The influence of operating temperature and bearing steel structure in shakedown of three-dimensional elastic-plastic rolling contacts

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Abstract. This paper describes a model for the prediction of micro-plastic material transformation and associated residual stress field development in through-hardened and case-hardened bearing steels during over-rolling, considering the influence of operating temperature. The main challenge in analysing three-dimensional elastic-plastic rolling contacts is the accurate description of material properties in case of two-phase material, either is a constant amount of retained austenite (through-hardened AISI 52100 bearing steel) or variable amount of retained austenite along depth (case-hardened steel, i. e. 16MnCr5 bearing steel). Material parameters at room temperature, 65^0 and 100^0 C degrees were obtained by half-compressive cycles tests on an INSTRON^{TM} apparatus with a climate cell and further verified by performing experimental and numerical analyses in case of static indentation between a ceramic ball and a flat steel plate. To check the ability of the proposed models to simulate the elastic-plastic rolling contact in various loading condition, experiments were made on a special designated test rig and recorded values were compared with the numerical simulations obtained by using a semi-analytical solver. Measurements of residual cyclic profiles and residual stresses show a good agreement with theoretical values, leading to a better understanding of the fatigue process in hardened bearing steels.

1. Introduction

Through-hardened and case-hardened bearing steels were investigated. Their elastic-plastic behaviour shows important differences regarding the shakedown phenomenon. Retained austenite level, either is constant (through-hardened steel) or variable (case-hardened steel), plays a major role on the final values of plastic quantities (plastic displacements and residual stresses).

Through-hardened AISI 52100 bearing steel with a structure consisting of martensite and 13% retained austenite was modelled as combined isotropic and kinematic material, with non-linear hardening. Due to the cyclic stress-induced transformation of retained austenite (depending on the local value of the equivalent stress) the micro-yield limit increases and shakedown will be faster compared to the steels with low retained austenite, [1]. Because the austenite level is almost constant along the depth, the material's plastic parameters can be obtained by performing monotonic or half-compressive tests. Parameters describing the influence of retained austenite (the size of the yield surface and the plastic strain rate) are modelled by using the Armstrong-Frederick non-linear law, [2]. In the elastic-plastic analysis, Prandtl-Reuss equations [3] were used in association with von Mises flow rule. 16MnCr5 case-hardened steel also presents combined isotropic-kinematic non-linear behaviour. Because of a wide range of typical carburizing steels, every grade must be analysed

individually. The case microstructure consists of high-carbon martensite with retained austenite. The initial yield depth profile can be associated with martensitic structure, but also the retained austenite contributes to hardness. The interdependence between initial yield limit, carbon content, and retained austenite cannot be easily quantified. The alloying elements may also play a significant role in the plastic behaviour. Böhmer et al. [4] investigated the rolling contact fatigue behaviour of heat resistant bearing steels at high operational temperatures and shows the influence of load and temperature on the characteristic deformation number for SAE 52100 at low rotational speed. The characteristic deformation number is defined as the Hertzian pressure at which the rolling contact fatigue endurance limit supersedes due to the occurrence of plastic deformation affecting the residual stresses.

Voskamp [5] made extensive research to investigate the relation between microstructure and the rolling contact fatigue properties of bearing steel at various operating temperatures, showing the alterations of the steel microstructure at various contact loads. No material models were used, but the experimental values of the residual stresses were of great importance in validating new material models and numerical programs in analysing the elastic-plastic cyclic rolling contact.

2. Theoretical model for elastic-plastic material properties as affected by temperature

In case of AISI 52100 through-hardened bearing steel the initial level of retained austenite depends mainly on the austenitizing temperature. Since the carbon distribution and initial yield limit present small variations along the depth, the material plastic behaviour can be obtained from monotonic or half-cycle compressive tests. In order to quantify the influence of retained austenite in case of cyclic loading in the elastic-plastic domain, a non-linear relation proposed by Armstrong and Frederick was used. As effect of stress-induced transformation of retained austenite, the micro-yield limit increases locally, based on the relation:

$$\sigma_{YIELD} = \sigma_E + Q_\infty \cdot (1 - e^{-b \cdot \varepsilon^{pl}}) \tag{1}$$

where Q_∞ represents the size of the yield surface, σ_E is the elastic limit, b is the plastic strain rate and ε^{pl} is the total equivalent plastic strain. If Q_∞ is positive, then is isotropic hardening, while if Q_∞ is negative is soft hardening.

Performing repeated half-compression cycles on cylindrical bars 3 mm round and 7 mm length, on an INSTRON^{TM} device equipped with a climate cell, equivalent stress-equivalent plastic strain dependence as affected by temperature is given in figure 1. The influence of temperature can be seen in small variations of Young's modulus, E, as in Gupta [6], and Poisson's coefficient, υ, but the major change was in the size of the initial yield surface (table 1). Even the initial amount of retained austenite was around 13% in all samples, increasing the operating temperature results in a drop of this parameter (i.e. temperature-induced transformation). In the same time, the value of the plastic strain rate could be considered constant, assuming that depends only of the type of loading (tensile or compressive). The obtained material parameters which describe the plastic behaviour based on non-linear Ramberg-Osgood strain-stress relation (2) are also given in table 1.

$$\varepsilon = \frac{\sigma_E}{E} + \left(\frac{\sigma_E}{B}\right)^N \tag{2}$$

Table 1. Material parameters for kinematic and isotropic hardening behaviour of 52100 bearing steel.

| Parameter	Room temperature	65^0 C	100^0 C
E [MPa]	214,000	212,000	210,000
σ_E [MPa]	1,400	1,150	950
Q_∞ [MPa]	2,200	1,950	1,700
B [MPa]	4316.67	8386.26	5608.16
N [-]	12.603	10.965	9.177
b [-]	245	245	245
υ [-]	0.281	0.2816	0.2825
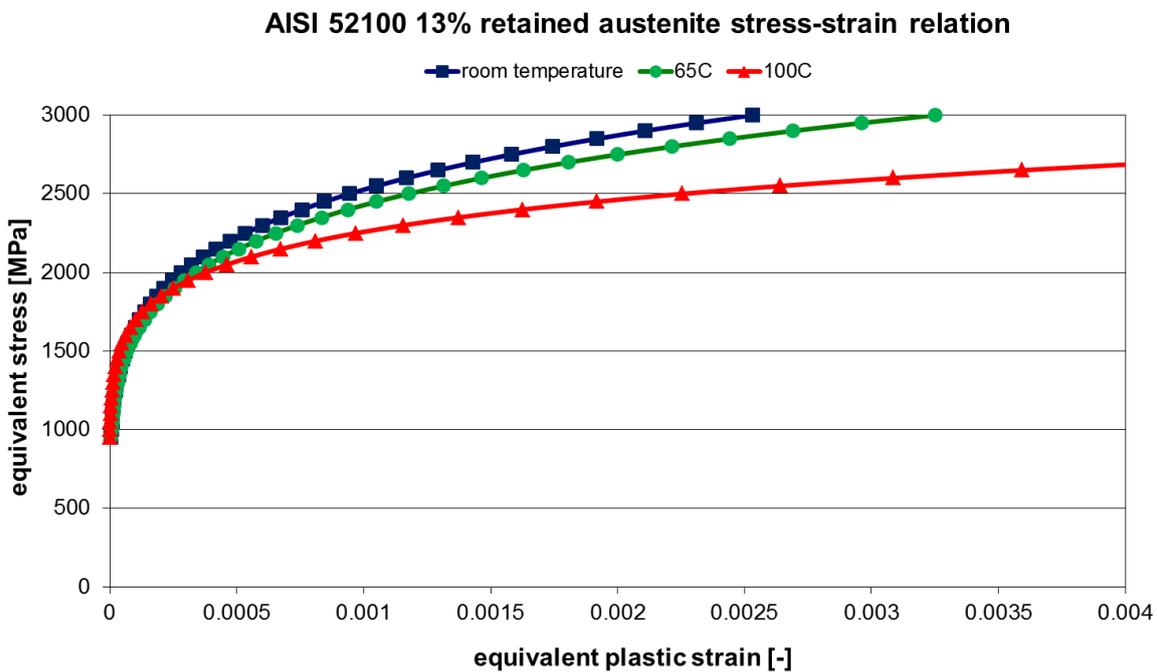
Figure 1. Ramberg-Osgood non-linear representation of the flow curve for 52100 bearing steel.

The 16MnCr5 carburized bearing steel is characterized by a large number of material parameters that depend on the carbon concentration along the depth, variable hardness of the core and the case, and the percentage of the retained austenite that also varies along depth. More, the initial yield limit presents variations due to variable carbon content along depth, [7]. Vincent [8] investigated the influence of carbon content in 16NiCrMo13 case-hardened steel and, similar as Petterson [7], showed that Young's modulus is weakly affected by the surface treatment, and can be considered constant for all carbon concentrations along depth. A material model that incorporates all the above mentioned parameters previously developed by the author [1, 9] was extended to include the influence of the operating temperature in case of elastic-plastic static and rolling contact.

3. Experimental results and correlation with theoretical results

Test roller specimens round 18 mm and 30 mm length were used for both materials. A special test rig with two ceramic rollers 19.05 mm diameter (Young modulus 315,000 MPa and Poisson coefficient 0.26) pressing on the test roller with various contact pressures: 3.2, 4, 4.5 and 5 [GPa].

The operating temperature inside the sealed chamber is obtained using a heat gun and is measured by an infrared sensor (65 and 100 Celsius degrees). Under load, the roller will suffer permanent deformation and residual profiles (along x-transverse axis) were recorded by laser profilometry.

Some results are presented in the next figures. Residual circumferential stress (y-axis, rolling direction) for various loading cases, theoretical and experimental values are presented in the next figures.

Theoretical contact model is developed based on Prandtl-Reuss equations associated with von Mises flow rule, [3]. The plastic deformation model consists of an isotropic part, as a result of cyclic austenite transformation, and a kinematic part, as a result of cyclic residual stresses. All plastic quantities (plastic strains, residual stresses and deformations) are derived analytically, based on an improved Chiu's model [10, 11].

In all cases the shakedown is attained very fast, lest than 100 rolling cycles for the AISI52100 steel and less than 20 rolling cycles for 16MnCr5 case-hardened steel. This particular aspect is related to the

AISI 52100, 65 Celsius degress, contact pressure 4.5 GPa
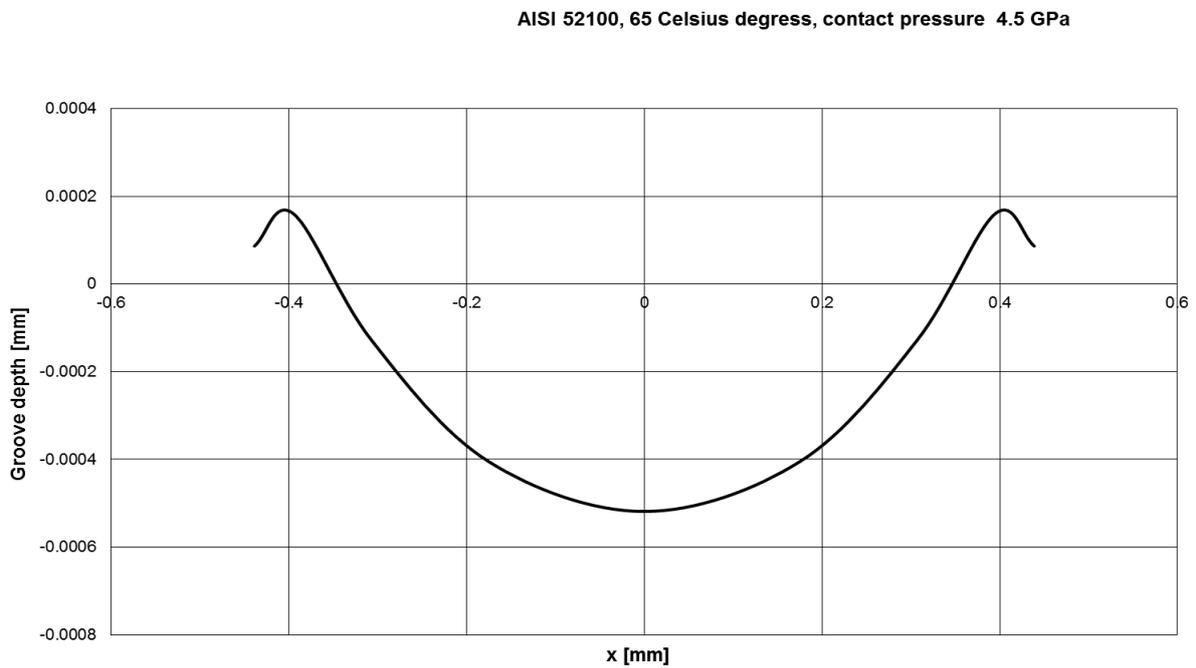
Figure 2. Theoretical residual roller profile at shakedown, AISI bearing steel loaded at 4.5 GPa and 65^0 C.

AISI 52100, 65 Celsius degrees, contact pressure 4.5 GPa
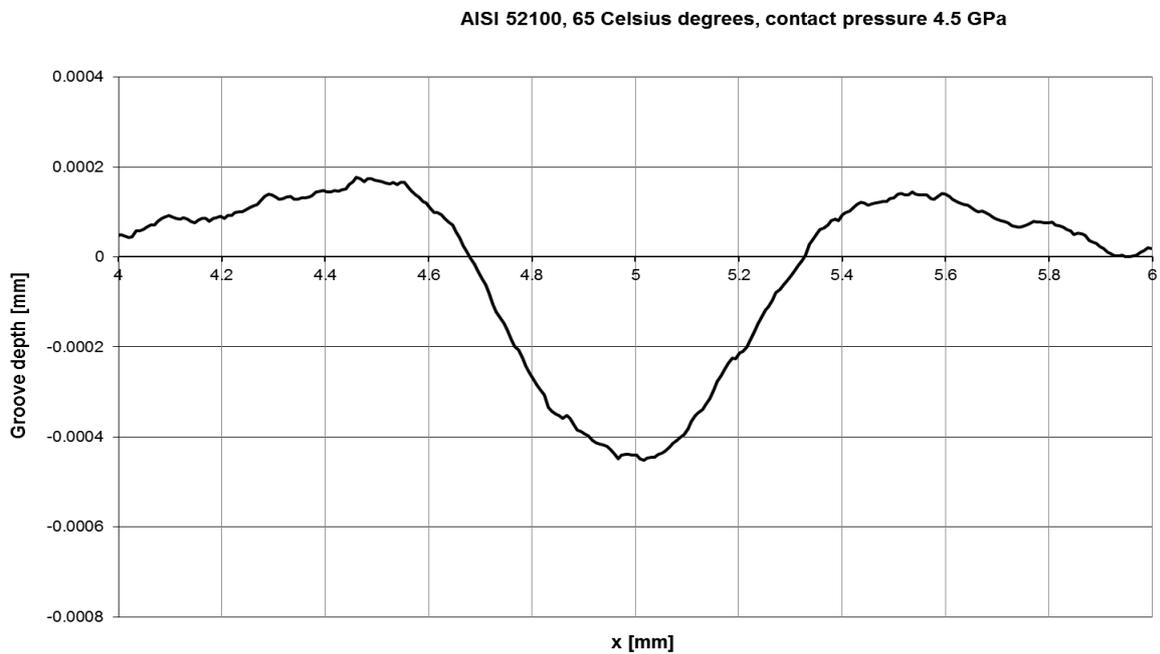
Figure 3. Measured residual roller profile at shakedown, AISI bearing steel loaded at 4.5 GPa and 65^0 C.

AISI 52100, 100 Celsius degrees, contact pressure 4.5 GPa
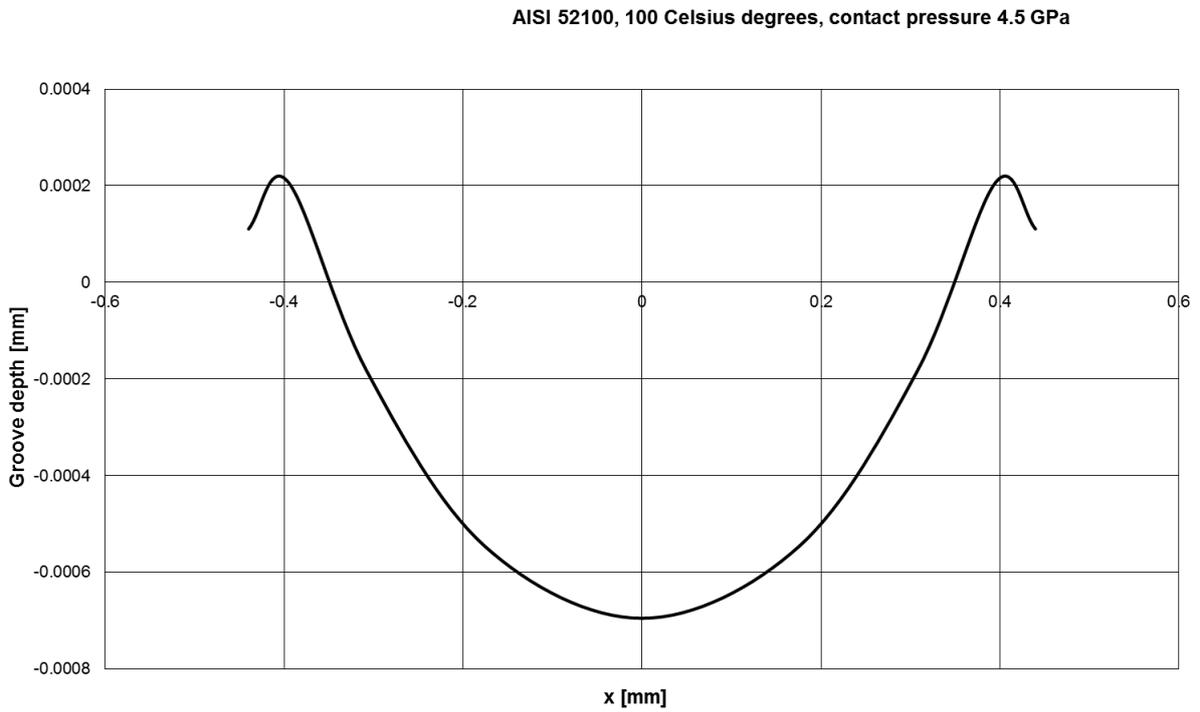
**Figure 4.** Theoretical residual roller profile at shakedown, AISI bearing steel loaded at 4.5 GPa and 100^0 C.

AISI 52100, 100 Celsius degrees, contact pressure 4.5 GPa
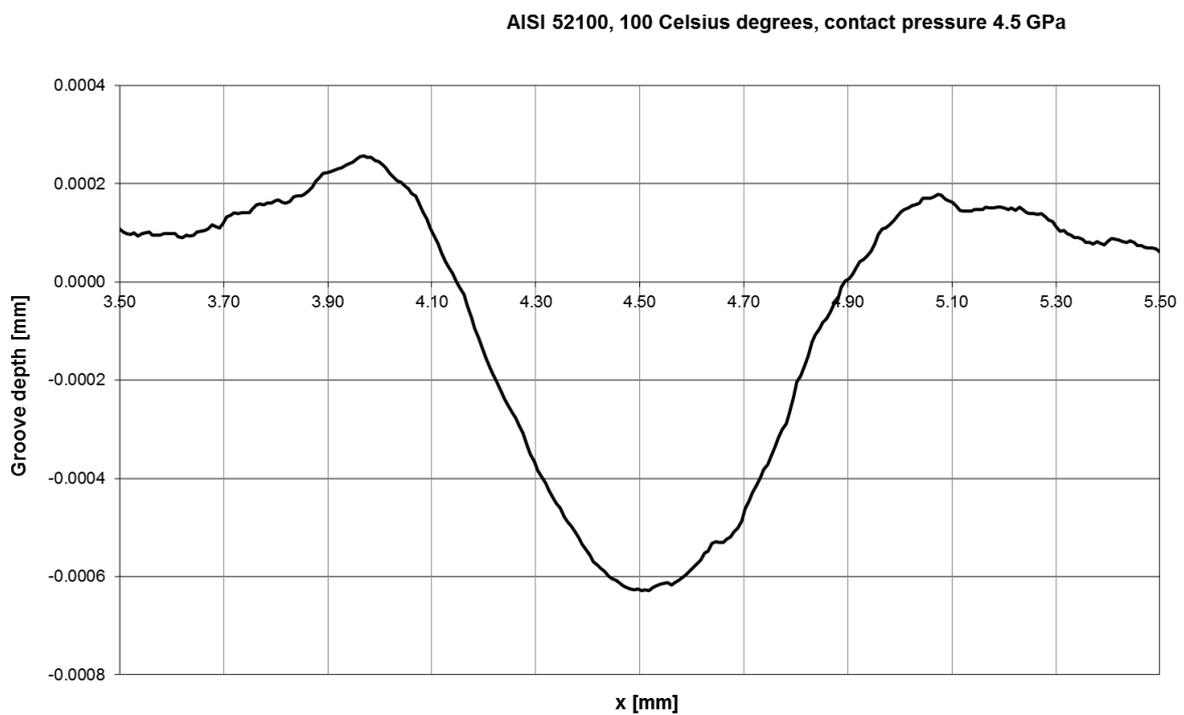
Figure 5. Measured residual roller profile at shakedown, AISI bearing steel loaded at 4.5 GPa and 100^0 C.

16MnCr5, 100 Celsius degrees, contact pressure 5 GPa
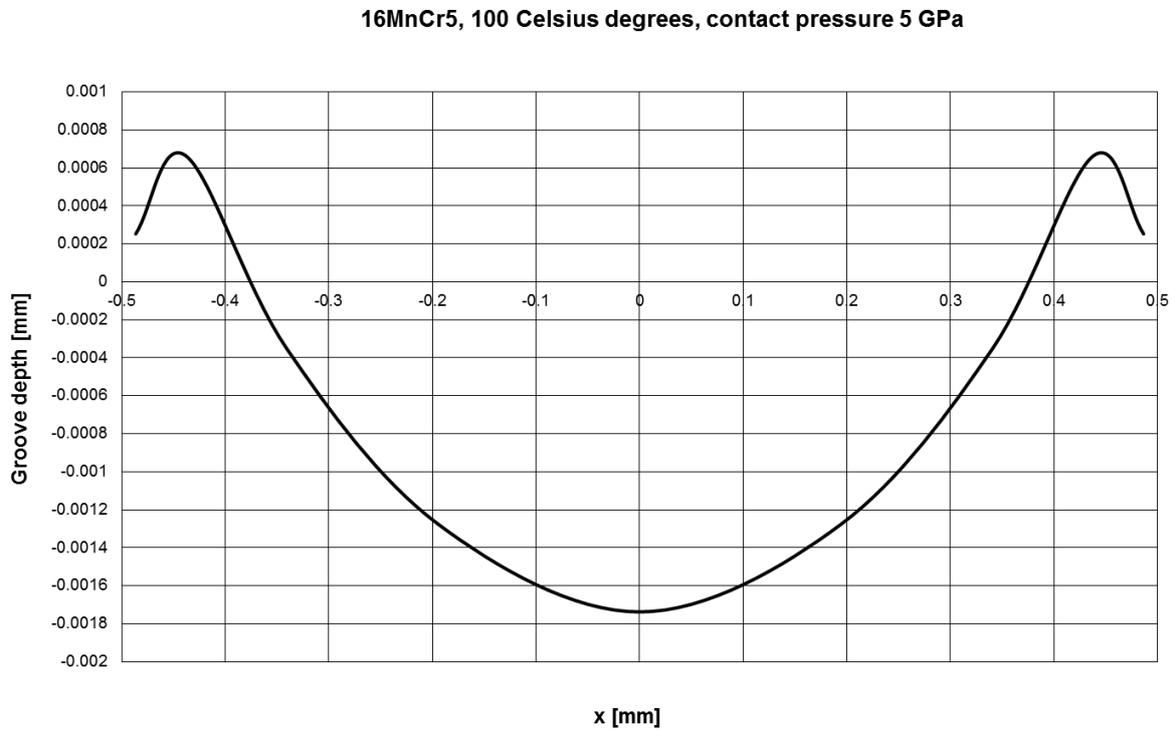
Figure 6. Theoretical residual roller profile at shakedown, 16MnCr5 bearing steel loaded at 5 GPa and 100^0 C.

**16MnCr5, 100 Celsius degrees, contact pressure 5 Gpa**
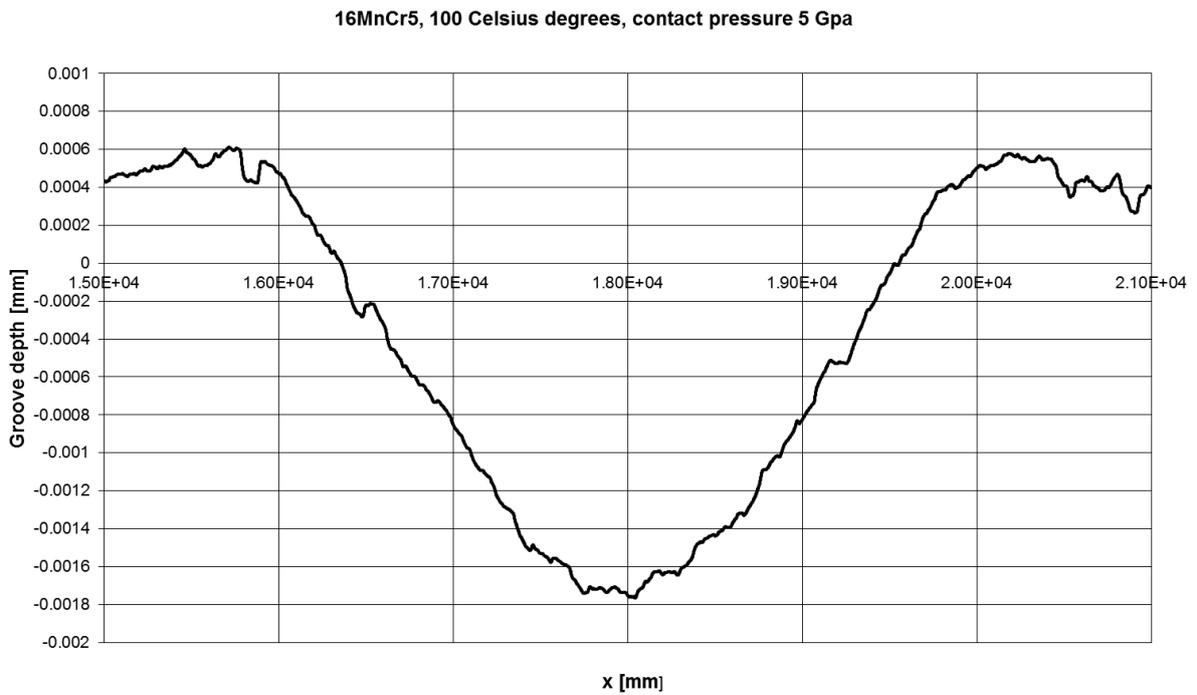
Figure 7. Measured residual roller profile at shakedown, 16MnCr5 bearing steel loaded at 5 GPa and 100^0 C.
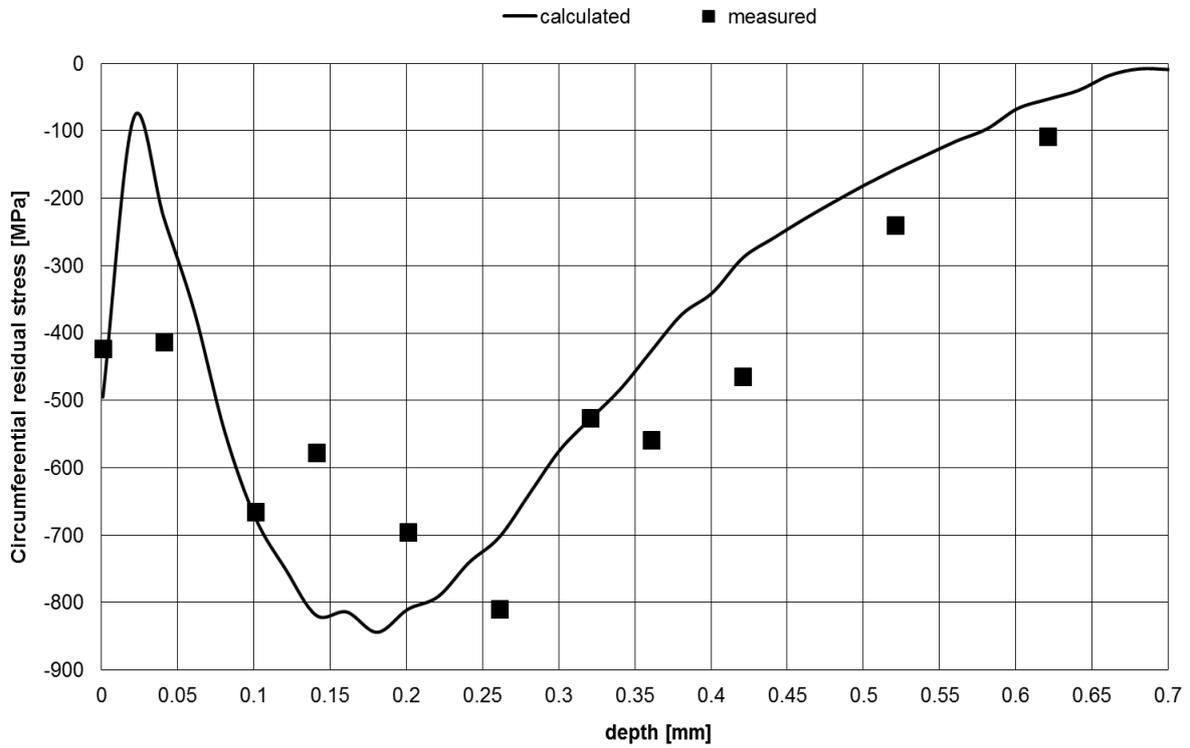
Figure 8. 16 MnCr5, residual circumferential stress at shakedown in case of 5 GPa contact pressure operating at room temperature.
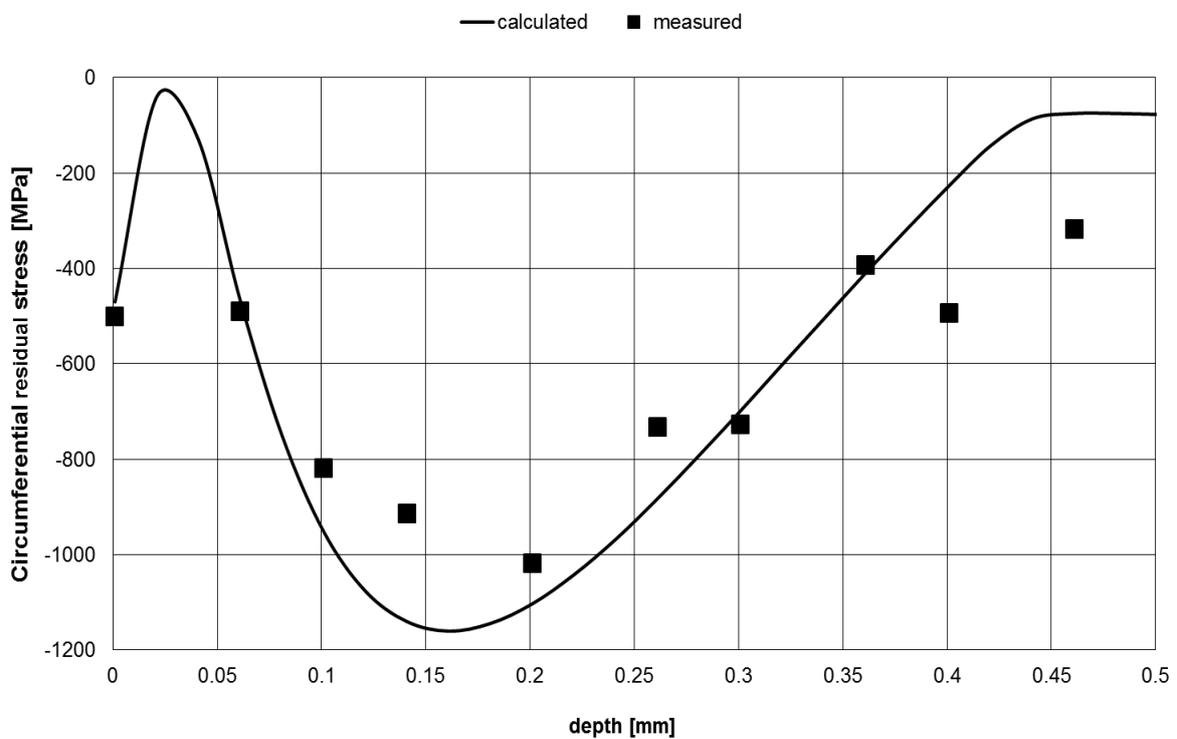

Figure 9. 16 MnCr5, residual circumferential stress at shakedown in case of 5 GPa contact pressure operating at 100^0 C temperature.

bigger initial amount of retained austenite in case-hardened steel; that transforms in martensite faster than in case of through-hardened steel and the major result is a higher increase of the local yield stress and subsequent lower plastic deformation in the following rolling cycles. Also, the groove depth is higher in case of case-hardened material and, naturally, higher residual stresses were measured, no matter the operating temperature. In case of AISI 52100, the operating change in temperature gives a permanent groove profile of about 0.5 micron depth and around 0.15 micron ridge height at 65 Celsius degrees, as compared to 0.7 micron groove depth and 0.25 micron ridge height at 100 Celsius degrees; similar theoretical and experimental results for 4.5 GPa contact pressure (figures 2 to 5). 16 MnCr5 bearing steel exhibits a more pronounced plastic deformation, the results obtained at 5 GPa contact pressure and 100 Celsius degrees operating temperature are at least double than for the AISI 52100 bearing steel (groove depth around 1.7 micron and ridge height about 0.7 micron, as in theoretical and experimental results, figures 6 and 7).

4. Conclusions

A complex model for the investigation of elastic-plastic rolling contact in case of bearing materials that exhibit combined isotropic and kinematic hardening behaviour has been developed.

Numerical simulations are in good agreement with experimentally recorded values of deformed profiles and residual stress measurements.

The model will allow further development of retained austenite transformation cycle-by-cycle, leading to a better understanding of the fatigue phenomenon in bearings. From this point of view, the current relations for bearing life calculation should be properly modified.

5. References

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