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Ecological and Economical Aspects of Modern Modeling of Thread Rolling Process

Krzysztof Kukiełka
Politechnika Koszalińska

1. Introduction

Modern methods of plastic metals processing such as cutting processes (Bohdal & Walczak 2013, Bohdal & Kukielka L. 2014), cutting and burnishing processes sliding (Bohdal et al. 2014), cutting by an abrasive single grain (Chodór 2014, Forysiewicz et al 2016, Kukielka L. & Kustra 2003, Kukielka L. et al 2005), drawpiece forming process (Kałduński & Kukielka L. 2014) thread rolling (Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. et. al 2014, Kukiełka K. 2016, Kukiełka L. & Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012), duplex burnishing (Patyk & Kukielka L. 2008, Patyk et al 2014), burnishing rolling (Kukiełka L. 1994, Kukiełka L. 1999, Kukiełka L. & Krzyżyński T. 2000, Kukiełka L. 2001, Kukiełka L. 2002, Kukiełka L. et al 2012, Kukiełka L. et al 2012, Kułakowska et al 2009, Kułakowska, Kukiełka L et al 2014, Myśliński et al 2004), rolling process (Kowalik, 2010), shot penning (Zaleski & Bławucki 2014), grinding process (Sutowski & Nadolny 2016, Nadolny et al 2014), plastic deformations of measured object surface (Kowalik et al. 2016), surface roughness measured after machining (Valicek et al 2012, Kusnerova et al 2013) other like water jet cutting (Perec 2016) and mechanical/abrasive polishing (MP), standard electropolishing (EP) and magnetoelectropolishing (MEP) (Rokosz 2016), plasma cutting (Skoczylas & Zaleski 2015) and modern material behaviour modelling (Malag et al 2014).

In applications using a theoretical calculations and modelling processes precision machining of modern parts (Kukiełka L. 1994, Kukiełka L. 1999, Kukiełka L. & Krzyżyński T. 2000, Kukiełka L. 2001, Kukiełka L. et al 2012, Kukiełka L. et al 2014, Kukiełka L. & Kukiełka K 2015, Myślński et al 2004) are geometrical, physical and thermal nonlinear boundary–initial problem, where there are nonlinear, movable and variable in time and in time and state of: stress, strain and space heat sources and boundary conditions were described by using the incremental models. Wherein, the boundary conditions are unknown in the contact zones between the tool and workpieces.

The implementation of a new process into industrial practice is long process, laborious-, energy- and material-consuming. The traditional methods are based on the on multiple improvements of the prototype solutions until the established requirements regarding the quality of the product.

Whereas, very often are made the assumption that the processes are isothermal treatment and are realized on cold (Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. et al. 2014, Kukiełka K. 2016, Kukiełka L. & Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012) do not take into account the variability of thermophysical constant with temperature. This results in significant errors in both qualitative and quantitative. For example on Fig. 1 shows the influence of temperature on variation of the Poisson ratio and Young's modulus.

At present is required that the prepare production of new products apply the principle of "eco-design product," which base on reduce the negative impact on the surrounding natural environment of man. The dominant role in this action plays the rational use of energy and environment protection. In this case, an important step is the correct development and the proper implementation of the process.

This article is about a new method of modelling machining processes, including thermodynamics of physical phenomena. The methodology was developed in team of prof. L. Kukiełka with the author (Kukielka L. 1994, Kukielka L. 1999, Kukielka, L. & Krzyzynski 2000, Kukielka L. et al. 2012, Kukielka L. et al., Kukiełka L. & Kukiełka K. 2015). The application of the developed general methodology to solve complex problems of modelling specific problems seen in several examples of technology. In particular, it shows examples of modelling of thread rolling process.

One of the post-machining methods used to form the outer layer, characterized by advantageous exploitational properties, is thread rolling (Domblesky & Feng 2002, Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. et al. 2014, Kukiełka K. 2016, Kukiełka L.& Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012, Łyczko 2010, Olszak 2008). The increase of life and reliability of a product are achieved, mainly, by means of the consolidation and hardening of the surface layer, by generating a resultant small-gradient compressive stress and by the decrease of roughness where the volume of the surface load is increased. Thread rolling is usually considered as a cold process with no pre-heating of the elements and with rigid (Fig. 2) pressure of the threaded element[1] onto object.

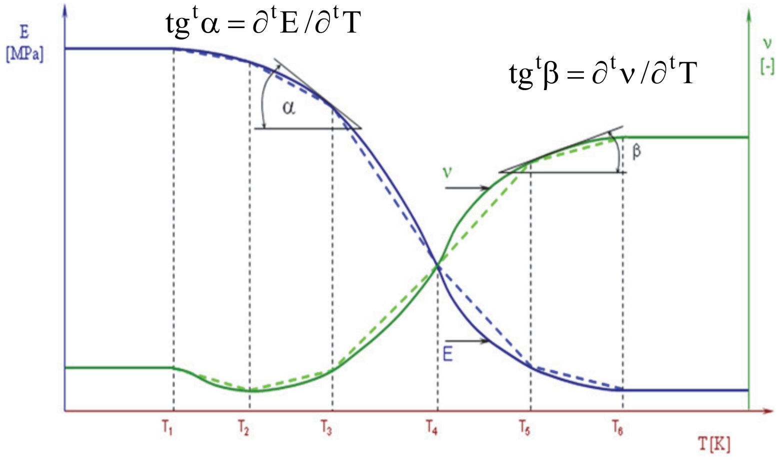

Fig. 1. Graphs of functions of Poisson's ratio ${}^t\nu = {}^t\nu({}^tT)$ and Young's modulus ${}^tE = {}^tE({}^tT)$ and a geometric interpretation of partial derivatives $\partial^t E / \partial^t T$ and $\partial^t \nu / \partial^t \nu$ in time t

Rys. 1. Wykresy funkcji współczynnika Poissona ${}^t\nu = {}^t\nu({}^tT)$ i modułu Younga ${}^tE = {}^tE({}^tT)$ oraz geometryczna interpretacja pochodnych cząstkowych $\partial^t E / \partial^t T$ i $\partial^t \nu / \partial^t \nu$ w chwili t

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[1] The rolling element (roller) constitutes that part of the tool which is indirect contact with the rolled surface of the object.

The thread rolling process is a new technological process, such as the thread rolling quick pitch, therefore directly contributes to reduce the negative impact of this process on the surrounding environment. The new method of thread rolling, developed at the Department of Automatics, Mechanics and Constructions at the Faculty of Mechanical Engineering Technical University of Koszalin (Kukiełka K. & Kukielka L. 2013).

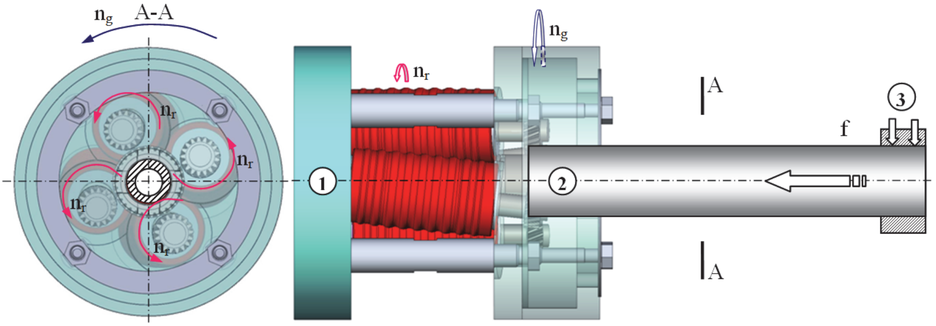

Fig. 2. The external thread rolling process schema on bars or pipe by rolling axial head with four rolls: 1 – head, 2 – blank, 3 – grip
Rys. 2. Schemat procesu walcowania gwintów łukowych na prętach lub rurach głowicą kątową czterorolkową metodą osiową: 1 – głowica, 2 – półwyrób, 3 – uchwyt

Knowledge of the physical phenomena with thermal phenomena occurring in the material in areas, where the threading element is in contact with the object and in the threading element while the thread process is carried out, is a basic necessity. It also enables the control of the properties of the outer layer of the product and achieving of the greatest shape-dimensional accuracy.

Thus, one of the most important technological problems in the thread rolling is the calculation of displacement, strain, stress and temperature in the surface layer.

So far there is no universal model of the thread rolling process and numerical algorithms for the analysis of these phenomena for various conditions of the process realization. The most frequently used regression equations obtained from the experimental investigations realized in accordance with the developed plan (Kukielka L. 1994, Kukielka L. 2002, Kukiełka K. 2009, Kukiełka K. 2014). Statistical relationships between a random variable was determined with the use of a statistical method of identification from the experimental data.

The analysis of the literature on the rolling process, e.g. (Domblesky & Feng 2002, Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. 2014, Kukiełka K. 2016, Kukiełka L.& Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012, Łyczko 2010, Olszak 2008), own studies and computer simulations (Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. et al. 2014, Kukiełka K. 2016, Kukiełka L. & Kukiełka K. 2006, Kukiełka L. & Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012) shows that the technological quality of the rolled thread, can influence from the following factors:

1) Material factors: Young's modulus, Poisson ratio, initial yield point, plastic hardening modulus, sensitivity on the strain rate, plastic anisotropy, value of border-strain, inclination to brittle cracking;
2) Geometrical of the thread and tool factors: thread dimensions, outside diameter and wall thickness of the pipe, surface state and physical state of surface layer zones (state of stress) of the pipe after preceded treatment, roller geometry, number and spacing of the rolls, kind of the tool profile (in the shape of screw line or ring-shaped), material and set of the rest, single or multi-turn thread);
3) Technological parameters (depends of the rolling mill type and special head): speed of the roller put in, rolling speed, contact force;
4) Friction conditions in the contact zones (depends of the kind of lubricant): friction moment, friction forces;

and for its complex analysis it is necessary to develop adequate mathematical model and numerical methods of solving it.

This work describes the thread rolling as a real object and its physical and mathematical modelling. The update Lagranian description (Bathe 1982) has been used to describe nonlinear phenomena, on a typical incremental step, assuming the stepwise and co-rotational coordinate system. The states of strain and strain rate have been described by mean of nonlinear dependence without any linearization. The proper measures of strain and stress increments, i.e. the increment of Green-Lagrange's strain tensors and the increment of the second symmetric Pioli-Kirchhoff's strain tensors were applied. The nonlinearity of the material was described using the incremental model, making allowance for the effects of strain, strain rate and temperature history. The work pieces (pipe or bar) have been considered treating an object as a body which can undergo elastic strains or thermo-elastic strains (in the reversible zone) and thermo-visco-plastic and phasis (in non-reversible zone). The material model was prepared making use of Huber-Mises-Hencky's nonlinear condition of thermo-plasticity, the associated law of flow and the mixed (isotropic-kinematical) strain hardening. The state of material after preprocessing was also taken into consideration introducing the initial conditions of displacement, strain, strain rate, stress and temperature. The incremental contact model obtained comprises the contact forces, contact rigidity, contact boundary conditions and friction conditions in this area (Kukiełka K. 2009). Then, the incremental functional of the total system energy and enthalpy, were derived. From stationary condition of this functionals derived variational, nonlinear two equations: one of motion and deformation of object and the second - heat transfer on the typical incremental step time $t \rightarrow \tau = t + \Delta t$. These equations has been solved with finite element spatial discretization, where the discrete system of motions and deformations equations of objects and heat transfer in the thread rolling process, were received. This model with initial and boundary conditions are used to numerical analysis of deformation and temperature in the thread rolled.

2. Algorithm of thermo-mechanical modelling and numerical analysis of the thread rolling process

The incremental mathematical model of thread rolling process, in the updated Lagrange formulation, contain the constitutive equations (model of thermo-dynamical yield stress, thermo-elastic/thermo-visco-plastic-phasis strains model, thermo-elastic/ thermo-visco-plastic-phasis 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, and heat transfer for a typical step time. Then, these equations with Finite Element Method (FEM) were discretized, given the equations of motion and deformation and heat transfer of a discrete object. Then, the explicit (DEM) scheme to step by step numerical solution is adopted.

The algorithms of numerical analysis without of temperature (on cold) in ANSYS program for different technological processes were elaborated (Domblesky & Feng 2002, Kukiełka K. 2009, Kukiełka K. & Kukielka L. 2013, Kukiełka K. 2014, Kukiełka K. et al. 2014, Kukiełka K. 2016, Kukiełka L. & Kukiełka K. 2006, Kukiełka L. & Kukiełka K. 2007, Kukiełka L. & Kukiełka K. 2012, Kukiełka L. & Kukiełka K. 2015), where discrete equations was applied together with initial and boundary conditions. Especially, modelling of the thread rolling process, including the mechanics of the process are shown in publications (Kukiełka K. 2009, Kukiełka K. 2016, Kukiełka L. & Kukiełka K. 2012, Kukiełka L. et al 2014) (Fig. 3).

For approve the design and control of thread rolling process, knowledge of the course of thermal distribution and temperature fields in the system (object-tool) is needed.

The paper presents a physical model of thermal phenomena in thread rolling process and description of the heat sources in an incremental differential equation with appropriate initial and boundary conditions for temperature.

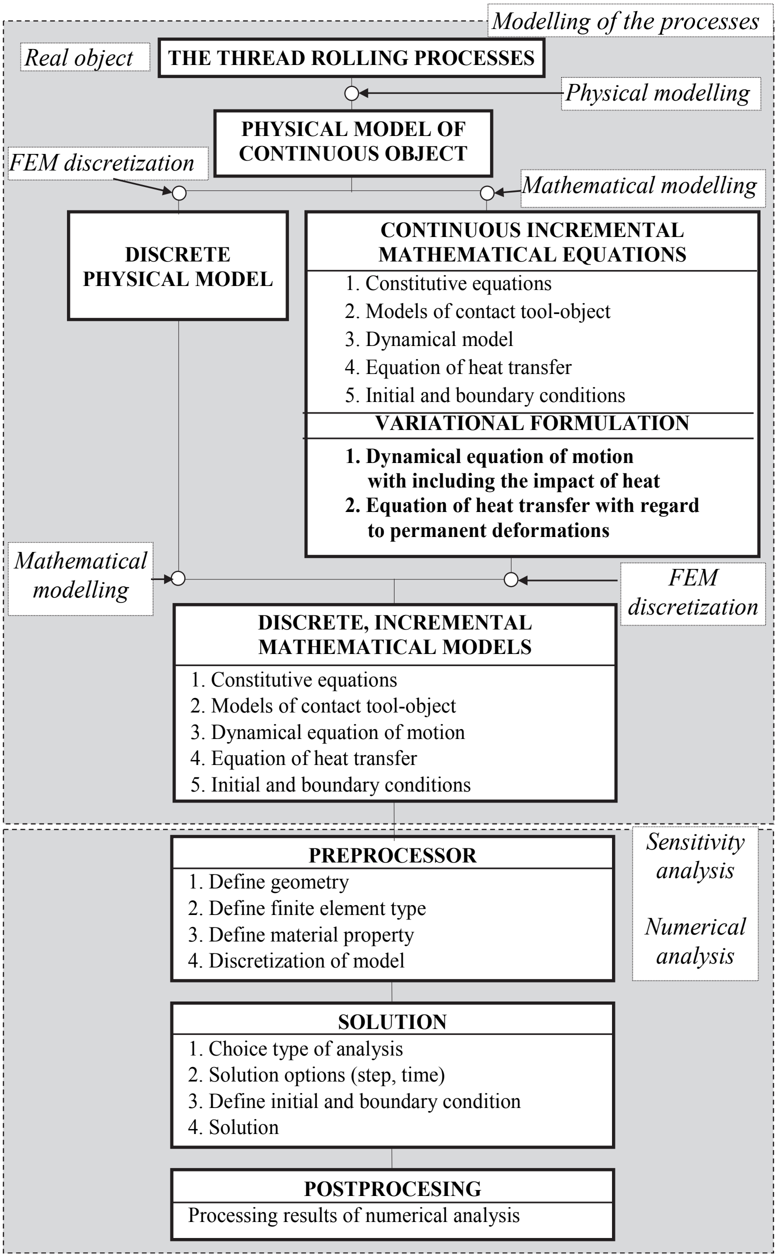

Fig. 3. Scheme of modern modelling and analysis of thread rolling process
Rys. 3. Schemat modelowania i analizy procesu walcowania gwintów

2.1. Mathematical incremental model of heat transfer

Uses an updated Lagrange description, assuming knowledge of the temperature field in the initial moments t_0 and present time t, while looking for a solution to the next time $\tau = t + \Delta t$, where Δt is a very small incremental of time (Bathe 1982). Then the equation for a typical incremental step $t \rightarrow \tau$, in the global coordinate $\{z\}$ is assumed:

$$\mathrm{div}\{\lambda(T)\cdot \mathrm{grad}[\Delta T(z,\Delta t)]\} + \Delta q_{VD}[\cdot] = C(T)\cdot \rho(T)\cdot \Delta\dot{T}(z,\Delta t), \tag{1}$$

where:

$$\Delta\dot{T}(\mathbf{z},\Delta t) = \frac{\partial[\Delta T(\mathbf{z},\Delta t)]}{\partial\, t} \tag{2}$$

is the speed of incremental of the temperature,
$\lambda(T), C(T), \rho(T)$ are depended on the temperature in the time t: heat conductivity, heat capacity and mass density, however:

$$\begin{aligned}\Delta q_{VD}[\cdot] = {} & \frac{(1-\xi)\cdot{}^{\tau}V}{t+\Delta t}\int_{{}^{t}_{t}\varepsilon_i^{(VP)}}^{{}^{\tau}_{\tau}\varepsilon_i^{(VP)}} {}^{\tau}_{\tau}\sigma_Y({}^{\tau}_{\tau}\varepsilon_i^{(VP)},\ {}^{\tau}_{\tau}\dot{\varepsilon}_i^{(VP)},\ {}^{\tau}T) + \\ & -\frac{(1-\xi)\cdot{}^{t}V}{t}\int_{{}^{t-\Delta t}_{t-\Delta t}\varepsilon_i^{(VP)}}^{{}^{t}_{t}\varepsilon_i^{(VP)}} {}^{t}_{t}\sigma_Y({}^{t}_{t}\varepsilon_i^{(VP)},\ {}^{t}_{t}\dot{\varepsilon}_i^{(VP)},\ {}^{t}T),\end{aligned} \tag{3}$$

are the rate of incremental spatial heat sources generated by visco-plastic deformation, where ${}^{\tau}_{\tau}\sigma_Y({}^{\tau}_{\tau}\varepsilon_i^{(VP)},\ {}^{\tau}_{\tau}\dot{\varepsilon}_i^{(VP)},\ {}^{\tau}T)$ is accumulated yield stress, depending on the history of visco-plastic strain $\varepsilon_i^{(VP)}$ and strain rate $\dot{\varepsilon}_i^{(VP)}$ and temperature T, $\xi = 0.05 \div 0.1$ is the coefficient energy absorption.

2.2. Initial and boundary conditions for temperature

The equation of heat transfer (1) is completed with the initial condition and the four boundary conditions.

Initial condition

Initial condition describes the temperature field at time which is the initial moment:

$$T(\mathbf{z}, t = t_0) = T_0(\mathbf{z}), \quad \mathbf{z} \in V. \tag{4a}$$

In typical processing conditions thread rolling, the temperature of the object at time $t = t_0$ is constant then:

$$T(\mathbf{z}, t = t_0) = T_0 = \text{const}, \tag{4b}$$

where T_0 is ambient temperature.

Boundary conditions

- *conditions of I gender* - the temperature may be prescribed at specific points in the surfaces, denoted by Σ_T, and/or at the specific points in the volume of the body, denoted by V_T:

$$T(\mathbf{z}, t) = T_o(\mathbf{z}, t), \text{ or } \Delta T(\mathbf{z}, \Delta t) = \Delta T_o(\mathbf{z}, \Delta t), \ \mathbf{z} \in \Sigma_T \tag{5}$$

- *conditions of II gender* – in the contact area tool and object Σ_k, heat flows:

$$-\lambda_o(T)\, \mathbf{n} \circ \text{grad}\, [\Delta T_o(\mathbf{z}, \Delta t)] = b_o \Delta q_{F\mu}, \ \mathbf{z} \in \Sigma_k, \tag{6a}$$

$$-\lambda_b(T)\, \mathbf{n} \circ \text{grad}\, [\Delta T_b(\mathbf{z}, \Delta t)] = b_b \Delta q_{F\mu}, \ \mathbf{z} \in \Sigma_k, \tag{6b}$$

- *conditions of III gender* (continuity of the heat flows):

$$-\lambda_o(T)\mathbf{n} \circ \text{grad}[\Delta T_o(\mathbf{z}, \Delta t)] = \frac{\Delta T_o(\mathbf{z}, \Delta t) - \Delta T_b(\mathbf{z}, \Delta t)}{R_s(\mathbf{z}, \Delta t)} =$$

$$= -\lambda_b(T)\mathbf{n} \circ \text{grad}[\Delta T_b(\mathbf{z}, \Delta t)], \ \mathbf{z} \in \Sigma_k, \tag{7}$$

where R_s is the heat resistance in the surface contact (for ideal contact R_s=0), b_o and b_b is the heat division coefficients for roller (b) and object (o), $\mathbf{n} \circ \text{grad}[\Delta T(\cdot)]$ is the scalar product, $\Delta q_{S\mu}[\cdot]$ is the rate of incremental surface heat sources generated by fretting per unit surface,

- *conditions of IV gender* – they are in areas Σ_C i Σ_R, in which exchange heat is on road convection and radiation, then the boundary conditions is defined by:

$$\Delta q_C = \alpha_C(T) \cdot \Delta T = -\lambda(T)\mathbf{n} \circ \text{grad}[\Delta T(\mathbf{z}, \Delta t)], \mathbf{z} \in \Sigma_C, \tag{8a}$$

$$\Delta q_R = \alpha_R(T) \cdot \Delta T = -\lambda(T)\mathbf{n} \circ \text{grad}[\Delta T(\mathbf{z}, \Delta t)], \ \mathbf{z} \in \Sigma_R, \tag{8b}$$

where Δq_C and Δq_R are incremental intensity flow heat exchange with the environment by convection and radiation, $\alpha_C(T)$ and $\alpha_R(T)$ are temperature - dependent convection coefficient and radiation coefficient (Staniszewski 1982).

Equation (1) with initial condition (4) and boundary conditions (5)÷(8) are a full mathematical description of heat transfer during the thread rolling, at the typical incremental time step. The analytical solution is impossible, therefore variational formulation was introduced.

2.3. Variational formulation equations of heat transfer

For the variational formulation of the equations of heat transfer in the thread rolling, at the typical time step, introduced an incremental functional $\Delta\mathbf{F}(\Delta\dot{T}, \Delta T', \Delta T,...)$, in which is one independent field – it is temperature field, and its derivatives: $\Delta\dot{T} = d(\Delta T)/dt$, $\Delta T' = d(\Delta T)/dy_3$. This functional has differential equation (1) in the global Cartesians co-ordinate {z} and boundary conditions (5)÷(8). It is:

$$\begin{aligned}\Delta\mathbf{F}[\Delta\dot{T},\Delta T',\Delta T] &= \frac{1}{2}\int_V\left(\sum_{i=1}^{3}\lambda_i(T)\cdot L_{zi}^2(\Delta T)\right)\cdot dV + \int_V \Delta\dot{T}\cdot c(T)\cdot\rho(T)\cdot\Delta T\cdot dV\\ &-\int_V \Delta q_{VD}[\cdot]\cdot\Delta T\cdot dV - \int_{\Sigma_k} b\cdot\Delta q_{S\mu}[\cdot]\cdot\Delta T\cdot d\Sigma_k + \int_{\Sigma_k}\frac{\Delta T_o-\Delta T_b}{2R_s}\cdot\Delta T\cdot d\Sigma_k \qquad (9)\\ &\frac{1}{2}\int_{\Sigma_C}\alpha_C(T)\cdot\Delta T^2\cdot d\Sigma_C + \frac{1}{2}\int_{\Sigma_R}\alpha_R(T)\cdot\Delta T^2\cdot d\Sigma_R - \int_{\Sigma_T}\Delta T_b\cdot\Delta T\cdot d\Sigma_T,\end{aligned}$$

where the integrations are performed over the volume *V* and surface *Σ* of the body, respectively, $L_{zi}^2(\Delta T) = \partial^2(\Delta T)/\partial z_i^2$ is the differential operator.

Using the conditions of stationarity of functional (9):

$$\delta[\Delta\mathbf{F}(\Delta\dot{T},\Delta T',\Delta T)] = \frac{\partial[\Delta\mathbf{F}(\cdot)]}{\partial(\Delta T)}\delta(\Delta T) = 0, \qquad (10)$$

we obtain (because ΔT is the only variable) in the global system {z}:

$$\begin{aligned}\delta[\Delta\dot{T},\Delta T',\Delta T] &= \int_V\left[\sum_{i=1}^{3}\lambda_i(T)\cdot\frac{\partial(\Delta T)}{\partial z_i}\cdot\delta\left(\frac{\partial(\Delta T)}{\partial z_i}\right)\right]\cdot dV\\ &+\int_V\frac{\partial(\Delta T)}{\partial t}\cdot C(T)\cdot\rho(T)\cdot\delta(\Delta T)\cdot dV\\ &+\int_V\delta\left(\frac{\partial(\Delta T)}{\partial t}\right)\cdot C(T)\cdot\rho(T)\cdot\Delta T\cdot dV \qquad (11)\\ &-\int_V\Delta q_{VO}[\cdot]\cdot\delta(\Delta T)\cdot dV - \int_{\Sigma_k} b\cdot\Delta q_{F\mu}[\cdot]\cdot\delta(\Delta T)\cdot d\Sigma_k\\ &+\int_{\Sigma_k}\frac{\Delta T_o-\Delta T_b}{2R_s}\cdot\delta(\Delta T)\cdot d\Sigma_k + \int_{\Sigma_C}\alpha_C(T)\cdot\delta(\Delta T)\cdot d\Sigma_C\\ &+\int_{\Sigma_R}\alpha_R(T)\cdot\delta(\Delta T)\cdot d\Sigma_R - \int_{\Sigma_T}\Delta T\cdot\delta(\Delta T)\cdot d\Sigma_T = 0.\end{aligned}$$

Equation (11) is variational formulation of heat transfer at the typical step time in updated Lagrange's description in thread rolling process.

2.4. Implementation of the finite element method

Assume that the complete body under consideration has been idealised as an assemblage of finite elements, we have, at step time t→t+Δt for element e and m:

$$\begin{aligned}
&\Delta T^{(e)}(\cdot)=[\mathbf{H}^{(e)}(\cdot)]\cdot\{\Delta\boldsymbol{\Theta}^{(e)}\},\ \Delta T'^{(e)}(\cdot)=[\mathbf{B}^{(e)}(\cdot)]\cdot\{\Delta\boldsymbol{\Theta}^{(e)}\},\\
&\Delta T'^{(e)}(\cdot)=[\mathbf{B}_3{}^{(e)}(\cdot)]\cdot\{\Delta\boldsymbol{\Theta}^{(e)}\},\Delta T^{(m)}(\cdot)=[\mathbf{H}^{S(m)}(\cdot)]\cdot\{\Delta\boldsymbol{\Theta}^{(m)}\},\\
&\Delta\dot{T}^{(e)}(\cdot)=[\mathbf{B}^{(e)}(\cdot)]\cdot\{\Delta\dot{\boldsymbol{\Theta}}^{(e)}\},
\end{aligned}\tag{12}$$

where: $\Delta T^{(e)}$ is the temperature increment of finite element *e*, $\{\Delta\boldsymbol{\Theta}^{(e)}\}$ and $\{\Delta\dot{\boldsymbol{\Theta}}^{(e)}\}$ are vectors of increments in the nodal point temperature and of increments in the nodal point temperature rate, at all *n* nodal points, respectively (Kukielka L. 1998). Using the relation in (12) and substituting into the variational equation (11), we obtain the discretized equation of heat transfer equilibrium in the global coordinate {z} (the non stabilized heat transfer):

$$[\mathbf{C}]\{\Delta\dot{\boldsymbol{\Theta}}\}+([\mathbf{K}^{K}]+[\mathbf{K}^{C}]+[\mathbf{K}^{R}]+[\mathbf{K}^{IV}])\{\Delta\boldsymbol{\Theta}\}=\{\Delta\mathbf{Q}\}+\{\Delta\mathbf{Q}^{I}\}\tag{13}$$

where [**C**] and $[\mathbf{K}^{K}]$, $[\mathbf{K}^{C}]$, $[\mathbf{K}^{R}]$, $[\mathbf{K}^{IV}]$ are the heat capacities, conductivity, convection and radiation matrices and total nodal point conditions of IV gender, $\{\Delta\mathbf{Q}\}$ is the nodal point increment heat flow input vector, $\{\Delta\mathbf{Q}^{I}\}$ is the vector of nodal point of the boundary conditions of I gender.

The solution of equation (13) with initial (4a-4b) and boundary (5, 6a, 6b, 7, 8a and 8b) conditions and experimental verification of the results shown in article (Kukielka K. 2017).

3. Conclusions

Till now, the thread rolling process, was described by regression equations. This is the so-called phenomenological approach, using the principle of „black box". These equations although received correctly are limited to use in the same as treatment conditions when was examinated. Also, it is impossible to get established, particularly high requirements shaped thread. Also, it is not possible to obtain assumed, in particular high requirements of the shaped thread. These imperfections can be eliminated by increasing the accuracy of the modeling and analysis of the machining process. The complexity of the occurring physical phenomena and geometrical, physical and thermal non-linearity of the process, the partial knowledge of the boundary conditions require the use of adequate incremental description. That descriptions is updated Lagrange description, in which all searched quainties on the incremental step are related to the configuration of the well-known, established on the previous step. For this description a dynamic model of rolling process was developed and specifies the conditions for uniqueness, assuming that the work-piece is made of thermo-elastic/thermo-visco-plastic-phasis material with non-linear mixed hardening. Excessive complexity of the model means that it is impossible its analytical solution. It is possible an approximate solution on the numerical way.

In researches is made simplification like the thread rolling process is carried out on cold and doesn't include influence on variation of constant from temperature. As a result, there are significant differences in the predicted and obtained thread and are too large deviations of dimensions and shape of the thread.

Increasing the shaping accuracy of the thread technological quality makes it necessary to increase accuracy of modelling and analysis of physical phenomena occurring in the thread rolling process. Described in this paper thermo-mechanical contact problem is a basic problem. The complex nature of phenomena occurring during the contact and the difficulties in their study force us to look for a solutions in the theoretical way. Occurring geometrical, physical and thermal nonlinearity, also only a partial knowledge of boundary conditions, which are moving in the process make it necessary to apply incremental description.

The external thread rolling with round profile is a complex in process technological terms. The thread rolling process is a geometrical, physical and thermal non-linear initial and boundary problem. Measurement of a process parameters decide on the technological quality, such as: a displacement zone, a temperature, stress, structural change etc. during the thread rolling process with nowadays technique of a measurement is impossible. About their course, we could conclude on the property of the product after rolling.

It has been shown that the thread rolling process can be described by incremental mathematical models in an updated Lagrangian description: constitutive equations thermo-dynamic yield stress, strain and stress, the contact model, the equations of motion and deformation also equation of heat transfer of the object and the initial and boundary conditions.

Developed incremental mathematical models of motion and deformation of the object allow for complex analysis of the phenomena occurring during the thread rolling process by using Finite Element Method. Applied incremental models allow to solve many problems without knowing the boundary conditions in the contact zone. So far, in order to solve the equations of motion of the object and heat transfer with the corresponding boundary conditions for the displacements, these conditions had to be assumed or experimentally determined.

The paper presents a possibility of applying the variational and finite element methods for the analysis of heat transfer in thread rolling operation.

The developed methodology step by step solutions allows for:

- effective scheme solutions, various constitutive models,
- the ability to analyze a variety of physical problems: displacement, strain, stress and temperature,
- the opportunity to load a variety of boundary conditions and kinematic and thermal constraints,
- the opportunity to load a variety of initial conditions (and history),
- efficient algorithm for analysis of the contact issue.

An own application in ANSYS program for the thread rolling process were elaborated. Numerical analysis let for forecast behavior of rolled thread during whole multistage technological process. For the most important possibilities of the numerical analysis in application for the thread rolling is determination of:

- dimensions of the pipe before rolling (mainly nominal and outline diameter),
- local strain, stress and temperature states in the thread,
- geometry and thread outline during thread rolling and after elastic relieving,

- maximum strain – where crack of the thread is possible,
- expected rolling force,
- influence of the friction coefficient on the process flow and quality of the thread,
- number and geometry of the rolls, in that active rolls surface in the introducing, shaping, calibrating and outing zone,
- state of loads, stresses and strains of the tools,
- areas of contact, slip and stick.

The developed models and methodology for the analysis of physical phenomena in the thread rolling process increase the accuracy of the modeling and prediction of the thread properties and the quality of the thread on the design stage, without the need for complex, costly and harmful for the environment experimental research.

One of the major environmental advantages of the thread rolling process, unlike to the machining, is using rolling technology as volume plastic working, it is possible to make threads with usage of the full material (Kukiełka K. 2016, Łyczko 2010). The diameter of the workpieces (bar) for the rolled thread is smaller compared to the diameter of the machined thread, which results measurable savings of the material. This eliminates the chip waste management, which also reduces production costs.

Use of radial thread rolling method provides significant savings in the form of shortening the threading time due to the traditional of thread forming, which reduce production cost and saving energy (Kukiełka K. 2016). However, if those threads are made by turning process the threading time is extend minimum two time higher then rolling (Kukiełka K. 2009, Kukiełka K. 2016, Łyczko 2010).

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Ekologiczne i ekonomiczne aspekty nowoczesnego modelowania procesu walcowania gwintów

Streszczenie

W pracy przedstawiono nowoczesny sposób opracowania numerycznego modelu procesu walcowania gwintów przy wykorzystaniu rachunku wariacyjnego i Metody Elementów Skończonych oraz analizowano wpływ najważniejszych parametrów obróbki. Proces walcowania gwintów rozpatrywano jako geometrycznie, fizycznie oraz termicznie nieliniowy problem, z nieznanymi warunkami brzegowymi w strefie kontaktu narzędzia i przedmiotem.

Opisu nieliniowości materiału dokonano modelem przyrostowym uwzględniając wpływ historii odkształceń, prędkości odkształceń i temperatury. Przedmiot (pręt lub rurę) traktuje się, jako ciało, w którym mogą wystąpić odkształcenia termo-sprężyste (w zakresie odkształceń odwracalnych) oraz termiczne, lepkie, plastyczne i fazowe (w zakresie odkształceń nieodwracalnych), z nieliniowym umocnieniem. Ciało to oznaczono skrótowo TE/TVPF (termo-sprężyste/termo-lepko-plastyczno-fazowe). Do budowy modelu materiałowego zastosowano nieliniowy warunek termo-plastyczności Hubera-Mises'a-

Hencky'ego, stowarzyszone prawo płynięcia oraz wzmocnienie mieszane (izotropowo-kinematyczne). Uwzględniono również stan materiału po obróbkach poprzedzających przez wprowadzenie początkowych stanów: przemieszczeń, naprężeń, odkształceń, temperatury i ich prędkości. Model matematyczny uzupełniono przyrostowymi równaniami ruchu ciepła oraz warunkami jednoznaczności. Następnie, wprowadzono funkcjonał przyrostowy całkowitej entalpii układu. Z warunku stacjonarności tego funkcjonału wyprowadzono wariacyjne, nieliniowe równanie ruchu ciepła w obiekcie dla typowego kroku przyrostowego.

Abstract

In this study, a modern way to develop a numerical model of the thread rolling process was shown by using variational formulation and the finite element method also the effect of the main process parameters were analyzed. The thread rolling process was considered a geometrical, physical and thermal nonlinear problem with unknown boundary conditions in the contact area of the system, such as the tool and workpiece.

The nonlinearity of the material was described using the incremental model, making allowance for the effects of strain, strain rate and temperature history. The work pieces (pipe or bar) have been considered treating an object as a body which can undergo thermo-elastic strains (in the range of reversible strain), thermo, viscous, plastic and phasis (in the range of permanent strains). This body (thermo-elastic/thermo-visco-plastic-phasis) has been designated as TE/TVPF. The material model was prepared making use of Huber-Mises-Hencky's nonlinear condition of thermo-plasticity, the associated law of flow and the mixed (isotropic-kinematical) strain hardening. The state of material after pre-processing was also taken into consideration introducing the initial conditions of displacements, strains, stresses, temperature and their rates. Then, the incremental functional as the total enthalpy of the system, were derived. From stationary condition of this functional, nonlinear variational equation of motion and heat transfer for object on the typical incremental step time was derived.

Słowa kluczowe:
walcowanie gwintów, eko-modelowanie, ekologiczne procesy technologiczne, sformułowanie wariacyjne, metoda elementów skończonych

Keywords:
thread rolling, eco-modelling, ecological technological process,
variational formulation, Finite Element Method