THERMOCONTACT INTERACTION OF BODIES OF REVOLUTION DURING INDUCTION HEATING

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Summary A technique of numerical analysis of kinetics of thermal and stress-strain states of bodies of revolution joined with interference at their induction heating-based assembly and disassembly is presented. Theoretical considerations are supplemented with an illustrative example dealing with assembly and disassembly of a joint “chuck-drill” of a drilling machine.

One of effective methods of thermal assembly and disassembly of metal machine joints with interference fit is based on the induction heating. Determination of the assembly and disassembly parameters requires the simultaneous solution of electromagnetic, thermal and thermoelastic problems taking into account contact interactions. In general these problems are coupled because material properties depend on temperature. However, in the case of small temperatures it is possible to neglect its influence on the electromagnetic field. Interrelation between thermal and stress-strain states is essential.

During assembly and disassembly of interference fits of bodies of revolution a thin surface layer of metal of the external body is heated intensively. Heating is carried out by eddy currents induced by harmonic or transient electromagnetic field generated by inductor that surrounds the joint. As during disassembly the internal body is heated by means of heat transfer, it is necessary to carry out the heating sufficiently quickly, otherwise the disassembly may become impossible.

For the finite element analysis a mathematical model based on the variational formulation of axisymmetric problems of electromagnetics, heat conduction and mechanics of deformable bodies is used. In the cylindrical coordinate system $r\theta z$ the functionals for the two first problems read

$$I_1 = \frac{1}{2}\iint_S \left[\frac{1}{\mu}\left(\frac{\partial A}{\partial r}\right)^2 + \frac{1}{\mu}\left(\frac{\partial A}{\partial z}\right)^2 + \frac{1}{\mu}\cdot\frac{A^2}{r^2} + \frac{2}{\mu}\cdot\frac{A}{r}\cdot\frac{\partial A}{\partial r} + 2\gamma A\frac{\partial A}{\partial t} - 2j_0 A \right] rdS + \int_{L_r} \alpha^*\left(\frac{A}{2} - A_\infty\right) ArdL,$$

$$I_2 = \frac{1}{2}\iint_S \left[k_r\left(\frac{\partial T}{\partial r}\right)^2 + k_z\left(\frac{\partial T}{\partial z}\right)^2 + k_{rz}\cdot\frac{\partial T}{\partial r}\cdot\frac{\partial T}{\partial z} + 2QT - 2\rho c\cdot\frac{\partial T}{\partial t}\cdot T \right] rdS - \int_{L_q} qTrdL + \int_{L_\alpha} \alpha\cdot\left(\frac{T}{2} - T_\infty\right) TrdL$$

where A denotes the magnetic vector potential, $\mu\,(H, T)$ the magnetic permeability depending on magnetic field strength H and temperature T, $\gamma(T)$ the electric conductivity, j_0 the external harmonic current density (within the inductor), A_∞ the value of the magnetic vector potential along the distant boundary Γ, α^* the “magnetic field transfer coefficient” to satisfy approximately the boundary conditions $A\,|_\Gamma = A_\infty$, t the time, $k_r(T)$, $k_z(T)$, $k_{rz}(T)$ the thermal conductivities, $\rho c(T)$ the volume specific heat, $Q(r, z, t)$ the specific internal heat sources (specific Joule losses), q the intensity of the heat flow through the boundary L_q, α and T_∞ the heat transfer coefficient and temperature of the medium along the boundary L_α.

To determine the stress-strain state the linearized Lagrange variational equation for increments is used

$$\iint_{S_0}\left(\Delta\sigma^{ij}\delta\Delta e_{ij} + \sigma^{ij}\delta\Delta\eta_{ij} - \Delta F^i\delta\Delta u_i\right)rdS - \int_{L_0}\Delta P^i\delta\Delta u_i rdL + \iint_{S_0}\left(\sigma^{ij}\delta\Delta e_{ij} - F^i\delta\Delta u_i\right)rdS - \int_{L_0}P^i\delta\Delta u_i rdL = 0$$

where S_0 and L_0 denote the surface and boundary of the meridian cross-section of the body in the initial non-deforming state, σ^{ij}, $\Delta\sigma^{ij}$ the components of the stress tensor and its increments, Δe_{ij}, $\Delta\eta_{ij}$ the increments of the linear and nonlinear parts of the strain tensor, Δu_i the increments of the displacements (Δu_r, Δu_z), F^i, ΔF^i the components of the volume load and its increments, and, finally, P^i, ΔP^i the components of the surface load and its increments.

Problems are solved using the time-stepping method with internal iterative processes for the parameters determination. The fact that the contact zone is unknown in advance does not allow setting conditions of interaction of bodies for the mechanical problem as well as for the thermal problem that determines their coupling.

When modeling the assembly and disassembly, the internal heat sources exist only during operation of the inductor. Redistribution of temperatures takes place as a result of thermal conductivity in the process of forced convective cooling. During the entry of the bodies in the contact or leaving from it the exchange of heat between them is realized through the time-varying contact zone (or zones) that must be determined iteratively. The contact thermal resistance is determined from empirical formula [1] and depends on the contact pressure, thermal conductivity of the bodies and medium in clearances between them, height of microroughness, etc. Conditions of the thermal and mechanical interaction are guaranteed by special thermocontact finite elements having no thickness. Contact interaction of the surface points are determined by inequalities $u_n^1 - u_n^2 - \delta_n \le 0,\ \sigma_n \le 0$ where u_n^1, u_n^2, δ_n are the displacements of the points and gap (interference) in the direction of the common normal, σ_n the contact stress. For these points we introduce a sufficiently high stiffness to neglect the penetration of bodies.

As an example, numerical analysis of the process of assembly and disassembly of the joint "chuck-drill" of a drilling machine is carried out. The cross-section of the arrangement is depicted in Fig. 1. The drill is divided into 10 finite elements through the thickness while the chuck into 17 elements. The upper layer of the chuck with thickness of 1 mm containing heat sources is divided into 8 elements with mesh decreasing to the surface. Contact surfaces have a conic shape (conicity is 1:100). Their length is 40 mm (65 mm $< z <$ 105 mm). To guarantee the uniform distribution of the contact pressure along the axis the varying interference is set (from 10 μm to 12.5 μm). Radius of the drill is 7 mm.

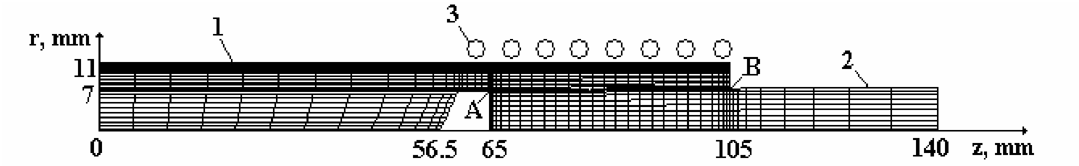

Fig. 1. Basic arrangement of the chuck (1) and drill (2), 3 denoting the inductor

Material of the chuck is a carbon steel with $k_r = k_z = k_{rz} = k = 16$ W/(m·K), $\rho c = 4\cdot10^6$ J/m^3, Young's modulus $E = 2\cdot10^5$ MPa, Poisson ratio $\nu = 0.3$, coefficient of the linear expansion $\alpha_{\mathrm{T}} = 1.7\cdot10^{-5}$ K^{-1}. Material of the tool (hard alloy): $k =$ 85 W/(m·K); $\rho c = 1.5\cdot10^6$ J/m^3, $E = 5.3\cdot10^5$ MPa; $\nu = 0.25$; $\alpha_{\mathrm{T}} = 0.5\cdot10^{-5}$ K^{-1}. The total power of the internal heat sources is about 9.5 kW, frequency of current is 1 kHz. On the chuck face ($z = 0$) $\alpha = 10^4$ W/(m^2·K), $T_\infty = 20$ °C (heat removal along the chuck), on other free surfaces $\alpha = 2\cdot10^2$ W/(m^2·K), $T_\infty = 20$ °C (forced air cooling).

To realize the assembly, the chuck has to be heated about 3.5 s. Maximal temperature in it is 228 °C, maximal difference through the thickness is 86 °C. After 7.5 s of cooling (at $t = 11$ s) the chuck enters in contact with drill at point B (see Fig. 1) and at $t = 15$ s along the whole surface. At the moment $t = 22$ s the temperature of the joint becomes practically uniform along the radius and contact pressures reach the values which guarantee the serviceability of the joint (the joint is able to transfer the real torque taking place during drilling [1]). Then, the contact pressure increases till the joint is cooled to 20 °C. This state is obtained by stationary thermomechanical problem solution ($t \to \infty$).

Part I of Tab. 1 presents the contact pressures at assembly for different times.

Tab. 1: Contact pressures (MPa) on cylindrical surface AB (Fig. 1) during assembly I and disassembly II

	t (s)	*z* (mm)								
		65.15	66.60	73.00	79.00	85.00	91.00	97.00	103.40	104.85
Assembly I	12	0	0	0	0	0	0	0	9,6	35.7
	14	0	0	0	0	7.7	13.8	37.3	56.7	147.8
	15	21.8	5.9	3.8	14.7	28.1	38.1	53.3	64.9	120.2
	22	192.4	71.9	50.6	58.0	63.0	70.0	77.0	82.5	111.2
	43	268.8	97.7	69.3	76.9	81.5	85.8	90.3	93.2	122.2
	∞	440.3	155.2	107.0	114.3	116.5	118.0	119.0	119.3	156.8
Disassembly II	2	227.4	56.7	32.7	39.9	43.0	45.8	37.8	50.8	251.2
	2.5	181.1	36.4	18.8	26.0	29.2	32.2	23.4	36.7	242.1
	3.5	80.4	0	0	0.5	4.8	5.6	0	0	172.9
	3.8	0.6	0	0	0	0.5	0	0	0	140.6
	4.0	0	0	0	0	0	0	0	0	0

Complete disassembly of the joint takes place in about 4 s after switching on the inductor. Maximal temperature in the chuck is now 231 °C (external edge of its face), in the drill (point A) - 85 °C. The distribution of the contact pressure during the disassembly of the joint is presented in part II of the table. Disassembly of the joint starts about 4 mm to the left from the point B at $t = 2.5$ s and at the maximal temperature in the chuck 181 °C. Then, the clearance appears in the region of the point A and the thin end of the drill gets free. The point B leaves from the contact later.

In order to obtain an interference of 10 μm along cylindrical contact surfaces [1], very high precision of the manufacture is necessary. For conic surfaces such a precision is not necessary because the interference will depend on the depth of penetration of the drill into the chuck that is determined by fixed temperature of the assembly at the selected point of the chuck. If the assembly will start at higher temperature, the appearance of small plastic strains does not lead to breakdown of serviceability of the joint later on.

References

[1] Shulzhenko M., Gontarowskiy P., Matyukhin Yu., Pantelyat M., Doležel I., Ulrych B.: Numerical analysis of induction heating-based assembly and disassembly of shrink fits. *Proc. of AMTEE' 03*, Czech Republic, Pilsen, A65-A73, 2003.