Mechanical behaviour of a bainitic high strength roller bearing steel

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Preface

The work presented in this thesis has been carried out at the Department of Solid Mechanics, Royal Institute of Technology (KTH), Stockholm between June 2007 and October 2010. The financial support of SKF Engineering & Research Centre (SKF ERC), Netherlands is gratefully acknowledged.

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List of appended papers

**Paper A:** Elastic–plastic characterization of a highstrength bainitic roller bearing steel—experiments and modelling

**Paper B:** Non-linear elastic characterization of a high strength bainitic roller bearing steel
*Report 495, Department of Solid Mechanics, KTH Engineering Sciences, Royal Institute of Technology, Stockholm, Sweden.*
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>7</td>
</tr>
<tr>
<td>Summary of papers</td>
<td>9</td>
</tr>
<tr>
<td>Bibliography</td>
<td>11</td>
</tr>
</tbody>
</table>

**Paper A**

**Paper B**
Introduction

Rolling bearings are reliable components which allow rotational motion with minimum friction and accurate location while transmitting high loads. To avoid early failure from incorrect fitting, corrosion, inadequate lubrication, etc. the bearing companies offer advice and recommendations. However, even well maintained bearings may eventually fail by fatigue of the contacting surfaces (see Hoo (1982)). A generally accepted failure mode consists of subsurface crack nucleation at a pre-existing defect (see Figure 1a) in the region of the highest shear stress beneath a contact zone followed by propagation of the crack to eventually form a pit in the surface (see Figure 1b).

(a)  (b)

Figure 1. a) Butterfly crack initiated from a sub-surface inclusion due to rolling contact fatigue (courtesy of SKF ERC). b) Spalling of bearing raceway due to rolling contact fatigue (courtesy of SKF ERC).
A detailed analysis of crack propagation at bearing loads requires understanding of the fundamental material behaviour. The goal of this licentiate thesis was to determine an elastic-plastic material model for a bainitic high strength roller bearing steel. The material designation followed the German standard DIN 100CrMnMo8. Bainitic high strength steels exhibit a desirable combination of strength and ductility but the material behaviour can present substantial modelling challenges.

The flow stress of many high strength steels is larger in uni-axial compression than in uni-axial tension. This phenomenon is called the strength-differential effect (SDE). The SDE has been found in bainitic steels, see Rauch and Leslie (1972). The SDE involves the use of particular plasticity models. The von Mises yield surface criterion is widely used in ductile materials, such as low alloyed steels where the onset of yield in general does not depend on the hydrostatic stress component. For materials showing an SDE, the yield point exhibits a hydrostatic stress dependency and therefore a von Mises yield surface does not suffice. Hydrostatic stress dependent yield criteria such as the ones proposed by Drucker-Prager or Spitzig et al. (1975 and 1976) are able to model the SDE.

Another modelling challenge for materials with an SDE is how to model the evolution of plastic strains in the material, the flow rule. The use of the normality principle with the von Mises criterion is elegant and provides close agreement with experimental results for ductile steels. When using the normality principle, the increments of plastic strain are normal to the yield surface. Since the von Mises yield surface is pressure independent, the development of plastic strains is purely deviatoric. Suppose a hydrostatic stress dependent yield criterion. If the normality principle is assumed (associated flow rule) then the development of volumetric plastic strains will create a plastic volume expansion. Observations indicate (see Spitzig et al. (1975)) that the plastic volume expansion in high strength steels is relatively small, which requires the use of a non-associated flow rule where plastic strain increment is normal to a potential function.

With high yield point follows that the elastic strains can be observed in a wide strain range. Usually linear elasticity is assumed in steels but Sommer et al. (1991) performed cyclic tests on the SAE 52100 roller bearing steel and detected
asymmetric and distorted elastic-plastic hysteresis loops. The distorted loops were ascribed to a non-linear elastic material response.

High strength steels can also develop creep strains at room temperature. The room temperature creep is studied in some high strength steels by Oehlert and Atrens (1994) and Liu et al. (2001) among others. Under these low-temperature conditions, the total creep strains are usually very low, typically much less than 1%, and the creep deformation rarely leads to failure. The room temperature creep normally follows the logarithmic creep law and depends on, for instance, the stress level and the loading rate.

This licentiate thesis presents a material model for the bainitic DIN 100CrMnMo8 high strength bearing steel that takes into account the SDE without plastic volume expansion and non-linear elasticity. The work focused on cyclic load conditions. Hence, the combined non-linear isotropic and kinematic hardening behaviour was included. Following, the small creep strains were excluded from this work. The thesis presents a combination of: experiments, necessary to identify the mechanical behaviour of the material; material modelling, developed based on the observations from the experiments; parameter determination, performed using the material model to represent the experiment performed.

Summary of papers

Paper A: Elastic-plastic characterization of a high strength bainitic roller bearing steel—experiments and modelling

Paper A was divided in three main subjects: experiments, material modelling and parameter determination. Firstly, experiments for bainitic and martensitic bearing steels that had been manufactured from the same base material were presented. The series included: monotonic experiments in tension, compression and torsion; cyclic push pull tests; density measurements. The yield surface was hydrostatic stress dependent. Together with the results of the density measurements it was concluded that the von Mises yield surface and flow rule should be discarded for modelling the flow behaviour of the steels. Instead, the Drucker-Prager yield criterion was combined with a non-associated flow rule. Secondly, the modelling focused on
plasticity based on linear elasticity. The goal was to model not only the monotonic 
behaviour but also to capture the cyclic push-pull behaviour tests including 
ratchetting. The plasticity model included Drucker-Prager yield surface combined 
with a non-associated flow rule and nonlinear kinematic and isotropic hardening. The 
model was implemented for a uniaxially loaded rod using an Euler forward 
algorithm. Finally, once the material model was defined a method for the 
determination of the material parameters was presented together with the 
comparison of the material model and the test results. This work focused on the 
bainitic material characterization. However, comparative tests and material modelling 
were performed for the martensitic material.

Paper B: Non-linear elastic characterization of a high strength bainitic roller bearing steel

In Paper B the material characterization of the bainitic steel focused on the elasticity 
model. The assumption of linear elasticity was evaluated by analysing elastic 
unloading during the cyclic push-pull experiments. Non-linear elastic behaviour was 
found for the push-pull loading. Cyclic torsion tests were performed. The results 
from these tests showed that the elastic behaviour in torsion loading could be 
considered as linear. A phenomenological analysis of the change in cyclic elastic 
properties suggested isotropic damage of the elastic properties, i.e. similar amount of 
degradation in both torsion and push-pull experiments. Once the nature of the non-
linear elastic behaviour was identified, the elastic material model was characterized 
with the non-linearity for push-pull loading relying on the bulk properties. The shear 
elastic behaviour was considered as linear. The limited damage was excluded from 
the model. The non-linear elastic model was combined with the plasticity model 
from Paper A. The model was implemented for a uniaxially loaded rod using an 
Euler forward algorithm.
Bibliography

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