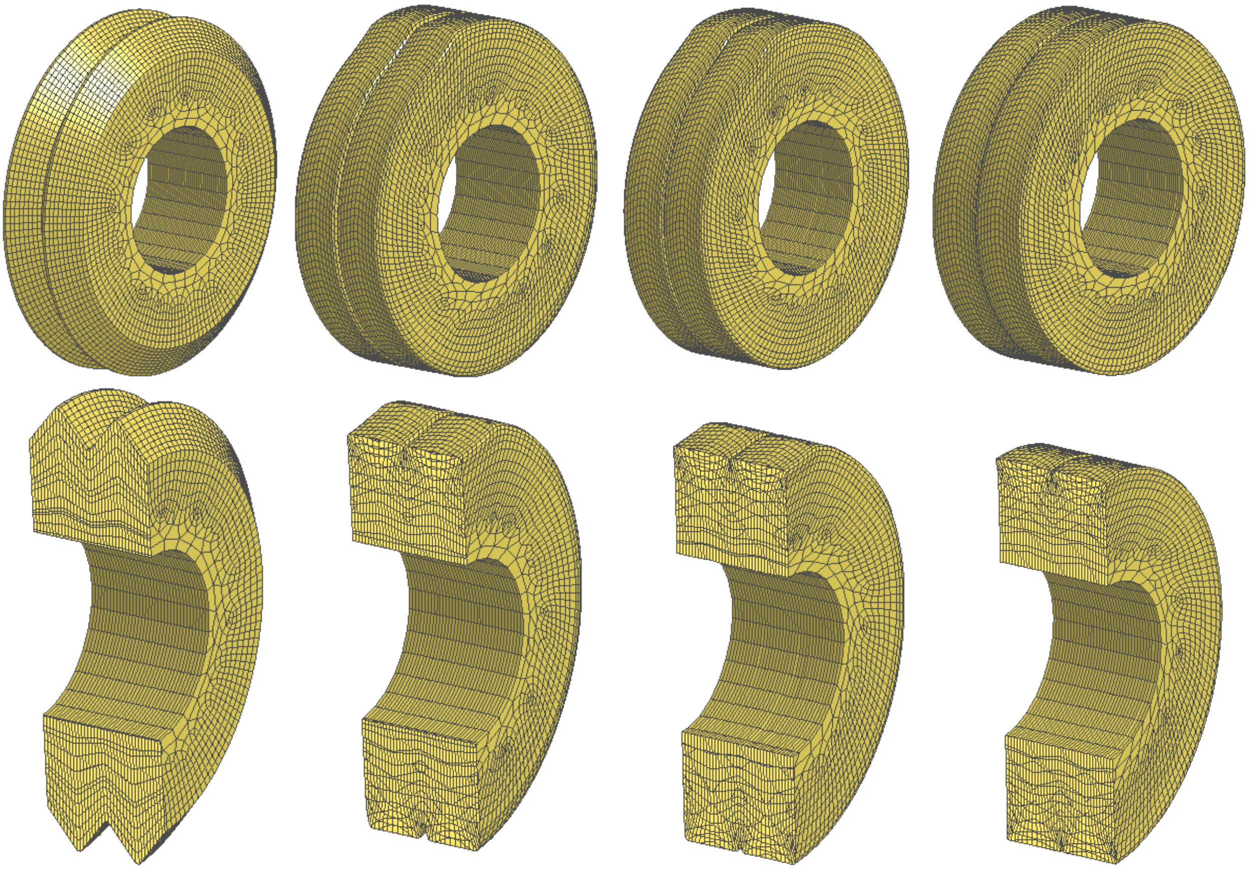

***Fig. 3.** Displacement and deformation of the finite element mesh grid in subsequent time steps (from the left): t=0, t=2,035 t=2,58, t=3,5 s*

asperity s=2,7 mm=const. with the scale indicating the obtained result are shown in Figure 4.

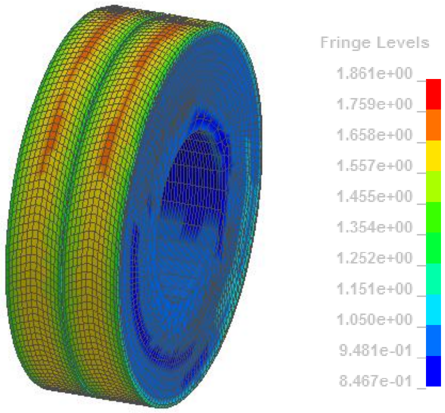

Fig. 4. *Map of reduced strain in asperities with vertical angles θ=75° for the depth of burnishing a_n=0,5 Rt*

Under the influence of burnishing axial forces operating in the machining system and the burnishing speed and feed, burnishing element causes in the contact zone with the workpiece, local elastic strains as well as viscous and plastic. As a result of strains following the deformation of grains of metal in a thin layer underlying the surface burnishing. In addition, grains are shredded. They are flattened and elongated in the direction of a major strain creating deformation texture, showing the anisotropy of mechanical properties.

The cause of compressive internal stresses during the burnishing rolling is primarily plastic strain, and then temperature and structural changes. As a result of plastic strain decreases the density of the metal in layers closest to the burnished surface. Deeper layers of metal does not allow for free and fully spread into the plastic strains. As a result, in the surface layer the stress state is prepared. Maps of reduced stress in the fragment of the shaft and cross section, for vertical angles of asperity θ=75° and the spacing of asperity s=2,7 mm=const. with the scale indicating the obtained result are shown in Figure 7.

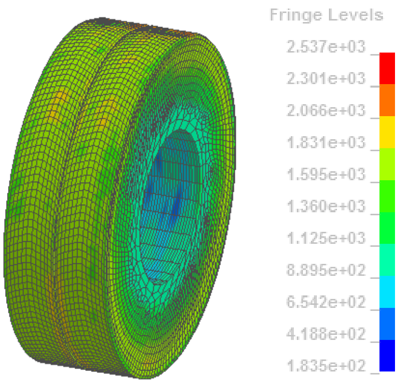

Fig. 4. *Map of reduced stress in asperities with vertical angles θ=75° for the depth of burnishing a_n=0,5 Rt*

SUMMARY

Burnishing rolling was considered as a geometrical and physical boundary and initial value problem, with unknown boundary conditions in the contact area. Developed application using the incremental theory in updated Lagrange description allows to analyze the geometric structure of the surface and the distribution of stresses in the surface layer at any time during the process.

The paper presents a modern way of simulation of physical phenomena in the process of burnishing rolling of regular, triangular asperities with vertical angle θ=75°. The correctness of the various stages of modeling and simulation - both modeling and discretization and assumed initial and boundary conditions allow to analyze the process in short time without costs on the experimental researches. The developed application in the system ANSYS allows for properly analysis of temporal displacement conditions, strains and stresses in the asperities material with regard to physical and geometric nonlinearity and strengthening of the material in the process of burnishing. In addition, it is possible to determine the component states of the displacement and strains and stresses what means the elastic and plastic parts. It is possible to carry Young module), the state of stresses and strains after treatment previous treatment and determination their effects on the surface roughness and the state of stress and strain in the surface layer after the process of burnishing. You can also specify the location of the area of maximum stress and strain and elastic recovery. This will allow, for specified processing conditions, determine the status of the surface layer of the object or vice versa, to required state of WW article, determine the conditions of the process of burnishing.

Numerical simulations of the process of burnishing confirmed the ability to control distribution of stresses. Based on the simulations it was found that it is necessary to analyze the possibility of stress distribution steering by the vertical angle of asperities.

Numerical algorithms can be used for an assessment of the influence of the surface after previous treatment on the burnished product. They facilitate a better understanding of the phenomena which occur in the zones of contact and strains, and therefore can constitute the basis for the development of guidelines for the selection of the conditions of rolling and burnishing processes considering the required technological quality of the product.

BIBLIOGRAPHY

1. Kułakowska A., Kukiełka L., Patyk R.: *Numerical analysis and Experimental researches of burnishing rolling process of workpieces with real surface*, WMSCI, Vol. II. International Institute of Informatics and Systemics, ISBN -13: 978-1-934272-59-6, pg.63-68
2. A. Kulakowska, L. Kukielka: Numerical analysis and experimental researches of burnishing rolling process with taking into account deviations in the surface asperities outline after previous treatment, Steel Research International, 2 (2008) 42-48.
3. A. Kulakowska: Problems of surface preparation under Burnishing rolling in aspect of product quality, Steel Research International, 81/9 (2010) 218-221.
4. A. Kulakowska: *Experimental Researches of Burnishing Rolling Process of Regular Surface Asperities Prepared in Turning Process*, Steel Research International, Special Edition: 14th International Conference on Metal Forming (2012) 127-131.
5. R. Patyk, L. Kukielka, A. Kulakowska, Numerical analysis of embossing process of regular inequalities with triangular outline on cylindrical semi product, J. Sys., Cyb. Inf. 8/3 (2010) 36-41.
6. L. Bohdal.: *Finite element simulation of 3D sheet metal guillotining using elastic/visco-plastic damage model*, Steel Research International. Special Edition: 14th International Conference on Metal Forming (2012) 1419-1422.
7. L. Kukielka, K. Kukielka: *Numerical analysis of the physical phenomena in the working zone in the rolling process of the round thread*, in: J.T.M. de Hosson, C.A. Brebbia, S-I Nishida

(Eds.), Computer Methods and Experimental Measurements for Surface Effects and Contact Mechanics VIII, WITPRESS, Southampton-Boston, (2007) 125-124.

8. L. Kukielka, K. Kukielka: *Numerical analysis of the process of trapezoidal thread rolling*, in: C.A. Brebbia (Eds.), High Performance Structures and Materials III, Southampton-Boston, WITPRESS (2006) 663-672.
9. P. Kaldunski: Numerical method for determining product dimensions in the drawing process, PAK 5 (2011) 547-550.
10. K.J. Bathe, *Finite Element Procedures in Engineering Analysis*, Prentice-Hall, Englewood Cliffs, New Jersey, 1982.
11. K.L. Johnson, *Contact mechanics,* Cambridge University Press, 1985.
12. Kukielka L., Kukielka K., Kulakowska A., Patyk R., Malag L., Bohdal L.: Incremental Modelling and Numerical Solution of the Contact Problem between Movable Elastic and Elastic/Visco-Plastic Bodies and Application in the Technological Processes. Applied Mechanics and Materials Novel Trends in Production Devices and Systems, Editors: Karol Velíšek, Peter Košťál and Milan Nad, 2014, USA-SLOVAKIA, pp. 159-165. ISSN 1662-7482.
13. Kukielka K., Kukielka L., Bohdal L., Kulakowska A., Malag L., Patyk R.: *3D Numerical Analysis the State of Elastic/Visco-Plastic Strain in the External Round Thread Rolled on Cold*. Applied Mechanics and Materials Novel Trends in Production Devices and Systems, Editors: Karol Velíšek, Peter Košťál and Milan Nad, 2014, USA-SLOVAKIA, pp. 436-441. ISSN 1662-7482.
14. J. Chodor, L. Kukielka, B. Storch, New method of determination of tool rake angle on the basis of crack angle of specimen in tensile test and numerical simulations, in J.T.M. De Hosson, C.A. Brebbia (Eds.), Surface Effects and Contact Mechanics IX: Computational Methods and Experiments, WITPRESS, Ashurst, Southampton, United Kingdom, 2009, pp. 207-216
15. J. Chodor, L. Kukielka. Numerical analysis of the influence of abrasive grain geometry and cutting angle on states of strain and stress in the surface layer of object, in J.T.M. De Hosson, C.A. Brebbia, S-I Nishida (Eds.), Computer Methods and Experimental Measurements for Surface Effects and Contact Mechanics VIII, WITPRESS, Ashurst, Southampton, United Kingdom, 2007, pp. 183-193
16. J. Chodor, L. Kukielka, Using Nonlinear Contact Mechanics in Process of Tool Edge Movement on Deformable Body to Analysis of Cutting and Sliding Burnishing Processes, Applied Mechanics and Materials, Vol 474, pp. 339-344, Jan. 2014.
17. Kukielka L., Geleta K., Kukielka K.: Modelling of Initial and Boundary Problems with Geometrical and Physical Nonlinearity and its Application in Burnishing Processes in: K. Mori, M. Pietrzyk, J. Kusiak, J. Majta, P Hartley, J. Lin (Eds.), Steel Research International. Special Edition: 14th International Conference Metal Forming, 2012, pp. 1375-1378.
18. L. Kukiełka, A. Kułakowska, R. Patyk, *Numerical modeling and simulation of the movable contact tool-worpiece and application in technological processes.* Journal of Systemics, Cybernetics and Informatics, Orlando, Floryda (2009) 57-62.
19. Kułakowska A., Bohdal Ł., Kukiełka L., Kukiełka K., Maląg L., Patyk R.: *Possibility of Steering of Product Surface Layers Properties in Burnishing Rolling Process*, *Applied Mechanics and Materials*, Tom: 474
20. Kułakowska A., Bohdal Ł., Patyk R.: *Zastosowanie obróbki nagniataniem w tworzeniu ekologicznego produktu*, Annual Set The Environment Protection, Vol. 16, year 2014, ISSN 1506-218X
21. Patyk R., Kułakowska A., Bohdal Ł.: *Ekologiczne, ekonomiczne i eksploatacyjne aspekty obróbki nagniataniem*, Annual Set The Environment Protection, Vol. 16, year 2014, ISSN 1506-218X
22. Bohdal Ł., Kułakowska A., Patyk R.: *Analysis of slitting of aluminium body panels in the aspect of scrap reduction*, Annual Set The Environment Protection, Vol. 16, year 2014, ISSN 1506-218X

ANALIZA NUMERYCZNA I SYMULACJE KOMPUTEROWE PROCESU NAGNIATANIA POWIERZCHNI CHROPOWATYCH

Streszczenie

W pracy proces nagniatania naporowego tocznego rozpatrzono jako geometrycznie i fizycznie nieliniowe zagadnienie brzegowo-początkowe, z nieznanymi warunkami brzegowymi w obszarze kontaktu. symulacje komputerowe 3D przeprowadzono, z zastosowaniem metody explicit w środowisku Ansys. Powierzchnie do nagniatania traktowano jako chropowate, przygotowane w obróbce poprzedzającej toczeniem. Analizą objęto powierzchnie charakteryzujące się kątem wierzchołkowym nierówności powierzchni $\theta=75^\circ$*. Uzyskane wyniki (deformacje, stany odkształceń i naprężeń) przedstawiono w postaci wykresów i map rozkładów.*

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