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NUMERICAL DETERMINATION OF THE CARRYING CAPACITY OF ROLLING ROTATIONAL CONNECTIONS

NUMERIČNA DOLOČITEV NOSILNOSTI VTRLJIVIH KOTALNIH ZVEZ

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The exploitation of large axial bearings includes load peaks, which cause permanent deformation of the rolling contact. The plastic strain of the base material under the hardened rolling layer starts to grow and micro-cracks on the edge of the hardened layer and the peeling of this layer may occur. In our computation we have used an elasto-plastic model that combines isotropic and kinematic hardening and the growth of material damage. The damage model allows us to follow the variation of the elastic and plastic stress and deformation as a function of the number of cycles. In the article, an experimental verification of the described numerical model is shown, which can be used to determine the actual carrying capacity of the rolling contact for low-speed axial bearings.

Key words: rotational connections, low cycle fatigue, cyclic plasticity, damage

Pri uporabi velikih aksialnih ležajev se pojavljajo preobremenitve, ki povzročijo trajno deformacijo ležajnega kontakta. Plastična deformacija osnovnega materiala pod utrjeno ležajno površino začne rasti in lahko nastanejo mikrorazpoke na robu kaljene plasti ter njeno luščenje. Pri našem izračunu smo uporabili elastoplastični model, ki kombinira izotropno in kinematsko utrjevanje ter rast poškodovanosti materiala. Ta model omogoča sledenje spremembe elastoplastične napetosti in deformacije kot funkcijo števila ciklov. V članku je opisana eksperimentalna verifikacija opisanega numeričnega modela, ki ga lahko uporabimo za določitev prave nosilnosti ležajnega spoja za aksialne ležaje, ki delujejo pri majhni hitrosti.

Ključne besede: vrtljiva zveza, malociklična utrujenost, ciklična plastičnost, poškodbe

1 INTRODUCTION

Bearings are among the most frequently used elements in machine engineering. Owing to their widespread use, the requirements that a bearing must meet are highly diverse. Bearing use ranges from applications in which a bearing collapse does not constitute a major problem, to applications where the collapse of a bearing could lead to enormous economic losses and potentially disastrous consequences for people. The large bearings used in rolling rotational connections are an example of such an application.

The basic element of a rotational connection is a large rolling bearing, with attachment holes in the bearing rings, and a gear wheel (**Figure 1**). Alloyed steels such as 42 CrMo 4 and C 45 – ISO 683/1 are normally used in the production of bearing rings since the process requires thermal and mechanical treatments. The raceway is surface-hardened to attain the minimum hardness necessary to prevent the pressing-in of the rolling element. The actual external load and the elasticity of the upper and support structures cause an uneven distribution of the external loads over the rolling bearing's diameter [1-3]. This leads to local plastic deformations of the bearing raceway and to the initiation of damage, largely conditioned by the load size and material fatigue [4-5]. The existing models for determining the carrying capacity of large rolling-bearing connections with surface-hardened raceways do not fully consider or even greatly simplify the actual state of the bearing ring [3-12].

In analyzing the actual carrying capacity of rolling contacts in large rolling bearings with surface-hardened raceways we have decided to use a combined elasto-plastic constitutive model, which links the material

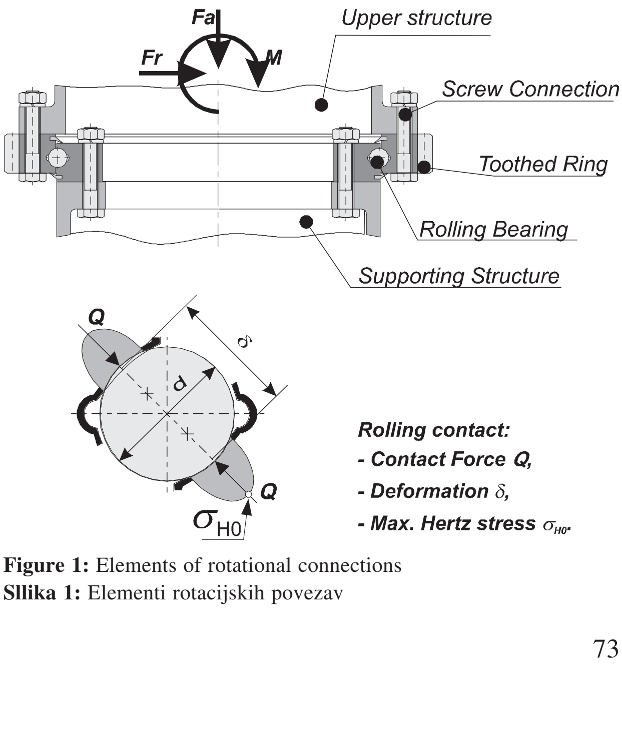

Figure 1: Elements of rotational connections
Sllika 1: Elementi rotacijskih povezav

damage mechanics with the isotropic and kinematic hardening/softening [13-15]. The material model considers 17 material parameters, selected from a series of monotone and cyclic experimental tests. The model, which was built in the finite-element code, was used to investigate the development of elasto-plastic deformations, stress areas and damage occurrence for low-cycle loads that occur in the raceways of large rolling bearings at a low rotational speed. In the article an experimental verification of the described numerical model is shown, which can be used for the determination of the actual carrying capacity of the rolling contact in low-speed axial bearings.

2 NUMERICAL MODEL

A developed and built-in finite element is used in the application of a numerical model focusing on the rolling contact between a raceway model and a rolling element, and is carried out in the ELFEN© commercial software environment. The discretisation of a bearing raceway's geometric model applies a developed finite element that covers isotropic hardening/softening, kinematic hardening and material damage [13-15]. This makes it possible to monitor the actual low-cycle development of the strain deformation or the hardening/softening and material damage growth. The end code of a developed element is written in the FORTRAN programming language. The geometry of the contact between the rolling element and the raceway is determined with square surface-contact elements (**Figure 2**).

The numerical model of a rolling contact considers the actual geometrical and material characteristics of bearing raceway models. The characteristics of a bearing ring model change in line with the raceway depth. After having measured the changes in hardness along the cross-section of a bearing raceway model, we entered various material parameters into the damage model.

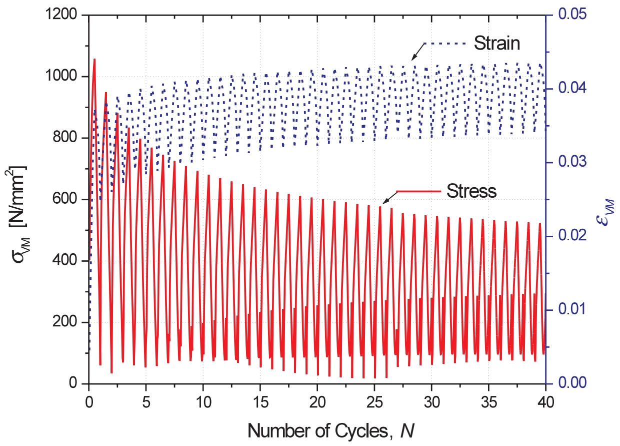

Figure 3: Development of the stress σ_{VM} and strain ε_{VM} paths on the edge of the raceway-model hardened layer
Slika 3: Razvoj napetosti σ_{VM} in deformacije ε_{VM} na robu utrjene plasti ležajne tečine

These parameters were derived from the results obtained from single-axis monotone and cyclic tear tests [13]. In describing the material characteristics of raceway models, we also took into account the remaining material stresses that occurred during the production of the test raceways [14].

3 NUMERICAL RESULTS

The numerical rolling-contact model was used to simulate a contact of the rolling element and a surface-hardened bearing raceway at a varying contact force from F_{max} = 35.2 kN to F_{min} = 1 kN. The model enables every element to be assigned its deformation strain state and growth of damage relative to the number of contact load cycles. **Figure 3** shows the evolution of the equivalent von Mises stresses σ_{VM} and strains ε_{VM} at the location of maximum-damage accumulation for the first 40 loading cycles, and **Figure 4** shows a distribution

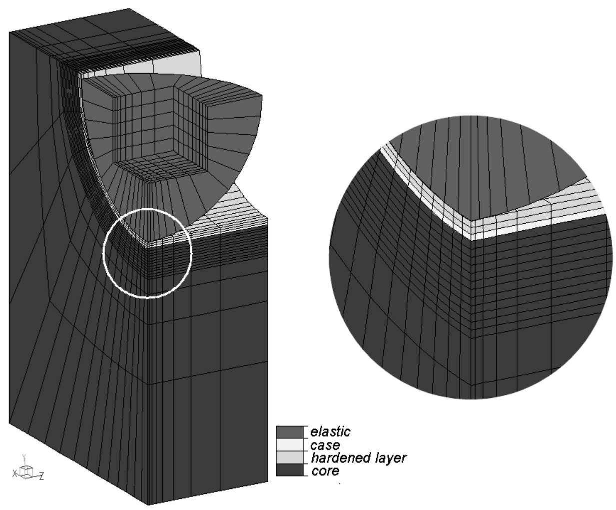

Figure 2: Numerical model
Slika 2: Numerični model

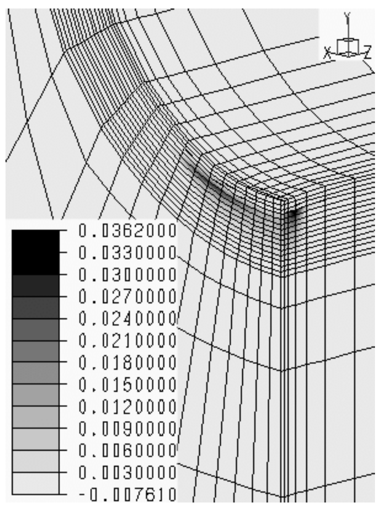

Figure 4: Damage distribution in 3D model after 100 load cycles
Slika 4: Porazdelitev poškodbe v 3D-modelu po 100 nihajih

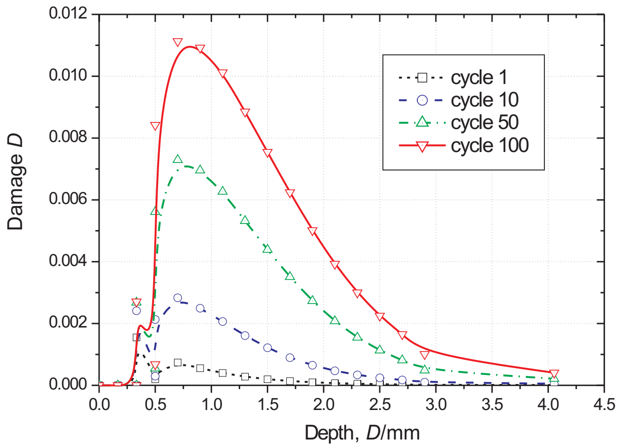

Figure 5: Damage distribution in ring depth
Slika 5: Porazdelitev poškodbe v globino ležajnega obroča

of the damage after 100 contact force cycles. In contrast, **Figure 5** shows the damage distribution along the ring depth that determines the damage accumulations in the base material on the edge of a hardened layer. The carrying capacity of the raceway model for rolling elements of different diameters was determined on the basis of a diagram showing the growth of material damage relative to the number of load cycles (**Figure 5**)[14].

4 VERIFICATION OF THE MODEL

A comparison of the results of the experimental work and the numerical calculations of the contact between the raceway model and the rolling element can only be made by comparing the directions of the maximum total and permanent displacements of the bearing-raceway model. The comparison shows an even development of the raceway-model displacements and thus supports the use of the proposed mechanical and mathematical models to

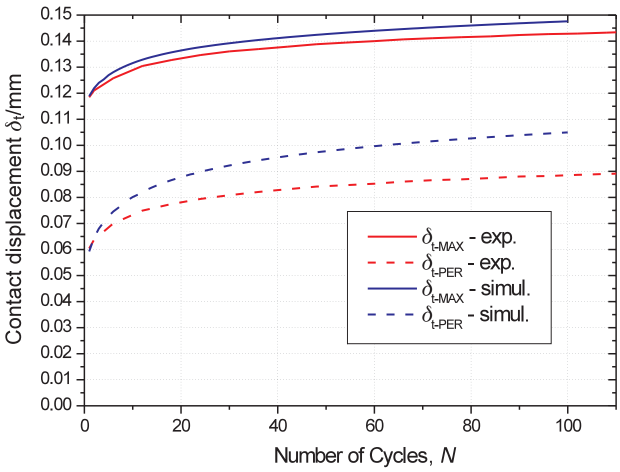

Figure 6: Comparison of the development of measured and calculated total and permanent displacements of the raceway-model damage distribution
Sllika 6: Primerjava razvoja izmerjenega in izračunanega skupnega in permanentnega pomika za porazdelitev poškodbe ležajne tečine

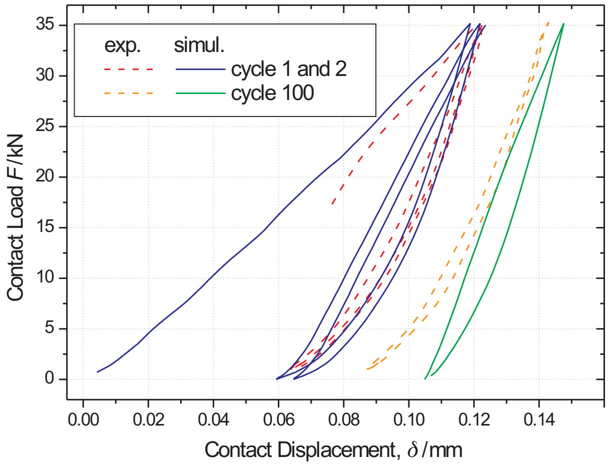

Figure 7: Comparison of the development of the measured and calculated displacement-contact force hysteresis of the raceway-model damage distribution
Sllika 7: Primerjava razvoja izmerjene in izračunane histereze v kontaktni sili za porazdelitev poškodbe ležajne tečine

determine the carrying capacity of large rolling bearings. There is a close match for the initial values of the measurements and the numerical calculations of the total and permanent displacement of the bearing raceway (**Figure 6**).

The matching is also evident from the comparison of the results obtained from measurements and numerical calculations of the first displacement-contact force hysteresis loop (**Figure 7**). Even when they are subjected to different loads and different geometric contact models, the measured and the calculated results of the total and permanent raceway displacements, which depend on the number of cycles, match closely their initial value and the deformation growth gradient [14].

5 CONCLUSION

The determination of the low-cycle carrying capacity of a large bearing raceway with the numerical model material behavior, which is applied with the finite-element method, is very effective. The model takes into account the geometric and construction characteristics of the bearing rings, the raceways, and the rolling elements as well as the material characteristics of the surface-hardened raceways, which link the continuum damage dynamics with the isotropic and kinematic hardening/softening. With regard to the expected loads and the geometric limitations of the rotational connection, both the geometry of the contact between the raceway and the rolling element as well as the heat treatment of the bearing rings can be optimized. We can also assess the life expectancy of a rotational connection, i.e., the time and location of the initiation of the macro-cracks on the surface-hardened bearing raceway.

Further investigations into the carrying capacity of a surface-hardened bearing raceway are focused on the possibility of upgrading the material model with a rheological model for a description of the natural limits of the material yield, which occurs in the normalized and optimized bearing-ring base material, and with a model to describe the growth of a crack and the life expectancy of heat-treated steels used for bearing raceways.

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