Проведено чисельне моделювання процесу штампування і розкочування підшипникового кільця методом скінченних елементів. Досліджено розподіл волокнистої структури матеріалу при деформуванні заготівки підшипникового кільця у вигляді ліній Лагранжа. Запропоновано спосіб двопрохідного формування, який забезпечує високу довговічність кільця. Металографічним способом підтверджено розподіл волокнистої структури матеріалу при штампуванні і розкочуванні підшипникового кільця, отриманий розрахунковим шляхом

Ключові слова: підшипникове кільце, волокниста структура, в'язкопластичність, штампування, розкочування, метод скінченних елементів

Проведено численное моделирование процесса штамповки и раскатки подшипникового кольца методом конечных элементов. Исследовано распределение волокнистой структуры материала при деформировании заготовки подшипникового кольца в виде линий Лагранжа. Предложен способ двухпроходной формовки, обеспечивающий высокую долговечность кольца. Металлографическим способом подтверждено распределение волокнистой структуры материала при штамповке и раскатке подшипникового кольца, полученное расчетным путем

Ключевые слова: подшипниковое кольцо, волокнистая структура, вязкопластичность, штамповка, раскатка, метод конечных элементов

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FORMATION OF FIBROUS MACROSTRUCTURE IN A BEARING RING AT STAMPING AND ROLLING

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1. Introduction

Among the critical highly loaded machine parts are the bearing assemblies whose failure can lead to an accident. Because of action of the significant frictional forces, one of the main reasons for the failure of a bearing assembly is the wear and the fatigue chipping of raceway of the bearing ring. That is why at the stage of production of a bearing ring, the characteristics should be predicted for its longevity so that they will make it possible to guarantee its reliability and prolonged period of service. The technological process of manufacturing a bearing ring includes the preheating of cylindrical billet and subsequent application of technological operations for pressure treatment (PT): die hot forging of forging rings and hot unrolling of the forging ring. Determining the optimum technological parameters of each stage of technical process at the stage of design makes it possible to improve the endurance of ring in the loaded zones by increasing the resistance to contact fatigue. It is known from sources [1, 2] that the fatigue indicators of material depend on the macrostructure of forging, which is formed at all stages of the technological process of manufacturing a bearing ring. All metals have heterogeneous structure in the form of granularity, admixtures, defects, etc. When applying the operations PT with high pressures and temperatures, there occurs the elongation and grinding of grains, the accumulation of nonmetallic inclusions, oriented in the direction of maximum deformation and which form fibrous structure. It is known that impact strength of metal in the fiber direction is 50–70 % higher than that perpendicular to fibers. Therefore, the purposeful modeling of shape-changing the billet of a bearing ring taking into account a change in the macrostructure of material at forging and unrolling will make it possible to fabricate a bearing ring with improved operating characteristics.

2. Literature review and problem statement

Development of modern software (ANSYS, Abacus, Deform (USA)) enabled conducting studies into numerical simulation of the technological processes of thermoplastic deformation of the billets of a bearing ring. The thermo-viscous-plastic stress-strain state of the ring in production depends on heating, tool feed rate, type of friction and other factors. As a rule, studies examine influence of only some of them. Thus, article [3] investigates the influence of friction on the process of unrolling a cylindrical bearing, but thermal effects are not considered. Paper [4] presents a model of sliding lines to evaluate a temperature effect on the growth

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of grains in the formation of bearing rings. The same model is employed in [5], however, the impact of characteristics of the machining tools on a change in the macrostructure was not analyzed in the given papers. In addition to experimental studies, article [6] solved a thermomechanical problem considering the history of accumulation of residual stresses. At the same time, the formation of micro- macrostructure in the process of deformation of the bearing ring was not examined. Paper [7] proposed a self-adjusting model for unrolling the bearing rings for optimization of time for their production. The authors did not analyze quality of the surface treatment and its effect on the bearings' life cycle. Article [8] carried out the simulation of the process of hot unrolling of the rings of bearings with the estimation of factors that influence the microstructure of their material. The influence of non-uniformity of temperature on the quality of machining a raceway is established. The analysis was conducted for titanium alloys while the formation of macrostructure for the steel rings of bearings was not explored. Paper [9] proposed a 12-stage elastic-plastic model of unrolling the bearings with the evaluation of influence of temperature modes without considering the macro- and micro-structural changes. The finite-element simulation of the process of hot rolling of bearing rings, constructed using the software DEFORM 3D, is presented in article [10]. The influence of rolls rotation speed on the process of deformation is investigated, but the structural changes in the material were not analyzed. The interconnected thermomechanical processes considering friction of unrolling the bearing rings made of titanium alloys are examined in paper [11]. The influence of friction on the temperature field distribution in the process of hot unrolling of a steel bearing ring is analyzed in [12]. These studies did not address the influence of temperature field distribution on the structural changes. Article [13] demonstrated, by using the method of optical microscopy and roentgenography, that at stamping the character of structural changes is determined by tangential stresses.

At the same time, technologically, the operation of die forging takes place prior to the unrolling. As is known, abrasion resistance of the raceway of a bearing ring depends on the micro- and macrostructure of material formed at stamping and unrolling. Therefore, it is expedient to form the fibrous macrostructure, oriented in the direction of a contact action on the component. The previously published studies have not tackled the problem in such statement.

3. The aim and tasks of research

The aim of present research is to create a predicted distribution of fibrous structure in a bearing ring in the process of its manufacturing by hot die forging and unrolling, which ensures improved fatigue resistance.

To accomplish the set aim, the following tasks had to be solved:

– to model the process of shape-changing the cylindrical billet of a bearing ring at hot die forging and hot unrolling;

– to account for the interrelation between parameters of state of the models (transfer of parameters of the state of a billet from one process to the other one);

– to conduct a numerical-experimental study into the distribution of fibrous structure of the rolled-out billet of a bearing ring after single-pass and double-pass molding.

4. Modeling the thermo-viscous-plastic deformation of billet in the process of manufacturing a bearing ring

When manufacturing the bearing rings, one of the problems is the formation of macrostructure of the material and laying of fibers in a special way. The raceway requires a special attention as its most intensive destruction in the process of operating the bearing occurs in places where the fibers emerge at the contact surface. In the present research, we propose the approach to examining a technological process, which makes it possible to correct this deficiency in many respects.

To manufacture bearing rings with improved operational stability, a mathematical modeling of technological processes at all stages of machining is necessary: preliminary induction heating, die forging and unrolling. For this purpose, we were solving thermo viscous plastic contact problems considering large deformations and deformation rates with the corresponding initial and boundary conditions. Calculating the parameters of stressed-strained state of the billet of a bearing ring for each operation makes it possible, using the Lagrange lines, to follow a change in the distribution of fibrous structure. Initially, the fibrous structure of a billet is formed at its production in the process of forging in the form of elongated lines, parallel to the generatrix. Preliminary high-temperature induction heating does not influence the distribution of fibrous structure in a cylindrical billet. At the stage of production of a bearing ring, in the operations of shrinking and molding, due to large plastic deformations, the distribution of fibrous structure of forging undergoes a substantial change. In the subsequent unrolling, there occurs only the compaction of fibrous structure. Therefore, to analyze the distribution of fibrous structure, we modeled only the process of the deformation of a bearing ring billet for the operations of stamping and unrolling.

A full system of resolving equations for the thermo viscous plastic state of a bearing ring includes the equations of equilibrium, continuity, plasticity condition, the physical determining relationships and boundary conditions.

$$\dot{\rho} = -\rho\frac{\partial v_i}{\partial x_i}, \quad \rho\dot{e} = \sigma_{ij}\frac{\partial v_i}{\partial x_j} + \rho r - \frac{\partial q_i}{\partial x_j}, \tag{1}$$

$$\sigma_{ij}^{T} = C_{ijkl}D_{kl}, \quad \sigma_{ij}^{T} = \dot{\sigma}_{ij} + \frac{\partial v_k}{\partial x_k}\sigma_{ij} - \frac{\partial v_i}{\partial x_k}\sigma_{jk} - \frac{\partial v_j}{\partial x_k}\sigma_{ik}, \tag{2}$$

$$\rho\dot{v}_i = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho f_i^B,$$

$$D_{kl} = \frac{1}{2}\left(\frac{\partial v_k}{\partial x_l} + \frac{\partial v_l}{\partial x_k}\right), \tag{3}$$

where ρ, $\dot{\rho}$ are the density and the rate of change in the density; v_i, $\dot{v}_i$ are the velocities and the accelerations of a material point; $e=e(\rho, T)$ is the specific inner energy; σ_{ij} are the components of stress tensor; r is the internal distributed heat sources; q_i are the components of heat flux vector; f_i^B are the components of volume force vector; $\dot{\sigma}_{ij}$ is the tensor of stress velocities; C_{ijkl} is the tensor of physical relation of stress-strain; D_{kl} is the strain rate tensor, which includes the plastic D_{ij}^{p} and the temperature D_{ij}^{T} constituents.

Plastic deformation of material abides by the associated law of the theory of flow in the speed form:

$$D^p_{ij} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}}, \quad (4)$$

where $\dot{\lambda}$ is the parameter of plasticity; F is the plastic potential.

The determining relationships are assigned by the nonlinear law considering a dependence of the physical-mechanical properties of a material on the temperatures and deformation rates:

$$\sigma_y = \sigma_y(\bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p, T), \quad (5)$$

where σ_y is the functional dependence for the current yield point; $\dot{\bar{\varepsilon}}_p$ is the rate of equivalent plastic deformation; T is the temperature.

Boundary conditions for a contact problem for slippage, the conditions of adhesion and break in the contact zone must satisfy:

$$|\tau_t| \le \mu_S |p_n|, \quad f^I_{cn} = H^I f^K_{cn}, \quad f^J_{cn} = H^J f^K_{cn}, \quad (6)$$

$$|\tau_t| \le 0, \quad g_n = 0 \text{ or } |\tau_t| = 0, \quad g_n \ge 0,$$

where $p_n=\sigma_n=f_{cn}$ and $\tau_t=f_{ct}$ are the contact pressure and the tangential effort in a contact point; μ_s is the friction coefficient; g_n is the gap in the direction of normal.

The integrity of the deformed material was evaluated by the Cockcroft & Latham fracture model. The index of damageability takes the form:

$$c = \int_0^{\varepsilon_i} \frac{\sigma_1}{\sigma_i} d\varepsilon_i, \quad (7)$$

where ε_1 is the intensity of deformations; σ_1 is the principal positive normal stress; σ_i is the intensity of stresses.

Distribution of temperature fields of the billet of a bearing ring in the process of die forging and unrolling is determined when solving the problem on non-stationary thermal conductivity. Boundary free-surface conditions of billet are the convective heat exchange, and in the zones of contact between a billet with the matrix and the punch – contact heat exchange. The solution of the problem on calculating the parameters of the stressed-strained state of the billet of a bearing ring for each technological operation makes it possible to follow a change in the distribution of fibrous structure using the Lagrange lines, directly connected to the process of deformation.

In a transfer from the stamping to the following technological operation of unrolling, we considered the cooling of forging caused by the convective heat irradiation and the emission to medium. The equation of thermal conductivity with the thermal-physical coefficients dependent on the temperature and the boundary conditions takes the form

$$\rho C(T)\frac{\partial T}{\partial t} = \mathrm{div}(\lambda(T)\mathrm{grad}T) + q_v(t),$$

$$\lambda\frac{\partial T}{\partial n}\bigg|_{out} = \alpha_k(T_{out} - T_{in}) + \sigma_2(T^4_{out} - T^4_{in}), \quad (8)$$

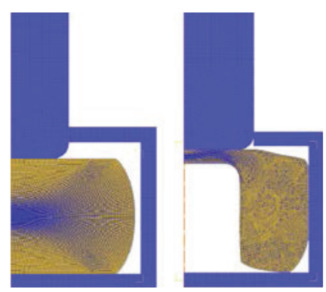
where C(T) is the heat capacity; λ(T) is the coefficient of thermal conductivity; ρ is the density; $q_v(t)$ is the heat release rate of the surface and volumetric heat sources; α_k, σ_e are the convection and emission heat-transfer coefficients; T_{out}, T_{in} are the temperatures of the surface and the environment.

Field temperature distribution in the billet during cooling after the operation of die forging is assigned as the initial state when solving a problem on determining the stressed-strained state of the forging of a bearing ring in the process of unrolling. The computation of deformation fields and displacements when solving a boundary problem (1)–(8) allows us to determine the distribution of fibrous structure of the billet of a bearing ring. Calculation is carried out stepwise in correspondence with the sequence of performed technological operations of die forging (shrinkage, molding, and punch-out) and unrolling.

5. Results of numerical modeling of the thermo-viscous-plastic deformation of a billet in the process of manufacturing a bearing ring

To examine the distribution of fibrous structure of a bearing ring, we were solving the problems of contact interaction between a preheated cylindrical billet and the die and the punch. In this case, we considered technological operations of shrinkage, single-pass molding and punching. We also investigated the deformation of billet in the process of double-pass molding [14], achieved in two stages. First, a heated forging of a bearing ring after the operation of shrinkage is processed by the punch of smaller diameter. Next, after turning the forging by 180°, it is again treated with the punch whose diameter corresponds to the inside diameter of the finished forging of the ring.

Fig. 1 shows a schematic of loading a cylindrical billet at double-pass molding.



a *b*

Fig. 1. Schematic of loading at double-pass molding [14] that includes a punch, matrix and a billet; *a* – first pass for obtaining the initial forging; *b* – second pass for punching the opening

In previous article [15], the authors obtained temperature distribution in the cylindrical billet after induction heating. Fig. 2 shows a temperature field after cooling for the subsequent modeling of the process of shrinking: maximum temperature reached T_{max}=1140 °C, and a drop-in temperature T_{max}–T_{min}=50 °C. When modeling the deformation in the process of shrinking and molding, the boundary conditions of two types were assigned: thermal contact at the contact surfaces between the punch and billet and the matrix – billet, as well as friction at the external surface between the matrix and the rigid fastening. Kinematic load was assigned as a vertical motion of punch at the set speed.

Numerical solution of the interconnected non-stationary problems on thermal conductivity and thermo-viscous-plasticity was performed by the method of finite elements and using the ANSYS software. The finite-element model includes 14821 nodes and 71971 elements of 4 nodal tetrahedra for the problem on stamping, and 40560 nodes and 36000 elements of 8 nodal hexahedra on unrolling. Material of the billet is steel ShKh15. At the contact surfaces between the punch and the forging, friction coefficient was accepted equal to $\mu=0.3$. Punch motion speed $v_n=100$ mm/s. At unrolling, the clamping roll feed rate is $v_p=3.5$ mm/s, the axial roll feed rate is $v_a=0.05$ mm/s, angular speed of the drive shaft is $\omega_d=8.7$ rad/s. Geometric dimensions of the cylindrical billet is $R_z=100$ mm and $h_z=190$ mm.

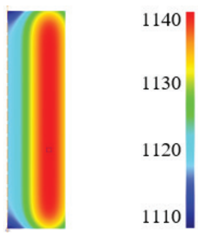
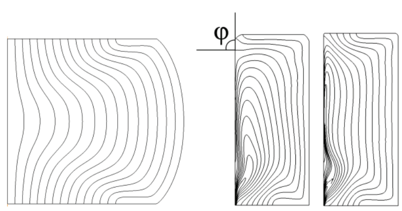


Fig. 2. Temperature field (°C) in the cross-section of billet after cooling

When solving the boundary contact non-stationary thermo-viscous-plastic problem, we determined the deformations and displacements in the forging and constructed the Lagrange lines for each stage of die forging, whose distribution is shown in Fig. 3. At the next stage, we examined cooling of the forging over the interval, set in line with technical task, in a transfer from the operation of stamping to the operation of unrolling. Was solved the non-stationary problem of thermal conductivity with the boundary conditions for convective heat exchange and emission on the surfaces of forging.

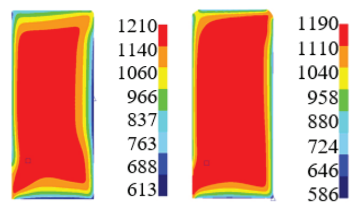


a *b* *c*

Fig. 3. Distribution of the Lagrange lines in the forging of ring after: *a* — shrinking; *b* — single-pass molding; *c* — double-pass molding

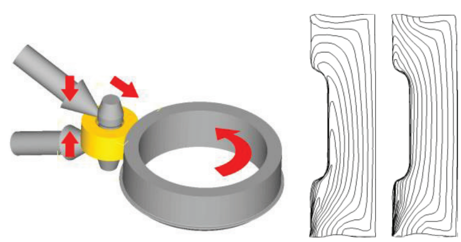
The temperature field distribution throughout the entire volume of forging after cooling is shown in Fig. 4. It should be noted that at double-pass molding the maximum temperature of inner layers of the cross-section of a billet reaches $T_{max}=1210$ °C. A drop-in temperatures $T_{max}-T_{min}=600$ °C substantially affects parameters of the stressed-strained state of the forging at unrolling. At the next step of solving a comprehensive problem on the simulation of the process of manufacture of a bearing ring, by using the initial temperature distribution, we assigned a non-uniform temperature field, which was established in the volume of forging after cooling at the end of stamping. Fig. 5 shows a schematic of the technological operation of unrolling, as well as obtained distribution of the fibrous structure of a bearing ring after unrolling.

A comparison of two variants of distribution of the fibrous macrostructure of a bearing ring has revealed differences in the orientation of fibers relative to the working surface – the raceway. Quality characteristic of structural fibrousness is the angle of fiber exit to the surface – φ_i. This angle is measured between the tangent to the Lagrange line (fiber) and the generatrix of the internal surface of a ring at the point where the Lagrange line emerges on the working surface of the forging. The magnitude φ_i must be minimal. During unrolling of the forging of a ring, after the single-pass molding (Fig. 5, *b*), some lines (fibers) emerge on the internal surface of the ring (raceway) at angle $\varphi_i=90°$. In the cross-section of a ring, the fibers are not parallel to the generatrix. In the case of unrolling the forging of a ring after the double-pass molding (Fig. 5, *c*), the Lagrange lines (fibers) are formed in parallel to the generatrix of a raceway and thus, at operation, they will be oriented perpendicularly to the normal contact pressures.



a *b*

Fig. 4. Temperature field (°C) of the forging of the ring before unrolling: *a* — after single-pass molding; *b* — after double-pass molding



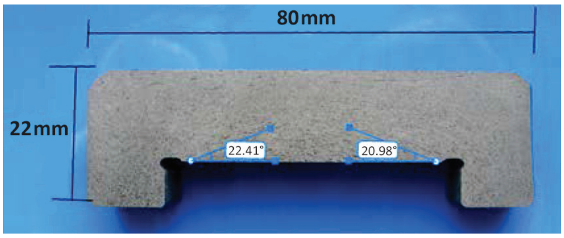
a *b* *c*

Fig. 5. Unrolling the ring: *a* — schematic of unrolling; *b* — laying the fibers after single-pass molding; *c* — laying the fibers after double-pass molding

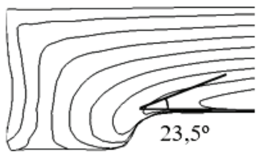
The exit of fibers to the surface displaces to the side of a bearing ring flange, where the emerging contact stresses are considerably less than those on the raceway.

To validate the estimated model, we made a microsection out of the rolled-out ring of the bearing, on which we measured fiber exit angles to the raceway.

Structural striation (fibrousness) was determined using the hardware-software complex Thixomet according to the standards ASTM E1268-01 by the method of directed secants applying the algorithms for restoration of badly pickled boundaries and the assigned direction of the rolling line. A comparison of the fiber exit angles at points with the assigned coordinates of the sample (Fig. 6, *a*) with the magnitudes of angles, obtained by computational technique (Fig. 6, *b*) revealed a good agreement with an error of 4.7 %.



a



b

Fig. 6. Fiber exit angles to the raceway:
a — macrophotograph of the sample with linear dimensions;
b — estimated angle at numerical simulation

6. Discussion of results of examining a change in the fibrous macrostructure of a bearing ring billet

We conducted mathematical modeling of the sequential series of technological operations in the fabrication of a bearing ring. When constructing the mathematical model, to approximate a real technological process, we considered a change in the physic mechanical characteristics of material on the temperature. As the determining relationships, while solving the thermo viscous plastic problem, we employed the experimental curves of deformation of temperatures over a wide range and deformation rates. Parameters of the stressed-strained state and the distribution of temperature field of the billet, obtained by computational technique, are assigned by the initial conditions for the simulation of subsequent technological operations. The relatedness of physical-mathematical models of the billet state at each stage of billet machining corresponds to actual conditions and the principle of heredity (temperature) of technological processes. We investigated the formation of fibrous macrostructure of the bearing ring billet material, which occurs in the technological operations of die forging and unrolling.

The modeling of technological process of manufacturing a bearing ring in the form of the non-stationary contact problems on thermal conductivity and thermo-viscous-plasticity for the operations of shrinking, molding, punching and unrolling allowed us to establish the following:

– the redistribution of macrostructure of the material occurs at the stage of molding and unrolling of the forging of ring and represents the process of plastic flow of metal; compaction and alignment of the fibers of the material occurs in the process of unrolling;

– metal flow non-uniformity, the non-uniform distribution of temperature field, geometric dimensions of punch, contact friction, tool motion speed influence the formation of fibrous structure of the forging of a bearing ring;

– based on the analysis of results of numerical simulation, it was proposed to use a double-pass molding [14] and, additionally, unrolling for displacing the exit of fibers from the raceway to the the bearing surface of the bead ring; it was demonstrated that it is possible to change fibrousness on the surface and to displace the exit of fibers from the raceway to the border. This will make it possible to significantly improve the strength properties and reliability of the raceway in bearings;

– the adequacy of the mathematical model to the actual process of operations of stamping and unrolling was confirmed – we experimentally demonstrated the agreement between the modeled and the real distribution of fibrous structure in the cross-section of the ring billet;

– results of the modeling make it possible to introduce changes to standard schemes of the bearing rings production, by modifying the fibrous macrostructure of the surface with the exit angles assigned in advance for different applications, thus improving their reliability and life cycle.

The distribution of stresses on the contact surfaces between a tool and a billet, as well as the formation of defects, affect the formation of the raceway of a bearing. Conducting additional studies is necessary to account for these factors. The results of experiment confirmed the adequacy of numerical simulation of the process of stamping with single-pass molding and unrolling of the ring of a bearing. It is possible to assume that the approach proposed in the present work is effective and correct for modeling the process of manufacturing a ring at double-pass molding, as well as in the analysis of changes in the formation of fibrous macrostructure in the ring billet.

7. Conclusions

1. By using the method of finite elements, we conducted numerical modeling of the shape-formation of the billet of a bearing ring in the process of die forging and unrolling. Within the framework of a discrete three-dimensional model, we considered the dependence of physical-mechanical properties and parameters of the state of material on temperature and deformation rate. Parameters of the stressed-strained state are obtained that vary over time, as well as the corresponding temperature fields; the Lagrange lines of plastic flow are built.

2. The mathematical model accounts for technological heredity, that is, changes in the physic mechanical properties of metal during previous and subsequent machining, as well as the preceding temperature distribution at each stage of machining and the interrelation between technological operations in the production of a bearing ring.

3. During numerical-experimental research, we also conducted a macroscopic analysis of the formation of fibrous structure in the cross-section of a bearing ring. We measured fiber exit angles to the raceway and the borders, which with an error of 4.7 % coincide with the computed values.

Results of the executed numerical modeling of die forging and unrolling of the billet make it possible to introduce changes to the existing technological operations in the production of bearing rings. To select the optimal parameters of the geometry of punch, tool feed rate, temperature of machining and the preferable type of friction. Reducing the fiber exit angle to the raceway and the uniform distribution of fibrous structure will make it possible to improve contact endurance and prolong life cycle of the bearing in operation.

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