EFFECTS OF OPERATION TEMPERATURE ON THERMAL EXPANSION AND MAIN PARAMETERS OF RADIAL BALL BEARINGS

by

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The research of influence of operation temperature on the thermal expansion and main parameters of radial ball bearings is presented in this paper. The main bearing parameters are identified in accordance with the increasing requests concerning stability and load capacity. A series of finite element analyses is performed for quasi-static analysis of all identified bearing parameters during contact period in referent temperature. Then, the dependence of bearing material characteristics on the operation temperature is discussed. Few series of finite element analyses are performed for a particular radial ball bearing type, with characteristics in accordance with manufacturer specifications, for several operation temperatures. These two problems analyses include consideration of relation between the initial radial clearance, thermal expansion strains, and contact deformations of the parts of the bearing assembly. The results for radial ball bearing parameters are monitored during a ball contact period for different temperatures and the appropriate discussion and conclusions are given. The conclusions about the contribution of developed procedure in defining the optimum operation temperature range are shown.

Key words: *radial ball bearings, thermal expansion, main parameters, finite element analyses*

Introduction

Ball bearings are one of the most important components in industrial machinery due to their high load-carrying capacity. Standards define only the boundary dimensions of bearings. Therefore, the bearing parameters are the scope for contemporary research in order to achieve better operation performances.

The research presented in this paper had the purpose to study operation performances of bearings by taking into consideration the operation temperature different from the reference (room) temperature [1, 2]. The phenomenon of friction which occurs in contact of roller bearing assembly parts leads to its heating at the operation temperature different from room temperature in a period of bearings run-up. Working temperature stays almost constant after that period [1-3]. The value of the operation temperature depends on the external load, rotational speed of parts of machine, manufacturing quality, as well as the characteristics of lubricants. Accordingly with the existing detailed research of the impact of the elastohydrodynamic lubrication phe-

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nomenon on improvement of bearing parameters [4-7], the influence of this phenomenon is not considered in presented research. It is accepted that an operation temperature of the bearing is a constant during a period of operation time. This is in accordance with the available experimental results [7]. The analysis which was performed and explained in this paper takes into account the structural analysis of the bearing assembly according to the experimentally obtained results about bearing material characteristics at different operation temperatures [8-12].

Identification and calculation of the main bearing parameters

The identification of main bearing parameters was dependent of the role of the bearing in complex assemblies and machines. The principles of design with aspect of stability and increasing of the load capacity of bearing were taking into account in order to choose the main bearing parameters. Therefore, the following parameters were defined as main parameters for analysing the influence of operation temperature on bearings:
- radial deformation,
- radial stiffness,
- contact stresses, and
- load distribution during a ball contact period.

The radial ball bearing deformation is a function of the material characteristics of ball bearing elements, geometry, dimensions of contact elements (inner ring, outer ring, and balls), intensity and characteristics of external load, variable number of balls in contact, operation temperature *etc.* [13-17]. It is a very important parameter of bearing operation whereas it directly determines all other operation parameters of radial ball bearing.

The radial ball bearing stiffness is one of the parameters that depend on radial deformations and influences the vibration characteristics of the bearings. Guo and Parker [18] developed a model to determine the bearing stiffness for a wide range of bearing types and parameters. They used a combined surface integral and finite element method (FEM) to solve the contact mechanics between the rolling elements and races. The radial ball bearing stiffness, C_r could be calculated as the ratio of the external radial load, F_r and the total deformation that this load causes in the force direction δ_r, eq. (1):

$$C_{\mathrm{r}} = \frac{F_{\mathrm{r}}}{\delta_{\mathrm{r}}} \tag{1}$$

The value of total deformation is elastic displacement of bearing axis that is equal to the total deformation of ball bearing in the radial direction, *i. e.* total radial displacement of axis of bearing in radial direction.

The radial ball bearing stiffness is a time-dependent parameter. The research described in previous papers as a part of complex research of radial ball bearings performances [19, 20], leads to the conclusion that the radial bearing stiffness depends on the number of balls in contact during operation period and has an influence on the dynamics of bearings. But, in the research presented in this paper, the focus has been put in the bearing parameters and main performances that depend from the operation temperature, so the radial stiffness is assumed to be constant and equal to the average value during operation period.

The contact phenomenon is another phenomenon with important influence on all bearings parameters and performances. During bearing operations contact exists between the parts of the bearing as assembly and also between the inner race of the bearing and the shaft.

Therefore, the calculation of the deformations and stresses in the contact parts is very important task during researching ball bearings regardless of the aspect of the research. The FEM is the most suitable for these calculations, so this method is chosen for modelling and simulating the operation conditions in bearings.

Also, one of very important parameters for bearing performance is load distribution. In the presented research, this parameter is defined as the value of force with direction normal to the common tangent of contact surfaces of ball and inner race $F(t)$. This parameter will be shown as the force on a particular ball during bearing rotation.

All parameters mentioned before have a crucial influence on the load capacity and vibration characteristics of radial ball bearings. Identification and calculation of the main parameters of roller bearings require a precise calculation of deformation and stress state in parts of bearings assembly. The FEM is confirmed as the most suitable and accurate for these purposes [19-22]. Depending of the rolling bearing type which is the subject of research, 2-D or 3-D models in FEM have to be developed. In research presented in this paper one particular bearing type has been chosen. It is marked as SKF 6310 type of radial ball bearing, and the main geometric characteristics as well as working performances of this bearing type are described in catalogues of manufacturers [23]. Roller bearings of this type are often built in the machinery and equipment in power plants [24]. Also, bearings have very important impact on the energy efficiency [25, 26]. Therefore, the precise determination and assessment of the parameters of this type of ball bearings are a very important task.

Finite element analysis (FEA) of radial ball bearing

The radial ball bearings operate as the supports in only radial direction, so for calculation of the deformation and stress states of their parts, 2-D FEM has been developed [27]. The following assumptions are considered in FEA given in [18]: rotation speed has limited effect on the radial stiffness of ball bearings, the centrifugal and gyroscopic effects are ignored, the sliding friction force is negligible, bearing damping has mild effect on bearing dynamic because of elastohydrodinamic lubrication in ball bearings, and the shape and dimensions are accurate without defects. The verification of 2-D FEM for radial single row ball bearing is performed by experimental verification in SKF 6206 ball bearing type [28].The commercial software ANSYS 13.0 is used for finite element modelling and calculations. The FEM of SKF 6310 radial ball bearing with internal clearance of 10 μm is shown in fig. 1. The 2-D isoparametric finite elements with four nodes are used for discretization of all parts of bearing assembly, inner race, balls and outer race, as well as for modelling the deformable shaft in which the bearing is mounted on. The fixed assembly of inner bearing race and shaft is modelled with appropriate contact finite elements and settings which simulate this type of connection – close gaps and initial contact settings. Likewise, the contacts between the inner race and balls, as well as between the balls and outer race are modelled with not bounded contact pairs to simulate real working condition. Only the most loaded ball is in initial contact with inner race, and the other balls come in contact during some sub-steps of the FEA iterative procedure for contact analysis. The cage for maintaining the fix balls displacements is simulated in FEM with appropriate displacement constraints.

The working condition is considered in this analysis during a ball contact period. A ball contact period is defined as the period of time that corresponds to the ball positions from the moment (point) when a ball comes in contact to the moment (point) when a ball comes out of contact. This period is equal or less than one half of a circle (≤180°) [29]. Then, a particular ball is out of contact for rest of the time that corresponds to one rotation of the bearing.

For determination of the main bearing parameters, the quasi-static approach is used. Hereof, the series of FEM of radial ball bearings have been created, each for one particular moment (point) during a ball contact period. The angle that corresponds to the research bearing type is obtained by rotating the FEM of the bearing and is validated with analytical expressions [29]. The calculated angle that corresponds to the ball contact period for particular bearing type has a value of 168º [20].

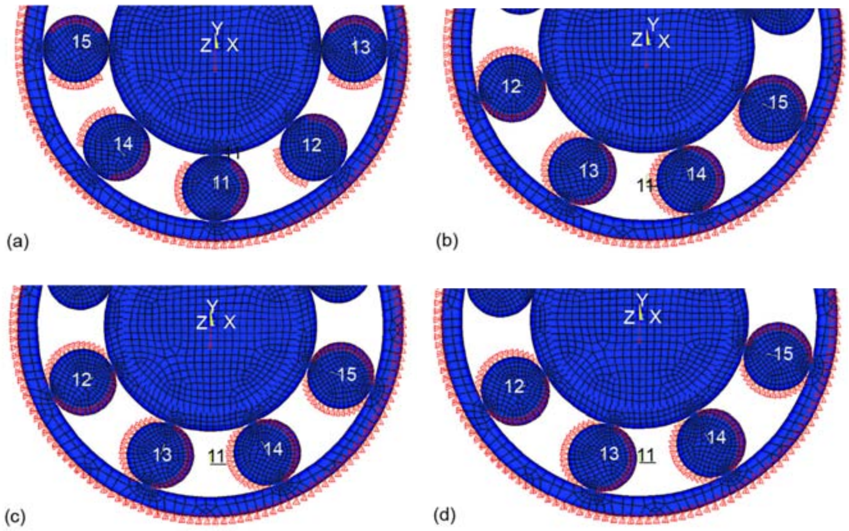

Figure 1. The FEM for few points during a ball contact period

In fig. 1 several model series are shown. In fig. 1(a) for first contact point of a ball contact period, in fig. 1(b) for point in angle of 12º from the first contact point, in fig. 1(c) for point in angle of 18º from the first contact point, and in fig. 1(d) for point in angle of 24º from the first contact point. The FEA calculations are performed for the external load of 5000 N and the results for equivalent stresses and for radial displacements are presented in figs. 2 and 3 for the same points during a ball contact period as points shown in fig. 1.

Results for main parameters on the referent temperature

The obtained results of FEA for the case of SKF 6310 radial ball bearing type, presented in figs. 2 and 3 are used for further calculation of the main bearing parameters. The results for equivalent stresses for few points during a ball contact period are presented in fig. 2 as better display then normal stresses in global radial direction, which fits with direction normal to contact only for the ball position with high distributed load. The radial ball bearing stiffness is calculated in accordance with the eq. (1) and the total radial deformation read from the FEA displacement results (fig. 3). The obtained value for average radial bearing stiffness is $40.98 \cdot 10^6$ N/m. From FEA series results, the force that each of balls in contact transfers during a ball contact period is read.

Figure 4(a) shows the results for load distribution during the time that corresponds to two rotations of the bearing when the rotation speed is n = 1000 min^{-1}. Figure 4(b) shows the same results during one ball contact period. The maximum values of contact stress appear in contact of ball and inner race surface, in every moment of bearing operation. The period for maximum equivalent stresses is equal to the angle of 45º, which correspond to the angle displacement between the balls (the bearing with 8 balls is research). Therefore, in fig. 5 the results for the variation of the equivalent stresses is shown for the angle that corresponds to the quarter circle. The nominal equivalent VonMises stresses is shown in fig. 5(a) and the relative equivalent VonMises stresses is shown in fig. 5(b).

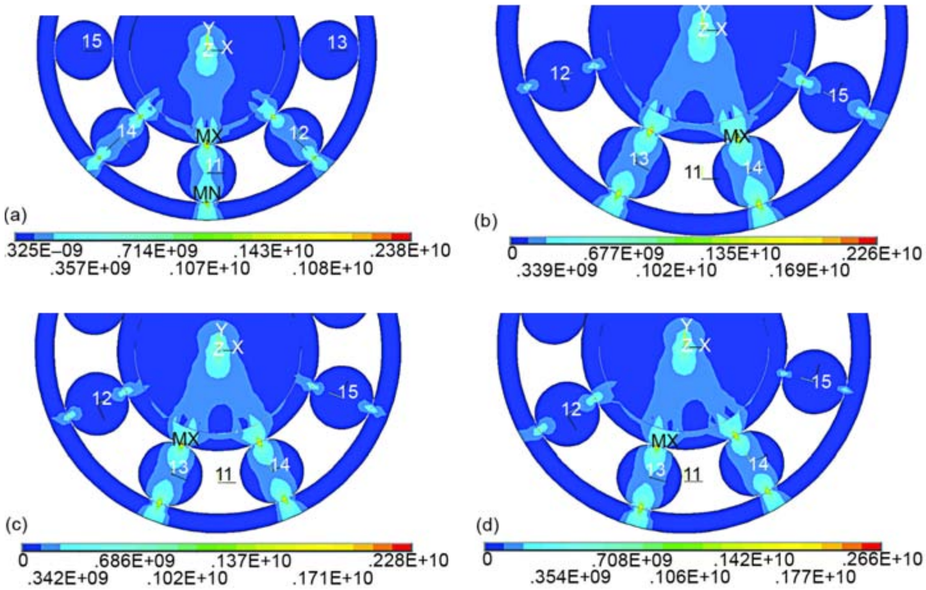

Figure 2. Results for equivalent stresses for few points during a ball contact period
(for color image see journal web-site)

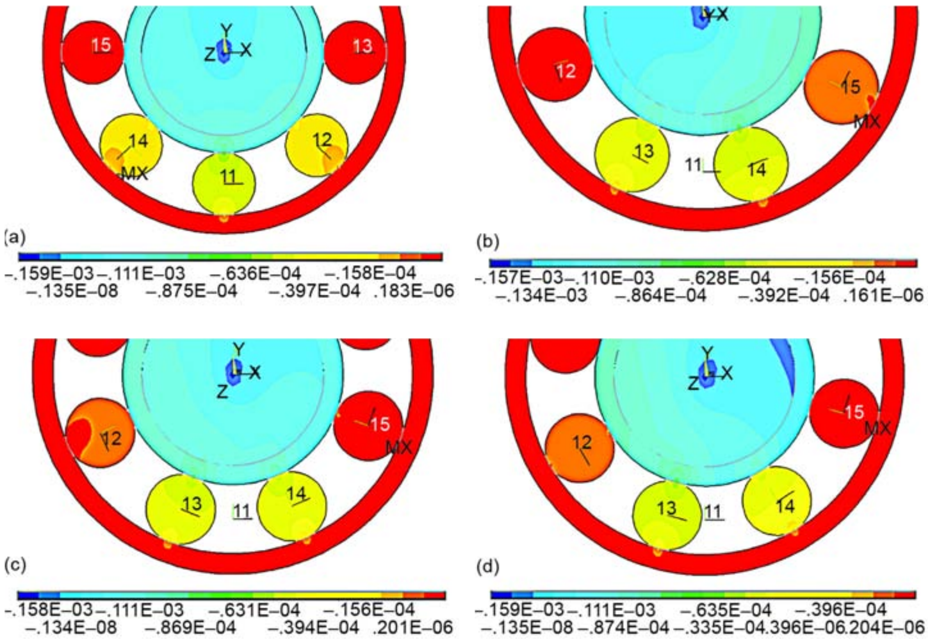

Figure 3. Results for radial displacements for few points during a ball contact period
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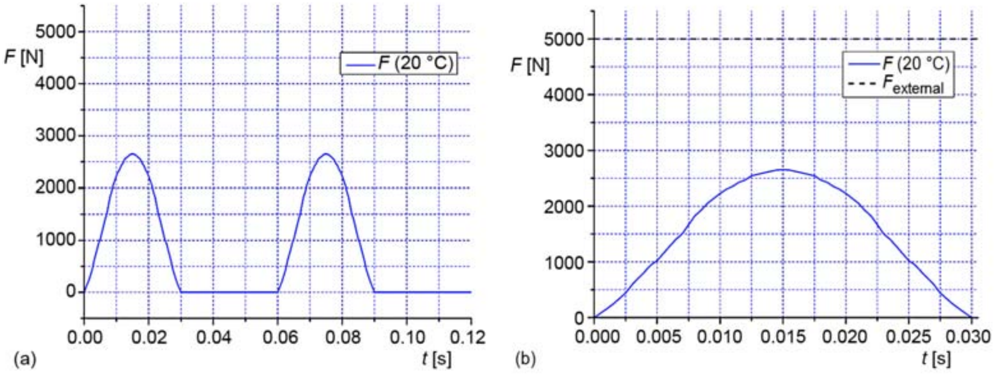

Figure 4. Load distribution: (a) during two rotations, (b) during a ball contact period

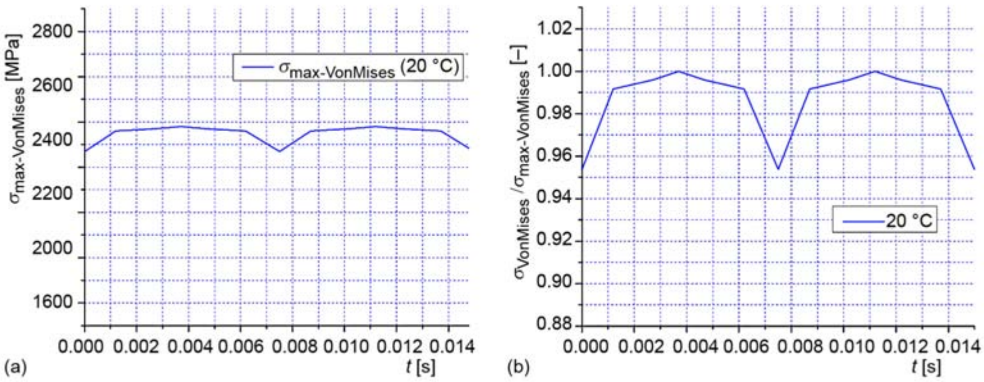

Figure 5. Contact stress: (a) equivalent VonMises stresses, (b) relative VonMises stresses

Material behaviour at different temperatures

Extensive study of steels for bearings is presented in reference [8]. In this study as one of the basic bearing steels is noted 100Cr6 steel – material for ball bearing type research in this paper. This steel belongs to the group of bearing steels that is not ductile, which means that usual elongation is less than 2% which correlates with delivery condition, quenched with subsequently tempered state. The value of elongation is not reported in data sheets for this steel, instead the value of hardness, with usual range of 59-66 HRC [8]. The higher value of hardness is obtained to reduced wear, *i. e.* higher values of hardness correlate positively with rolling contact fatigue life. However, this correlation of wear against hardness fails in tests involving the unlubricated sliding of 100Cr6 steel against a much harder ring [9] because of the effects of heat generation on material removal. The basic tensile properties as a function of temperature are presented in tab. 1. The 100Cr6 steel is not intended for elevated

Table 1. Tensile properties as a function of test temperature [10]

Temperature [°C]	20	200	400	600
Yield strength [MPa]	1394	1161	908	414
Reduction of area [%]	1.0	2,0	1,6	1,5
Young's modulus [GPa]	208	163	154	113
Thermal expansion coefficient	$12.5\cdot10^{-6}$ K^{-1} (20 °C to 150 °C)			

temperature service but the data are nevertheless useful in FEA [10]. Also, the results from table 1 are similar to the results presented in references [11, 12].

The coefficient of thermal expansion is incorporated in the total strain vector in the basic equation of FEM.

Effect of operation temperature on SKF 6310 bearing parameters

In the FEA calculations performed in order to solve the main parameters of ball bearings the instantaneous coefficient of thermal expansion is used. In accordance with the defined characteristics of the bearing material [8] and the temperature range in which the calculations are performed, the constant value for instantaneous coefficient of thermal expansion of 12.5 S 10^{-6} K^{-1} is input. The room temperature of 20 °C is defined as the referent temperature (the temperature at which all strains are zero).

For operation temperature of 50 °C, 80 °C, and 120 °C the new series of FEA are performed. The angle that corresponds to a ball contact period is read from the FEA calculations and has a value of 174º for the operation temperature of 50 °C, the value of 180º for the operation temperature of 80 °C and the value bigger than 180º for the operation temperature of 120 °C. The confirmation of these results is obtained by analysing the graphs of load distribution during a ball contact period for the operation temperature of 20 °C, 80 °C, and 120 °C, fig. 6. It is clear that the operation of bearing is impossible in the temperature higher of 80 °C, because the thermal strain has a value which cancels the initial clearance of the radial bearing (clearance has a value of 10 μm for the particular modelled bearing type). In the graphs of load distribution over contact period, shown in fig. 7, this problem is very obviously noticeable by the stepped changes of the load when operation temperature is 120 °C. Also, it is very important to analyse the graph for load distribution when operation temperature is 80 °C (fig. 8). The two zoomed details show the periods with five balls in contact, while in the case of the operation in all temperatures lower than 80 °C these periods do not exist, only the periods with three and four balls change each other during bearing rotation. The explanation of this appearance exists in the relation between the initial radial clearance, thermal expansion strains and contact deformations of the parts of the bearing assembly. A more detailed research of different radial ball bearing dimensions and initial radial clearance values should be performed to define the formula that explains this relation.

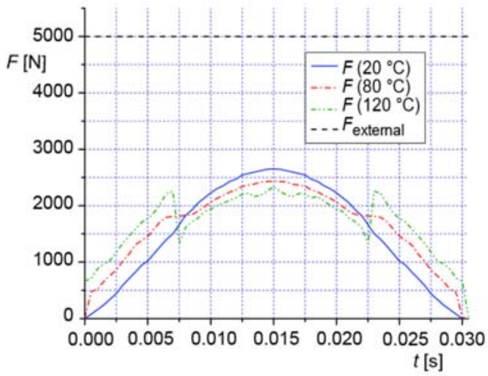

Figure 6. Load distribution during a ball contact period for different operation temperature

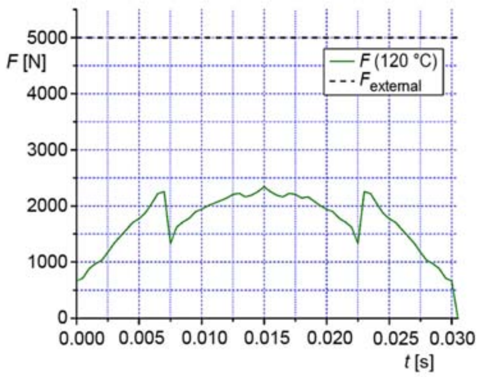

Figure 7. Load distribution during a ball contact period for operation temperature of 120 °C

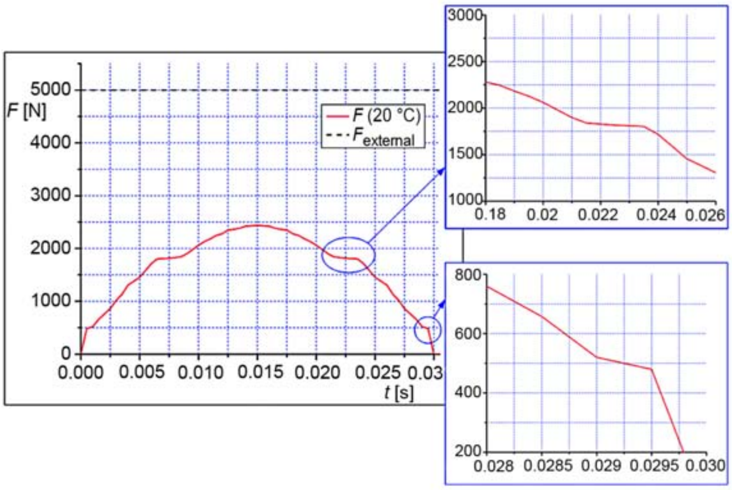

Figure 8. Load distribution during a ball contact period for operation temperature of 80 °C with detail zoom

The explained procedure could be used for determination of the optimal range of the operation temperature. In this particular case of radial ball bearing, the range of temperature for optimal operation is from 20 °C to 80 °C. The temperature higher than the maximum operation temperature obtained by this procedure will obviously lead to cancelling the initial radial clearance and cause operation problems.

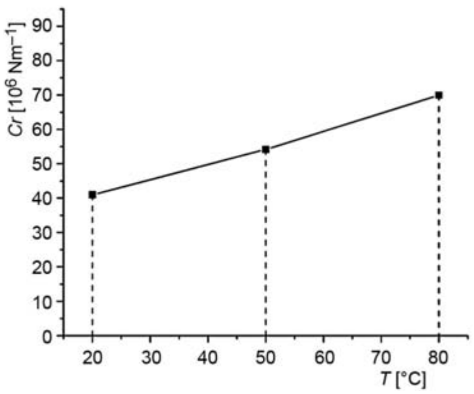

Figure 9. Radial bearing stiffness in function of operation temperature

In accordance with this conclusion, in future research presented in this paper, the comparative analyses are performed for the ball bearing operation parameters at operation temperature of 20 °C (reference temperature), the operation temperature of 50 °C, and at operation temperature of 80 °C (maximum operation temperature). Figure 9 shows the results obtained for average values of radial bearing stiffness at operation temperatures of 20 °C, 50 °C, and 80 °C. The trend of radial stiffness increasing with operation temperature increase is evident.

The results for equivalent stresses comparative analysis for the operation temperature of 20 °C and 80 °C are shown in fig. 10. The results for monitoring the variation of the equivalent stresses is shown for the angle that corresponds to the quarter circle. In fig. 10(a) the nominal equivalent VonMises stresses is shown and in fig. 10(b) the relative equivalent VonMises stresses is shown. Although it seems that the load capacity of the bearing increases with temperature increase, it is not a correct conclusion, because the material strength decreases with operation temperature increase, tab. 1.

Conclusions

The complex research of effects of operation temperature on main parameters and performances of radial ball bearing is presented in this paper. As the main parameters for the operation temperature influence assessment, the following parameters are defined and ana-

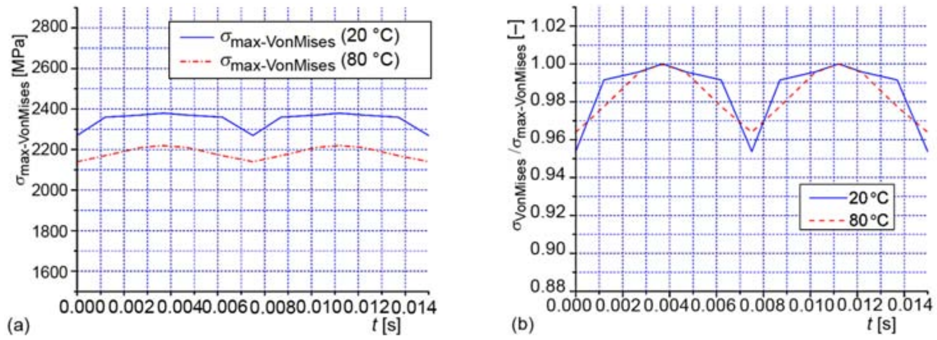

Figure 10. Comparative results for contact stress for different operation temperature; (a) equivalent VonMises stresses, (b) relative VonMises stresses

lysed: radial deformation, radial stiffness, equivalent contact stresses, and load distribution during a ball contact period. The contact FEA series are performed in order to calculate all bearing parameters for different operation temperatures. The specific procedure is defined for determination of the optimal range of the operation temperatures. For the particular radial ball bearing type, the usage of this procedure is shown. The conclusion that the temperature higher than the maximum operation temperature will obviously lead to problems in bearing operation is explained from obtained results.

It is shown that the radial stiffness increases when operation temperature increases. Although, the nominal equivalent VonMises stress decreases when operation temperature increases, this is not the load capacity of the bearing increasing, because the material strength decreases with operation temperature increasing.

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