

Increasing durability of bearings by the application of technological operations on the basis of cyclic elastic deformation of the rings

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Abstract. The appearance and growth of fatigue microcracks during the relaxation of residual stresses under the action of high-cycle loads is one of the main reasons of decreasing of durability of products. To reduce residual stress of the bearing rings, there was developed a technology on the basis of the cyclic elastic deformation instead of using energy-consuming thermal tempering. The technology consists of continuous running of the rings between three rollers under the load. A key feature of the technology is the controllability of cyclic loading of parts. The conducted study of an experimental batch of rings proved the reduction of residual stresses by more than 2 times in comparison with the average value of residual stresses after thermal tempering.

1. Introduction

Durability is one of the most important performance indicators of the quality of products which are made of structural materials. Therefore, provision of the required durability of structural materials under high-cycle loading is extremely relevant. As is known [1], up to 94% of the causes of machine and structure failures are related to the appearance and propagation of cracks. The majority of the cracks, leading to equipment failure, are caused by fatigue damage in parts and components that are subject to high-cycle dynamic loads. For example, among the failures of aircraft engines up to 60% have mechanical causes, 80% of which are associated with the accumulation of fatigue damage and propagation of fatigue cracks under vibration [1].

Rolling bearings are products, widely used in various types of mechanical engineering that are susceptible to high-cycle loading during operation. Therefore, to ensure the required durability of bearings, one have to meet particularly high requirements. The emergence and propagation of cracks in the bearing rings and reduction of their service life are the result of residual stresses arising in technological processes of forming and heat treatment of the part. Residual stresses are concentrated at the grain boundaries of the material, and this accumulation of residual stresses leads to the appearance of microcracks [2]. Subsequent cyclic loading of the bearing rings in the course of their operation leads to accumulation of internal energy and microcrack propagation.

To reduce residual stresses in bearing rings, they are subjected to thermal tempering, which is traditionally carried out via heating and slow cooling before the final operations of the technological process. Thermal methods of geometry stabilization, having low performance and relatively high energy consumption, do not allow complete relaxation of residual stresses. Therefore, under the



guidance of A.V. Korolev there was developed the technology of residual stress relaxation in the bearing rings on the basis of cyclic elastic deformation of products by their centerless running [3].

2. Technology description

The technology of residual stress relaxation consists in a continuous running of the rings between three rotating rolls under the action of external load, which ensures elastic deformation of the ring in the contact area with the rolls. A gradual accumulation of internal energy in the zones of residual stresses occurs under the action of cyclic elastic strain of the rings during running. During this accumulation of internal energy of the dislocation formations, there occurs shear plastic strain of the micrograins of the material, which is followed by the relaxation of residual stresses.

The controllability of cyclic elastic strain is a key feature of the technology. On the one hand, the magnitude of the energy input to the elastic strain per cycle should be sufficient for movement, integration and subsequent collapse of intergranular dislocations, accompanied by the relaxation of internal stresses. On the other hand, when a large amount of energy imparted per loading cycle, there occur the collapse of a critical number of dislocations with the emergence of cracks in the region of localization and the propagation of existing microcracks. As was noted above, the last phenomenon is the cause of the reduction of product life.

To implement the conditions of the rings loading, the authors developed a model [4] for the calculation of rational technological modes of processing:

$$\tau = \frac{c_p}{c_o} \cdot \frac{\sigma_m^2 \cdot K_p}{\sigma_{mo}^2 \cdot n} \cdot \frac{\frac{\alpha}{2} \int_0^{\theta_p} J_M(\theta)^2 d\theta + \frac{4k\sigma^2 \cdot h^6}{W^2} \int_{\theta_p}^0 J_P(\theta)^2 d\theta}{\frac{\alpha}{2} \int_0^{\theta_p} J_M(\theta)^2 d\theta} \quad (1)$$

where is the processing time; $J_M(\theta)$ and $J_P(\theta)$ are the introduced notations (they are not shown due to their inconvenience) [14]; σ_m is the maximum stress of elastic deformation of the part, determined without taking into account plastic deformation; σ_{mo} is the maximum stress occurring in the material of the ring during processing; c_o is the number of contact areas between rolls and the part; θ is the central angle of the cross-section; θ_p is the angle at which the zone of elastic strain transits to the plastic one; α is the angular pitch of the points of application of external load P (c_o); K_p is the ratio of energy absorption; the value c_p should be taken depending on the error of the geometric shape of the ring: if second harmonic prevails in the ring, then $c_p = 2$; if there prevails third harmonic, then $c_p = 3$; h is the distance from the central axis of the cross section to the extreme point of the cross section; W is the moment of resistance to bending; n is the frequency of the ring rotation.

3. Experiment description

To assess the effectiveness of this technology, the authors in cooperation with the bearing enterprise, JSC "EPK Samara", conducted experimental research. Forty five outer rings of the bearings 7000806 (GOST 8338-75) were selected as the object of research. The rings were numbered and divided into five batches of 9 rings each:

- 1) the first batch of the rings was used as a control one and was not subjected to treatment;
- 2) the second batch was subjected to tempering in a furnace at the temperature of $t=200^\circ\text{C}$ for 2.5 hours with cooling in open air;
- 3) the third batch of the rings was subjected to centerless running (CR-1) in the following mode: the frequency of rotation of the ring is $n=240$ rpm, the processing time is $T=5$ min, the technological deformation of the rings is $\Delta=0.016$ mm;

4) the fourth batch was subjected to centerless running (CR-2) in the following mode: the frequency of rotation of the ring is $n=240$ rpm, the processing time is $T=3$ min, the technological deformation of the rings is $\Delta=0.030$ mm;

5) the fifth batch of the rings was subjected to centerless running (CR-3) in the mode: the frequency of rotation of the ring is $n=350$ rpm, the processing time is $T=3$ min, the technological deformation of the rings is $\Delta=0.016$ mm.

To determine the residual stress, each ring was cut in the center plane. The magnitude of residual stresses was calculated by the magnitude of the ring deformation after cutting, which was defined as the difference of the diameter of the ring in the plane perpendicular to the cutting plane, before and after cutting. According to the results of measuring each batch of the rings, there was carried out calculation of the mathematical expectation (ME) and standard deviation (SD) of the values of deformation and residual stress of the rings, which is shown in Figure 1 and Figure 2.

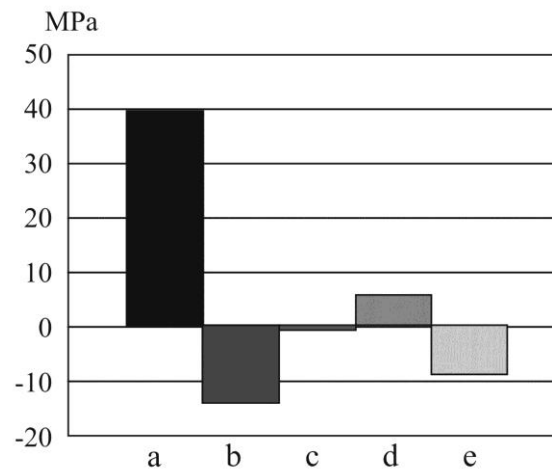


Figure 1. The mathematical expectation of the magnitude of residual stresses after 5 different types of processing: a – without treatment; b – after thermal tempering; c, d, e – after centerless running when 1, 2 and 3 are the processing modes, respectively.

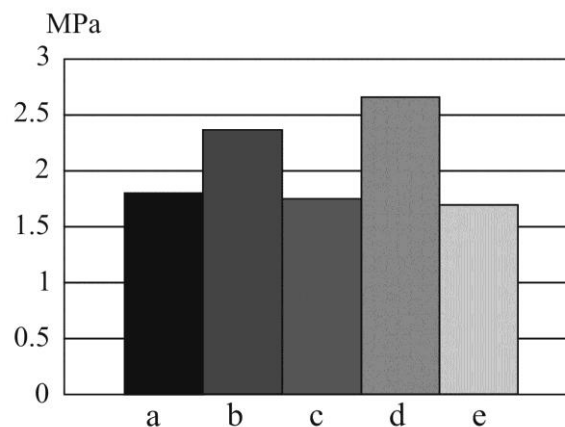


Figure 2. The standard deviation of the magnitude of residual stresses after 5 different types of processing: a – without treatment; b – after thermal tempering; c, d, e – after centerless running when 1, 2 and 3 are the processing modes, respectively.

The diagram in Figure 1 shows that significant tensile stresses dominate without relaxation of residual stresses (c). The reason for this can be explained by mechanical operations of edge cutting

and abrasive machining of the ring, which are accompanied by localized heating of the surface layers. This is due to the high rate of plastic strain and friction between the tool and the material of a part. The subsequent rapid cooling of the part leads to the appearance of significant tensile residual stresses in its surface layer.

Thermal tempering, used for relaxation of residual stresses after machining, consists in slow heating of the entire volume of the part and its subsequent slow cooling in the open air. As the velocity of the heat generation of the part surface is above the core, and then after thermal equilibrium of the surface layers is reached, the core will continue to cool for some time. With further cooling, the deformation of the surface layers stops and the core continues to shrink, which leads to the occurrence of compressive residual stresses. This phenomenon is confirmed by the section b of the diagram in Figure 1. It should be noted that the relaxation of residual stresses, while using the thermal method, has a diffusion mechanism and takes place by climbing of edge dislocations, and that is accompanied by significant energy consumption.

During cyclic elastic strain, the stress relaxation occurs due to the slip of dislocations caused by plastic strain of the micrograins of the material under the action of energy of elastic deformation. Thus less energy is required in comparison with the previous method. Energy of elastic strain, input with each cycle, due to viscoelasticity of the material, is absorbed until the equilibrium energy is reached. This state is characterized by the absence of residual stresses. Further communication of energy to elastic strain leads to the accumulation of internal energy and the growth of compressive residual stresses.

Comparison of the processing modes CR-1 and CR-2 shows that the number of cycles during the regime CR-2 is noticeably smaller at the same frequency of loading. Despite the large magnitude of elastic strain, the total amount of energy reported to the part at the CR-2 mode is less than at the CR-1, and that is insufficient for complete relaxation of residual stresses, as shown by section d in Figure 1.

Having compared the processing modes CR-1 and CR-3, it can be seen that for the same amount of elastic strain and a slightly smaller total number of cycles in the mode CR-3, the material of the part has compressive residual stresses (section e in Figure 1). This characterizes the transition of the equilibrium state and the subsequent strengthening of the part. This is because the frequency of elastic strain at the mode CR-3 is 1.45 times higher than the frequency at CR-1; and with the increase of frequency of elastic strain, part of the energy absorbed per cycle increases.

4. Conclusions

Durability of bearings depends on the stability of geometric shape throughout their operation. The presence of residual stresses is one of the main reasons for changing the geometry of the bearing rings. A gradual relaxation of residual stresses takes place during operation and this leads to the change of the rings geometry. During the relaxation of compressive residual stresses, there occurs the expansion of the volume of rings, which creates additional interference and increase in the contact area of surfaces of the rolling elements. During the relaxation of tensile residual stresses, the volume of the rings contracts and that creates a gap and wobbling of the bearing while in operation. In each of the two variants there occur some changes of the required operating conditions, which reduce the service life of the rolling bearings. The above mentioned results show that the stabilization technology based on cyclic elastic deformation of the rings by running has the advantage over thermal tempering, enabling us to achieve significant reduction of residual stresses, thereby increasing the durability of bearings.

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