Modern methods for modelling and analysis of technological processes of car parts and their topological optimization

Leon Kukiełka, Radosław Patyk, Krzysztof Kukiełka, Chodór Jarosław, Krzysztof Lipiński

Paper presents the problem of modelling and analysis of metalworking processes. Technological processes were considered as a geometrical, physical and thermal boundary and initial value problem, with unknown boundary conditions in the contact zone. An incremental model of the contact problem between movable rigid or thermo-elastic body (tool) and thermo-elastic/thermo-visco-plastic-phases body (object) in updated Lagrange formulation, for spatial states (3D) was considered. The incremental functional of the total energy and variational, non-linear equation of motion of object and heat transfer on the typical step time were derived. This equation has been discretized by finite element method, and the system of discrete equations of motion and heat transfer of objects were received. For solution of these equations the explicit or implicit methods was used. The applications were developed in the ANSYS/LS-Dyna system, which makes possible a complex time analysis of the states of displacements, strains and stresses, in the workpieces in fabrication processes. Application of this method was showed for examples the modelling and the analysis of burnishing rolling, thread rolling and turning processes. The numerical result were verified experimentally. The topic of topological optimization of car parts is also presented.

Keywords: car parts, topological optimization, technological processes, metal forming, surface layer, modelling, Finite Element Method, numerical analysis

Introduction

The dynamic development of technology means that the greater are the requirements that are put before modern machines and equipment; even greater are the requirements in respect of durability and reliability of associated units which, in certain operational conditions, constitute tribological systems.

Improper physical and stereometrical properties of the surface layer cause the failure damage in approximately 85% of modern machine units; they also influence the decrease in life and the increase of energy consumption to overcome frictional resistance. Nowadays, about 50% of the energy supplied is lost in the friction of elements in relative motion.

Thus, one of the most important technological problems in the manufacturing and in the recovery of elements is the formation of the surface layer, characterized by assigned physical and stereometrical properties and precision in dimension and form, that affects the target life and the reliability of the machined elements. Special attention should be paid to those machine elements which are costly to manufacture, or which have a bearing on machine reliability and environmental pollution, etc.

Knowledge of the guillotining process is based mainly on experimental methods, which are often expensive and unable to be extrapolated to other cutting configurations. Therefore, computational models, such as the finite element method (FEM), are valuable in reducing the number of trial-and-error experiments required to predict the state of material displacement, residual stresses, strains, material fracture, sheet deformations and quality of the sheared edge.

Numerical analysis is a valuable tool to extend the period of time and knowledge of phenomena whose experimental researches is difficult or impossible. These are mainly phenomena occurring in extremely small areas, running at high speeds, existing in a very short time, and determining the results of the treatment process. For such problems, in particular:

- friction, adhesion and slip,
- displacement, strain, stress and temperature in the surface layer of the workpiece,
- variability tool contact areas with the object and boundary conditions,
- variability of the workpiece during machining.

Understanding the effect of the treatment on the state of strain, stress and temperature in the surface layer of the workpiece is important for the correct design of the process.

One major steps to achieve effective solutions to the Finite Element Method is to develop a universal model of the investigated process. At Department of Technical Mechanics at the Faculty of Mechanical Engineering of the Koszalin University of Technology were developed applications on the system ANSYS (APDL language), which allow a comprehensive time analysis for deformation (displacement, velocity, strain, strain rate), stresses and boundary condition in contact zone tool-object occurring in the object, both the spatial conditions as well as plane, in the processes technological precision machining parts (Fig. 1): cutting processes [1-12], turning processes [13-22], burnishing rolling processes [79-84], sliding burnishing [13, 20], cutting by an abrasive single grain [24,25,69], embossing [88-103], thread rolling [30-47], duplex burnishing [99], drawing [27-29] and shot penning [104-106]. In applications were used a theoretical bases processes precision machining of modern parts, developed in [48-78].

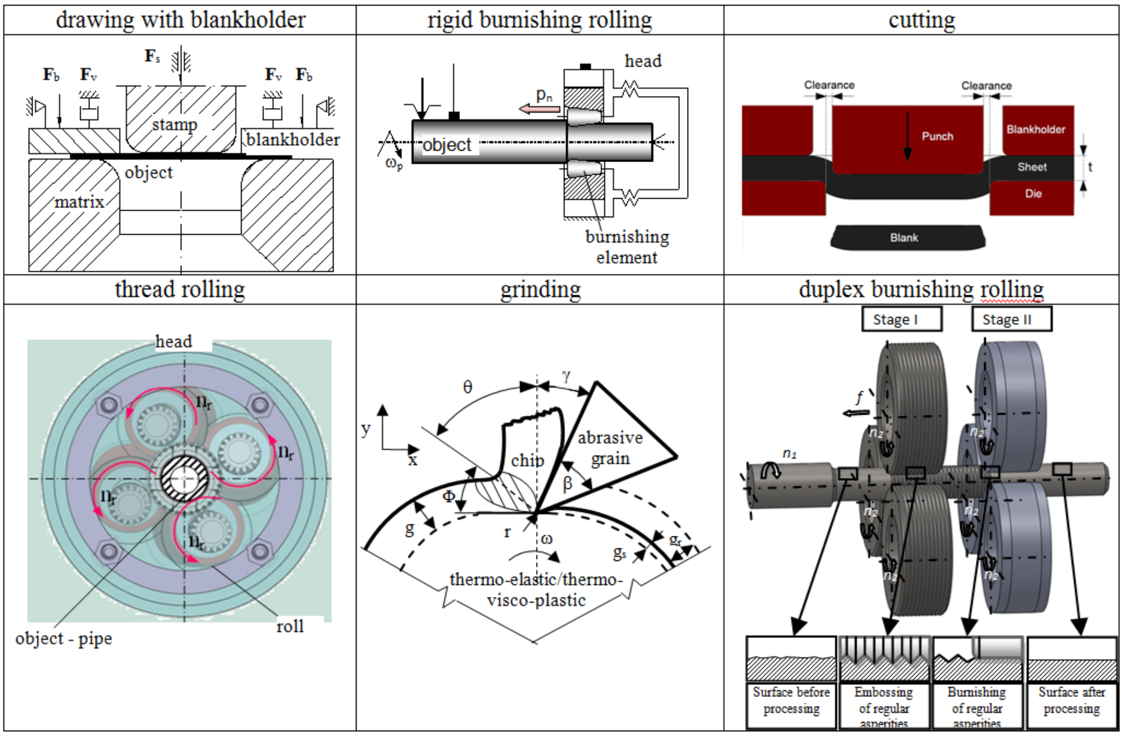


Fig. 1. *Schema of precision machining of modern parts*

The latest trend in the modelling and analysis processes is the numerical modelling using Finite Element Method (FEM). It involves replacing the continuous object (the real) discrete object with separate sub-volumes and/or sub-areas – finite elements containing a finite number of nodes. The development of the computational capabilities of computers and software allows analysis of modern technological processes precision machining of parts using computer programs using FEM and iterative calculation using the updated Lagrangian description.

Numerical analysis is a valuable tool for understanding phenomena that experimental study is difficult or impossible. These are mainly phenomena occurring in extremely small areas, running at high speeds, lasting a very short time and determining the results of the sliding cutting or burnishing. Until such problems are, in particular friction, adhesion and slip, movements, strain, stress and temperature of the workpiece, the workpiece variability of cracking material. Numerical analysis also allows to determine the impact of technology on the quality of the product: the type of material and its state, geometry tools, the effect of processing conditions on the state of strain, stress and temperatures in the subject, shapes burrs, chips, quality surface finish.

Knowledge of the physical phenomena occurring in the material, in areas where the tool is in contact with the object while the technological processes are carried out, is a basic necessity. It also enables the control of the properties of the surface layer of the product and the achieving of the greatest shape-dimensional accuracy. Thus, one of the most important technological problems in the metal forming processes is the calculation of displacement, strain and stress in the surface layer. The objective in this paper is to present the modern method to modelling, analysis and testing of a solution procedure for the geometrical, physical and thermal non-linear analysis of thermo-elastic/thermo-visco-plastic-phases behaviour with/without temperature-dependent material properties (Fig. 2).

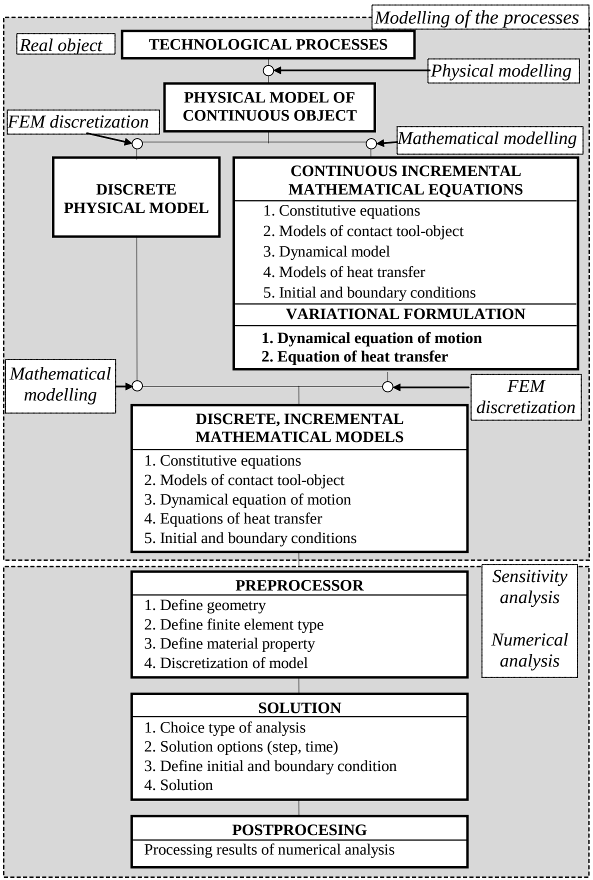


Fig. 2. *Schema of modern modelling and numerical analysis of technological processes and its implementation for the treatment of machine parts*

The incremental mathematical model of technological processes, in the updated Lagrange formulation, contain the constitutive equations (model of dynamical yield stress, thermo-elastic/thermo-visco-plastic-phases strains model, thermo-elastic/thermo-visco-plastic-phases stress model), the model of contact between tool-workpiece, dynamic equation of motion and deformation, equations of heat transfer, initial and boundary conditions. First, variational method developed equation of motion and deformation for a typical step time. Then, equation with Finite Element Method (FEM) was discretized, given the equations of motion and deformation and head transfer of a discrete object. Then, the explicit (DEM) or implicit (DIM) schemes to step by step numerical solution are adopted. The algorithms of numerical analysis in ANSYS program for different technological processes were elaborated ,where discrete equation was applied together with initial and boundary conditions.

1. Thread rolling process [31]

Simulation studies the rolling process of the thread (Fig. 3) was carried out in two stages. In the first stage, using a sensitivity analysis the effective discrete model of the process was determined. In a second step, using the discrete model developed, the calculations were performed in order to define the influence of friction coefficient on the state of deformation (displacements and strain) and stress in the surface layer of the object. The rolling process were considered as isothermal, carried out cold at ambient temperature.

The numerical analysis for 2D states of deformation and 3D states of stress was applied on the example of steel C55. The tool is considered as rigid $E \to \infty$ or elastic body, however the material model as an elasto/visco-plastic body with non-linear hardening. The model has discretized by finite element PLANE183 with non-linear function of the shape.

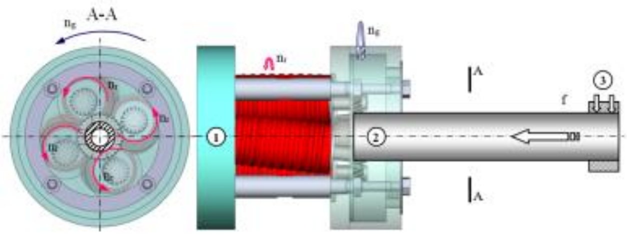


Fig. 3. Computer model of the axial thread rolling process on cold of the thread on the bars or pipes by an angle head comprising four rollers [31]: 1 – head 2 – blank 3 – handle

Influence of thread rolling conditions on the states of stress and strain in the round thread

Analyzing the distribution of deformation of the finite element grid and state of effective strains and stresses, presented in figures 4 and 5, where the influence of the lubrication condition is observed. For   in the contact zone tool – workpiece (Fig. 4a), during the forming the outline of the thread, material isn't braking by tool and slide through the contact surface. The curving of vertical line of the finite element grid is invisible. Other side, increase the friction coefficient causes increase braking of the material. For high value of the friction coefficient (Fig. 4c) occurs strong braking of material in the contact zone. Form also the adhesion zone of material. That cause higher displacements of material in the zone placed father from the contact zone. Then the line of the finite element grid are stronger curved.

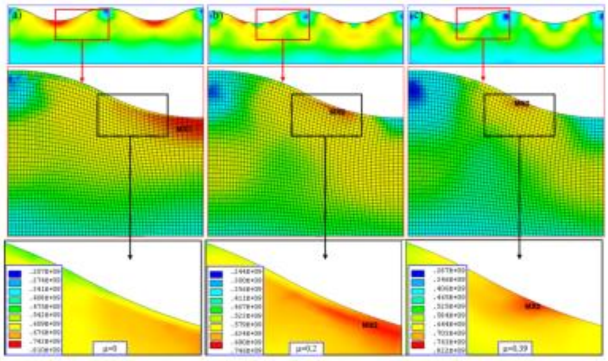


Fig. 4. The deformation of grid and the maps of effective stresses in the thread on a longitudinal cutting plane for various value of frictions coefficient

The friction coefficient has high influence on value and distribution of strain. For $\mu = 0$ the maximum of effective strain $\varepsilon_{eq} = 0{,}78$ is located on the bottom of the thread, near to the contact surface (MX1, Fig. 5a). For $\mu > 0$ appear an adhesion zone of material in the bottom of the thread, which take characteristic shape of a wedge. In this zone the value of strain is very small. For $\mu = 0{,}39$ strains are closer to the contact surface and getting smaller to value $\varepsilon_{eq} = 0{,}0016$ (elastic strains) (MN, Fig. 5b). Whereat the local maximum of strains (MX1) moving down in surface layer. Then appear additional two local maximums of the effective strains. Second maximum (MX2) is placed near to the contact zone of the side of the thread, where higher value of friction coefficient increase strains value from $\varepsilon_{eq} = 0{,}176$ for $\mu = 0$ (Fig. 5a) to value $\varepsilon_{eq} = 0{,}54$ for $\mu = 0{,}39$ (MX2, Fig. 5b). Next one local maximum (MX3) is located in depth of material on symmetry axis pass through top of the thread. Here, strains are getting smaller together with increasing of friction coefficient from value $\varepsilon_{eq} = 0{,}351$ for $\mu = 0$ (Fig. 5a) to $\varepsilon_{eq} = 0{,}423$ for $\mu = 0{,}39$ (Fig. 5b).

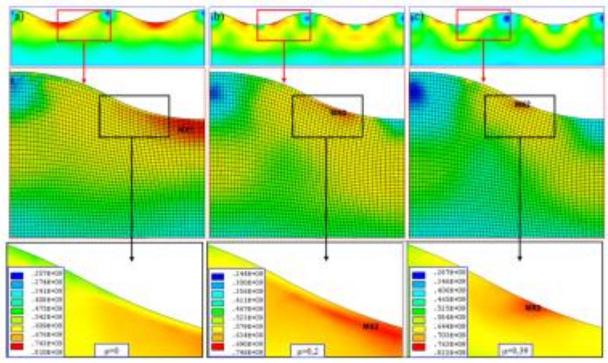


Fig. 5. The maps of effective strains in the thread on a longitudinal cutting plane for various value of friction coefficient

Figure 6 shows a comparison of the outline thread and the particle deformation (grid) (Fig. 6a), with the results of model studies (Fig. 6b) and results of numerical analysis according (Fig. 6c) and method II (Fig. 6d). Good agreement allows us to state that the effective discrete model for thread rolling is developed properly.

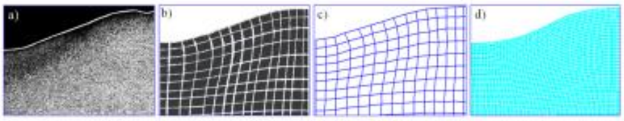


Fig. 6. *Comparison of experimental results (a, b) with the results of numerical calculations (c, d).*

3. Topological optimization

The purpose of topology optimization is to achieve the best possible placement in a certain area of material to be constructed in such a way that, under given boundary conditions and load conditions, the shape of the structure is optimal. Each optimization consists in finding the maximum or minimum value of a function or functional while fulfilling all the assumptions and limiting conditions. Optimizing the topology of the body is divided into two groups:

- Layout Optimization (LO) – used for bar structures, where the most important problem is to determine the optimal bar grid and optimize their cross-sections,
- Generalized Shape Optimization (GSO) – used for topology optimization of a material continuum, where optimization is made within a strictly defined design area, where sub-areas filled with material and sub-areas where
- material are excluded from the optimization process.

The considered continuous object is treated as continuous in the scale of the design area and at the same time discrete, identifying each material point as a separate, independent point having distinct material properties.

The mass of the completely filled design area Ω is determined by m and its density as ρ and the modulus of elasticity (Young's modulus) as E. The most important initial parameter is the mass available m_0. Defines the available mass during the optimization process as $m_0=\alpha$ m, dla $0<\alpha<1$, where $m=V\cdot\rho$. The coefficient α is the so-called a mass reduction factor that determines what part of mass m is involved in the optimization process and V is the volume of the area Ω.

The purpose of topological optimization is to maximize stiffness, and thus to minimize susceptibility, which is expressed as the work of mass forces (x) and external load (t):

$$\prod^{E}(x,\nu)=\int_{\Omega} x^{i}\ \nu_{i}\ d\Omega+\int_{\partial\Omega} t^{i}\ \nu_{i}\ dS, \qquad (1)$$

where n_i means the components of the displacement vector.

Using the identity of the value of structural susceptibility and the energy value of the strain accumulated in the material continuum:

$$\prod^{E}(x,\nu)=2\prod^{I}(x,\nu), \qquad (2)$$

where:

$$2\prod^{I}(x,\nu)=\int_{\Omega} C^{ijkl}(x,\nu,p(x))\, e_{ij}(\nu)\, e_{kl}(\nu)\, d\Omega. \qquad (3)$$

The minimum structural susceptibility therefore corresponds to the minimum energy value of the deformation that can accumulate in the considered continuum for the optimization process in question:

$$\prod^{E}(\gamma^{t})\rightarrow\prod^{E}(x,\nu)=\min_{e_{ij},e_{kl}\in Z}\int_{\Omega} C^{ijkl}\, e_{ij}\, e_{kl}\, d\Omega, \qquad (4)$$

where Z is the set of deformation fields.

In this case, the prerequisite for carrying out the process of minimizing vulnerability is to impose the following restrictions:

- firstly, we determine the amount of available mass that must satisfy the condition:

$$m_0=\int_{\Omega}\rho_h d\Omega, \qquad (5)$$

- Secondly, for a given mass m_0 it is assumed that the mass of the body during the optimization process (for the jth step) is equal to the mass at the beginning of the available mass.

Thus, the target function can be written as follows:

$$F(\rho(x))=\min\{\int_{\Omega} C^{ijkl}(x,\nu,\rho(x))\, e_{ij}(\nu)\, e_{kl}(\nu)\, d\Omega; \quad \forall x\in\Omega:\rho(x)\in R^{+};\ \int_{\Omega}\rho_h d\Omega=m_0. \qquad (6)$$

Topological optimization was carried out on the example of a pivot shaft fork. Functional determining the susceptibility of the structure will be minimized with the imposed constraints on the weight of the fork. Optimization will be carried out in a fixed, ongoing optimization process of the design area, where during this process there are sub-areas devoid of material and sub-areas filled with material. Solving the problem of optimizing the topology assumes that:

1) A continuous, homogeneous and isotropic medium will be tested.
2) The material is linearly elastic (E = const.).
3) The issue under analysis is static.
4) It is assumed that the strain tensor is linear (analysis for small deformations).
5) Throughout the optimization process, the problem is considered for the fixed design area Ω.
6) The Finite Element Method approach, updated Lagrange description and the variance calculation apply.
7) In the optimization process there is a certain body mass, called the mass available.

Topological optimization on the example of the articulated fork shaft

Pivot shafts shafts or articulated telescopic shafts are used for power transmission and are most commonly used in motor vehicles, agricultural machinery, forestry and construction machinery. In their design, the so-called. Cardan joint (articulation joint), which is a type of mechanical coupling, inseparable, self-aligning, angular. The diagram of this joint is shown in Figure 7. This solution allows the drive (power and torque) to be transferred between the shafts, which can be significantly deviated from one another.

The first stage of topological optimization is the development of a preliminary geometrical model (Figure 8), which should meet the design conditions (surfaces on which the boundary and initial conditions are assumed). Topological optimization was based on the Finite Element Method. Calculations were performed in ANSYS / LS-DYNA program where the object was discretized and the boundary conditions and initial conditions were assumed (the pin is fixed but the force moment is M = 900 Nm (Fig. 9).

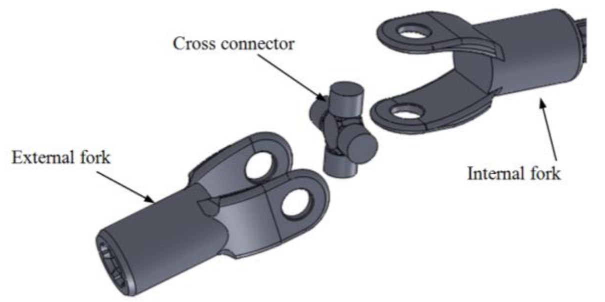


Fig. 7. *View of the Cardan joint*

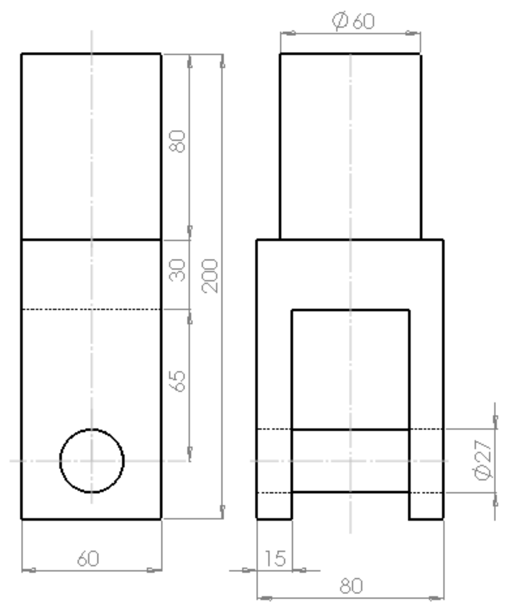
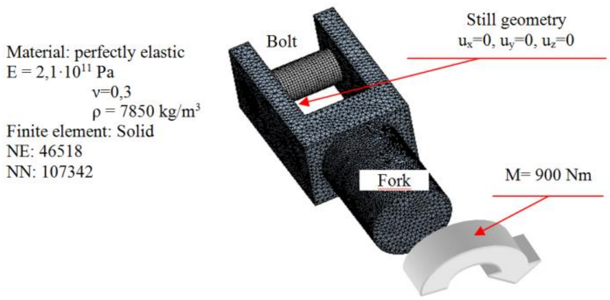


Fig. 8. *Construction drawing of a fork designed for topological optimization*



Rys. 9. *Discrete model of Cardan articulated fork with start and edge conditions applied for topological optimization*

The results of the topological optimization performed for selected values of the reduction coefficient α are shown in Figure 10.

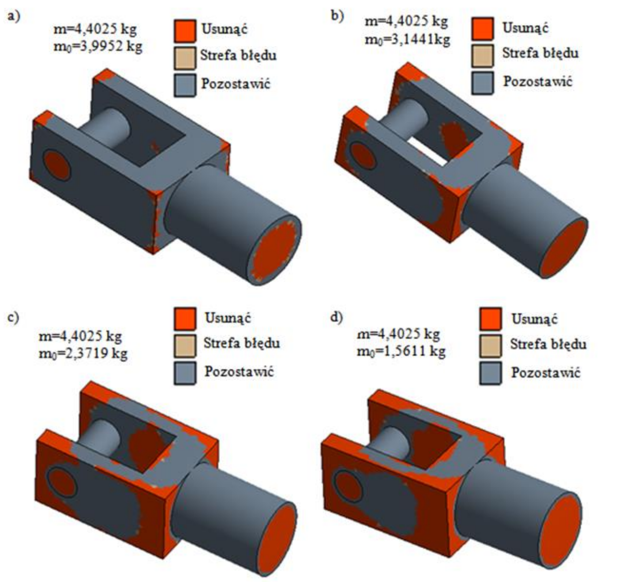


Fig. 10. Results of topological optimization for mass reduction factor α: a) for α=0,1, b) for α=0,3, c) for α=0,5 and d) for α=0,7

Conclutions

The paper presents a possibility of applying the variational and finite element methods for the analysis of physical phenomena in the technological processes.

The technological processes are geometrical, physical and thermal non-linear initial and boundary problem. Boundary conditions in the contact zone tool-object are not known. Measurement of a process parameters decide on the technological quality, such as: displacement, strain, stress, etc. during the process with nowadays technique of a measurement is impossible. About their course, we could conclude on the property of the product.

An application of modern mathematical modelling, numerical methods and computing systems allows an analysis of complex physical phenomena occurring in the process under investigation.

The obtained simulation results provide the basis for the next geometric parametric model (3D) taking into account the suggested changes - e.g. introduction of rounding radii, etc. The new geometrical model developed is the basis for carrying out static structural calculations and checking the required strength conditions.

The distributions of stresses obtained for different turning conditions, can be used of while designing machining: making a selection of the machining conditions and its optimising in the aspect of the technological quality of the product.

Good agreement numerical results with experimental results allows us to state that the effective discrete models were developed properly.

The methodology can be applied to the calculation of the state of strain, stress and temperature fields in other metal forming processes such as embossing of regular asperities before burnishing or thread rolling with electro contact heating and other technological processes i.e.: cutting processes, turning processes, burnishing rolling processes, cutting by an abrasive single grain, embossing, thread rolling, duplex burnishing, sliding burnishing and shot penning.

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Autorzy:

Prof. dr hab. inż. **Leon Kukiełka** – Politechnika Koszalińska, Wydział Mechaniczny

Dr inż. **Radosław Patyk** – Politechnika Koszalińska, Wydział Mechaniczny

Dr inż. **Krzysztof Kukiełka** – Politechnika Koszalińska, Wydział Mechaniczny

Dr inż. **Jarosław Chodór** – Politechnika Koszalińska, Wydział Mechaniczny

Mgr inż. **Krzysztof Lipiński** – Politechnika Koszalińska, Wydział Mechaniczny

Nowoczesne metody modelowania i analizy procesów technologicznych części samochodowych i ich optymalizacja topologiczna

W artykule przedstawiono problematykę modelowania i analizy numerycznej procesów technologicznych obróbki części samochodowych. Proces te rozpatrzono jako geometrycznie, fizycznie i cieplnie nieliniowe zagadnienie brzegowo-początkowe, z nieznanymi warunkami brzegowymi w obszarze kontaktu. Do opisu zjawisk nieliniowych, na typowym kroku przyrostowym, wykorzystano uaktualniony opis Lagrange'a, traktując narzędzie jako ciało sztywne lub termo-sprężyste natomiast przedmiot jako ciało termo-sprężyste/termo-lepko-plastyczne-fazowe. Równania ruchu obiektu i ciepła wyprowadzono wykorzystując rachunek wariacyjny. Otrzymane równania wariacyjne dyskretyzowano stosując aproksymację właściwą metodzie elementu skończonego. Dyskretne równania rozwiązano stosując jawne metody całkowania. Opracowano aplikacje w systemie ANSYS/LS-Dyna, które pozwalają na kompleksową analizę stanów przemieszczeń, odkształceń, naprężeń w dowolnym miejscu ciała i w dowolnej chwili realizacji procesu obróbki. Przedstawiono przykładowe wyniki obliczeń numerycznych stanów naprężeń i odkształceń wybranych procesów technologicznych: nagniatania, walcowania gwintów i toczenia. Wyniki obliczeń numerycznych weryfikowano eksperymentalnie. Przedstawiono również problematykę optymalizacji topologicznej części samochodowych.

Słowa kluczowe: części samochodowe, optmalizacja topologiczna, procesy technologiczne, obróbka plastyczna, warstwa wierzchnia, modelowanie, Metoda Elementu Skończonego.