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Elastic–plastic characterization of a high strength bainitic roller bearing steel—experiments and modelling

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ABSTRACT

Monotonic and cyclic deformations were studied for a high strength bainitic roller bearing steel. The temperature of 75 °C corresponded to normal roller bearing conditions. The materials showed hydrostatic influence on yielding, but no or marginal influence of plastic deformation on density change. Therefore, a linear elastic constitutive model with pressure dependent yielding, non-associated flow rule, combined non-linear kinematic and isotropic hardening was necessary to characterize the cyclic behaviour. A stepwise process is detailed for determining the material parameters of the pressure dependent model, where particular attention was placed on the hardening parameters. One set of parameters was sufficient to describe all tested load ranges including compressive ratchetting. Some comparative tests were performed at room temperature, 150 °C and on martensitic specimens at 75 °C. The temperature influence was limited to the isotropic hardening parameters.

1. Introduction

When the roller bearing steel DIN 100CrMnMo8 is exposed to different heat treatment procedures, different material structures can be attained. Of these structures, bainite and martensite are predominantly used for roller bearing applications. In particular, bainitic structured steels can combine a very high yield strength with substantial ductility. Bainitic steels are described in the literature, for instance by Bhadeshia [1] and Pickering [2]. With the bearing application in mind, the time independent linear elastic and plastic behaviour of bainitic steel was investigated through a series of monotonic and cyclic tests. Since bearing applications typically give slightly increased temperatures, the experiments were primarily performed at 75 °C with some comparative tests at room temperature (RT) and 150 °C. Comparison tests at 75 °C were also performed on the same base material, heat treated to a martensitic structure.

The bainitic heat treatment, or austempering, was carefully controlled to leave a minimum of retained austenite. The retained austenite content was measured using electron back scatter diffraction and was for the bainitic structure below the detection limit of the equipment, i.e. less than 0.5%. If retained austenite had been present, then stress induced transformation (SIT) of austenite to martensite with an accompanying volume change could have been an issue. The continuum effects of this transformation are described by, for instance, Olson and Cohen [3]; Neu and Sehitoglu [4]. The martensitic structure, on the other hand, contained 10–15% retained austenite. Hence, by comparing the two material structures, some effects of an SIT should become visible for martensite. The absence of these effects in bainite, would indicate that SIT was not an issue.

Some high strength steels display noticeably higher yield stress, and subsequent flow behaviour, during uni-axial compression than for tension. This yield difference is often denoted the strength differential effect (SDE) in the literature. Rauch and Leslie [5] document SDE for high strength steels with martensitic, bainitic and Widmanstätten ferrite–pearlitic structures. The importance of the material structure was illustrated by the lack of an SDE for an equiaxed ferrite–pearlite structured version of the Widmanstätten steel. Chait [6] and Singh et al. [7] find decreasing SDE with increasing tempering temperature. Chait [8] detects diverse SDE trends with test temperature for some steels and titanium alloys with different microstructures. On the other hand, Bridgman [9] concludes that for most common, ductile and low strength structural metals and alloys, the SDE is negligible in the hydrostatic pressure range between plus and minus the yield strength.

Spitzig et al. [10,11] compare uniaxial tension and compression curves for some steels. The SDE is only marginally affected by increasing plastic strain. Furthermore, an increasing yield strength is found when the monotonic tests are performed under hydrostatic pressure. For high strength steels, the flow stress depended linearly on superimposed hydrostatic pressure; see also Spitzig and Richmond [12], Richmond and Spitzig [13].

Drucker and Prager [14] point out that if the yield stress increases linearly with the hydrostatic pressure and the plastic

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strain increment is considered normal to the yield surface i.e. an associated flow rule, then plastic deformation will be accompanied by a volume increase. Spitzig et al. [10,11] measured the plastic volume expansion for various steels. The volume expansion was less than 1/15 of the prediction of the associated flow rule. Spitzig and Richmond [12] note that the small volume change that was detected corresponded to the dislocation volume that develops during plastic deformation. Garofalo and Wriedt [15] measured carefully the density change of plastically deformed austenitic steel with only marginal SDE and find that only a portion of the bulk density change could be due to dislocations. The remainder is ascribed to the generation of microcracks. Rauch et al. [16] measured volume expansion for a high strength martensitic steel containing retained austenite. Much of the initial volume increase was attributed to the transformation of the retained austenite during early plastic deformation. Subsequent density change was accounted for by the generation of dislocations. Thus, results in the literature indicate that a small volume increase due to dislocation generation may develop during plastic deformation. The volume increase is, however, much smaller than the predictions of the normality, or associated, flow rule at pressure sensitive yielding.

Brünig [17] notes, firstly that increasing flow stress with hydrostatic pressure agrees with the assumptions on pressure effects on plastically induced dislocation motion and, secondly that the small plastic volume effect that is noted in experiments is consistent with changes in dislocation density. High strength steels may to some extent be compared to frictional materials like granular solids and following, the traditionally used normality flow rule may not be appropriate. Casey and Sullivan [18] reach the same conclusion. However, to simplify the numerical computations, these effects are often ignored for plastic deformation in metals and plastic strain increments are computed using the associated flow rule. If a material with substantial SDE, experiences sizable plastic strains, then an associated flow rule would predict a significant volume increase, i.e. far to large compared to actual measurements. Therefore, a non-associated flow rule based on a plastic potential may be required for simulation of plastic deformation in high strength steels. Based on this conclusion, numerical models with non-associated plasticity have been developed by for instance Brünig [17,19]; Lee [20]; Loret and Prevost [21]; Stoughton and Yoon [22]. In commercial finite element codes, versatile non-linear combined hardening rules are available together with the associated flow rule. In the cases where non-associated flow rules are commercially available, the available hardening rules are limited. Therefore, Allen and Wilson [23] and Cvitanic et al. [24] among others develop user defined constitutive subroutines to include non-associated plasticity models into commercial finite element codes.

The purpose of this work was to predict the mechanical behaviour of bainitic steel with particular interest in the performance at cyclic loading of roller bearing applications. The work contained three parts: mechanical experiments, model building and matching model parameters to experimental results. Each part was equally important for the correct prediction of the actual material behaviour. The investigated high strength steel was expected to display an SDE, but no sizable plastic volume expansion. One objective was to identify and quantify the SDE from uni-axial experiments, the potential plastic volume expansion of the deformed specimens and the cyclic elastic–plastic material behaviour at different load types. Next, the material behaviour at the experiments required a continuum description with uni-axial stresses, but three-dimensional strains. The key issue for the work was how well a material model with linear pressure sensitive yield function, associated or non-associated flow rules, combined isotropic and non-linear kinematic hardening, could replicate the experimental findings for the bainitic steel. Finally, the parameter values required careful attention. The determination process is described in detail, while the parameter values were crucial for the prediction of the mechanical behaviour.

2. Material and specimen description

The specimens shown in Fig. 1a were supplied by an SKF in test ready-condition. The steel grade corresponded to the German standard DIN 100CrMnMo8. The specimens had been cut from a large forged and soft annealed ring with the longitudinal direction aligned with the ring axis, i.e. the forging direction. The specimens were either austempered to bainitic or quenched and tempered to martensitic microstructures. After heat treatment, all specimens were carefully ground to the nominal dimensions stated in Table 1. Those specimens used for cyclic testing were gently polished in the longitudinal direction. The surface roughness $R_a = 0.045\ \mu$m. Wåtz [25] estimated the residual stresses from manufacturing to be less than 20 MPa.

3. Monotonic tests

Tension, compression and torsion tests, summarized in Table 2, were performed in servo-hydraulic test machines. The upper and lower fixtures had been carefully aligned with the machine load line, to minimize unwanted stresses from assembly. The stresses were determined from the minimum diameter on each specimen. The strain average was calculated from two diametrically placed extensometers; see the left picture in Fig. 1b. To ensure steady-state temperature, the equipment rested for at least 30 min at the test temperature before test start. Each experiment started with three elastic cycles between 0 and 500 MPa that reduced non-linear deformation at low loads. They continued at fixed deformation rate to final rupture. The maximum load was reached at fracture and no detectable necking developed during the tests.

The compression specimens had flat end surfaces and were placed between equally flat fixture seats. Due to the specimen material hardness, cut bearing rollers were used as fixture contact seats. The alignment between specimen ends and fixture contact surfaces was checked prior to testing by performing a very light print on a carbon paper. The contact print was homogenously grey, which indicated that the surfaces were aligned within the carbon layer thickness. Thin Teflon films were placed as lubrication between specimen ends and the fixture seats in an attempt to reduce the radial friction constraint. The axial strain was directly measured as the average of two diametrically placed strain gages that had been glued directly on the specimen sides, see Fig. 1b (centre). A preliminary compression test at RT continued to final fracture at $\sigma_F = -3110$ MPa true stress ($\sigma_{eng,F} = -5110$ MPa engineering stress) and $\varepsilon_F = -0.55$ true strain. The fracture resulted in small irregular pieces with multiple fracture surfaces. Subsequent compression tests were halted before reaching the failure stress, see Table 2. By halting the experiments at controlled strain values, it was possible to later measure the density change from plastic deformation on compressed specimens.

Fig. 2a shows tension curves to fracture and compression curves. Complete compression curves are presented in Fig. 2b. During the compression tests, the strain gages reached their measurement limit at approximately 10% strain. Higher strains were estimated from the piston position by compensating for elastic deformation of equipment and machine as well as for the specimen test length being longer than the gage measuring