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THERMOMECHANICAL MODELIG AND ANALYSIS OF THE THREAD ROLLING PROCESS WITH ELECTROCONTACT HEATING

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Abstract: *The work presents application of the variational and finite element methods for the modelling and analysis of the physical phenomena in the thread rolling operation with electric current. This process is considered as geometrical, physical and thermal nonlinear boundary–initial problem with surface (as a result of friction and the flow of electrical current by contact zone) and volume heat source (as a result of visco-plastic deformation and the flow of electrical current), which move with the tool. But the boundary conditions for displacement and temperature are not known in the contact zone. Physical and mathematical model of the process of thread rolling and an thermo-elastic (for reversible zone) and thermo-visco-plastic (for non reversible zone) material model have been elaborated. The model takes into account the strain, strain rate, temperature histories of the material and the impact of visco-plastic deformation of the body on temperature rise.*

Keywords: Thread rolling process, Constitutive laws, Modelling, Variation formulation, FEM, DEM.

1. Introduction

This article is about a new method of modelling and analysis of the thread rolling 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. et al., 2012; Kukielka L. et al., 2014).

Wheras, very often are made the assumption that the processes are isothermal treatment and are realized on cold (Kukiełka K. et al., 2014; Kukiełka K., 2016) do not take into account the variability of thermo-physical constant with temperature. This results in significant errors in both qualitative and quantitative.

In applications using a theoretical calculations and modelling processes precision machining of modern parts (Kukiełka L., 1999; Kukiełka L., 2001; Kukiełka L. et al., 2015; Kukiełka L. et al., 2016; Myśliński 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 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.

Proposed in this paper a new way through the centerless rolling doesn't have the above drawbacks (Kukiełka K. et al., 2014; Kukiełka K., 2016; Kukiełka K. et al., 2013; Kukiełka L. et al., 2006). The analysis of the literature and own experimental studies and computer simulations shown (Kukiełka K. et al., 2014; Kukiełka K., 2016; Kukiełka L. et al., 2006; Kukiełka L. et al., 2007; Patyk et al., 2014), that the thread forming with desirable technological quality in the rolling process is very complex problem, because it depends significantly on many factors, which can be divided into four groups: factors and material, geometric factors and tools thread, technological parameters, force pressure, torque and friction force (type of lubricant) (Kukielka K., 2016; Kukielka K., 2017). Therefore, for a comprehensive analysis process it is necessary to develop adequate mathematical model and numerical methods of solving them.

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2. MODELLING OF HEAT TRANSFER

For the design and control of TRWC 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. It uses the application of the variational methods to modelling the temperature field during the thread rolling operation with electric current.

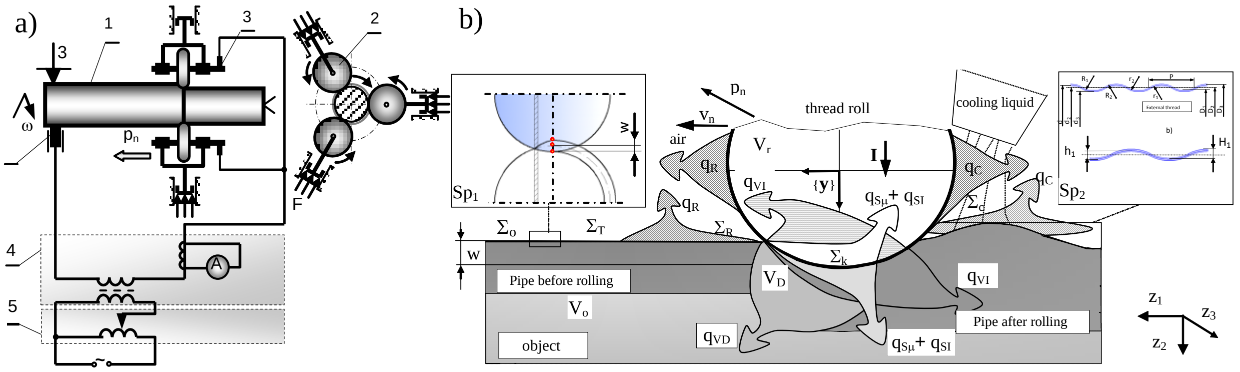

Fig. 1: a) Scheme thread rolling: 1 – workpiece, 2 – roller, 3 – brush plate, 4 – transformer, 5 – autotransformer; b) Diagram of the system of heat fluxes arising in characteristic volumes V and areas ∑ during thread rolling: pipe before rolling and pipe after - surface of the object and outer layer after previous treatment and after rolling, respectively.

2.1. Heat sources in the thread rolling with electric current

The TRWC process is performed with high speed heat sources which move with tool. Depending on where they occur, it is divided into (Fig. 1b):

- **plane** with capacities $q_{F\mu}$ (by friction tool-object) and q_{FI} (as a result of flow electrical current through the contact zone with electrical contact resistance R_S), they are in the contact area Σ_k tools with object,
- **spacious** with capacities q_{VO} in the zone of plastic deformation of the material, while the sources with capacities q_{VI} are in volumes tools and the object through which an electric current flows.

2.2. 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 (Kukielka L., 1999; Kukielka L. et al., 2012; Kukielka L., et al., 2014). Then the equation for a typical incremental step $t \rightarrow \tau$, in the global coordinate $\{\mathbf{z}\}$ is assumed:

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

where $\Delta\dot{T}(\mathbf{z},\Delta t) = \partial[\Delta T(\mathbf{z},\Delta t)]/\partial t$, is the speed of the temperature increment, $\lambda(T), C(T), \rho(T)$ are depended on the temperature in the initial step: heat conductivity, heat capacity and mass density, however:

$$\Delta q_{VI}[\cdot] = k_e\cdot\left[\frac{{}^\tau I^2\cdot{}^\tau R({}^\tau T)}{{}^\tau V} - \frac{{}^t I^2\cdot{}^t R({}^t T)}{{}^t V}\right] = k_e\cdot\left[\left(\frac{{}^\tau I}{{}^\tau S_\Sigma}\right)^2\cdot{}^\tau\rho_1({}^\tau T) - \left(\frac{{}^t I}{{}^t S_\Sigma}\right)^2\cdot{}^t\rho_1({}^t T)\right] \qquad (2)$$

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

are the rate of incremental spatial heat sources generated by electrical current (2) and by visco-plastic deformation (3), where $\sigma_Y(\varepsilon_i^{(VP)}, \dot{\varepsilon}_i^{(VP)}, T)$ 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, $R(T)$ is temperature-dependent electrical resistance of material, $\rho_1(T)$ is temperature-dependent resistivity of material, S_Σ is the field of the areas contact Σ_k, $\xi = 0.05 \div 0.1$ is the coefficient energy absorption, k_e is the coefficient (for constant current $k_e = 1$ and $k_e = 0.7 \div 0.97$ for alternating current).

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: $\mathrm{T}(\mathbf{z}, \mathrm{t} = \mathrm{t}_0) = \mathrm{T}_0(\mathbf{z})$, $\mathbf{z} \in V$. In typical processing conditions TRWC, the temperature of the object at time $\mathrm{t} = \mathrm{t}_0$ is constant then: $\mathrm{T}(\mathbf{z}, \mathrm{t} = \mathrm{t}_0) = \mathrm{T}_0 = \mathrm{const}$, 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.

conditions of II gender – in the contact area tool and object Σ_k, (heat flows).

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

$$\begin{aligned} -\lambda_o(T)\mathrm{n} \circ grad[\Delta T_o(\mathrm{z}, \Delta t)] &= [\Delta T_o(\mathrm{z}, \Delta t) - \Delta T_b(\mathrm{z}, \Delta t)] / R_s(\mathrm{z}, \Delta t) = \\ &= -\lambda_b(T)\mathrm{n} \circ grad[\Delta T_b(\mathrm{z}, \Delta t)], \end{aligned} \qquad \mathbf{z} \in \Sigma_k, \qquad (4)$$

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 rolling element *(b)* and object *(o)*, $\mathbf{n} \circ \mathrm{grad}[\Delta\mathrm{T}(\cdot)]$ is the scalar product, $\Delta \mathrm{q}_{\mathrm{SI}}[\cdot]$ and $\Delta \mathrm{q}_{\mathrm{S\mu}}[\cdot]$ are the rate of incremental surface heat sources generated by electrical current (heat of Joule's) and 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.

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

Variational formulation equations of heat transfer

For the variational formulation of the equations of heat transfer in the TRWC, at the typical time step, introduced an incremental functional $\Delta\mathbf{F}(\Delta\dot{\mathrm{T}}, \Delta\mathrm{T}', \Delta\mathrm{T}, \ldots)$, in which is one independent field – it is temperature field, and its derivatives: $\Delta\dot{\mathrm{T}} = \mathrm{d}(\Delta\mathrm{T}) / \mathrm{dt}$, $\Delta\mathrm{T}' = \mathrm{d}(\Delta\mathrm{T}) / \mathrm{dy}_3$. This functional has differential equation (1) in the global Cartesians coordinate $\{\mathbf{z}\}$ and boundary conditions. When using the conditions of stationarity of functional:

$$\delta[\Delta\mathbf{F}(\Delta\dot{\mathrm{T}}, \Delta\mathrm{T}', \Delta\mathrm{T})] = \{\partial[\Delta\mathbf{F}(\cdot)] / \partial(\Delta\mathrm{T})\}\, \delta(\Delta\mathrm{T}) = 0, \qquad (5)$$

and using the approximations adequate to the finite element method we obtain the discretized equation of heat transfer equilibrium in the global coordinate *{z}* (the non stabilized heat transfer):

$$[\mathbf{C}]\{\Delta\dot{\mathbf{\Theta}}\} + ([\mathbf{K}^{\mathrm{K}}] + [\mathbf{K}^{\mathrm{C}}] + [\mathbf{K}^{\mathrm{R}}] + [\mathbf{K}^{\mathrm{IV}}])\{\Delta\mathbf{\Theta}\} = \{\Delta\mathbf{Q}\} + \{\Delta\mathbf{Q}^{\mathrm{I}}\} \qquad (6)$$

where $[\mathbf{C}]$ and $[\mathbf{K}^{\mathrm{K}}]$, $[\mathbf{K}^{\mathrm{C}}]$, $[\mathbf{K}^{\mathrm{R}}]$, $[\mathbf{K}^{\mathrm{IV}}]$ 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, $\{\Delta\mathbf{Q}^{\mathrm{I}}\}$ is the vector of nodal point of the boundary conditions of I gender.

3. Conclusions

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

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 and areas of contact, slip and stick.

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