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A new reverse analysis to determine the constitutive response of plastically graded case hardened bearing steels

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ABSTRACT

A new reverse analysis is presented that determines the plastic response of both nongraded and plastically graded materials (PGMs) without the need for traditional tension or compression tests. The method utilizes the concepts of expanding cavity model for strain hardening materials, Tabor's rule of converting Vickers hardness to flow stress, representative plastic strain induced by indentation, and finite element modeling of the macro indentation process. A unique flow curve is determined when the experimentally measured increase in micro Vickers hardness matches that predicted by the proposed method within the plastic zone of a macro Vickers indent. The method is validated for a nongraded stainless steel first and then extended to determine the gradient in flow curves of plastically graded, case-hardened M50 NiL material, a widely used bearing steel. Such knowledge of the plastic response of the case hardened region will help optimize the design of case hardened bearings with longer rolling contact fatigue life and higher thrust load capabilities.

1. Introduction

Plastically graded materials (PGMs) are a class of materials which have a variation in plastic response with depth from the surface. A gradient in plastic response can be the result of a gradient in grain size or material composition. Critical applications of PGMs are case hardened raceway steels of high performance ball and roller bearings used in aircraft turbine engines. Case hardened bearing steels such as M50 NiL are widely used in turbine engines because of their high hot hardness and long rolling contact fatigue (RCF) life. The decreasing hardness profile with depth of the case-carburized raceway is designed to take advantage of the plastic strain amplitudes induced by RCF that also decrease with depth. The case hardening process produces a decreasing gradient in carbon concentration from the surface which results in a gradient in hardness, yield strength, and possibly strain hardening behavior. Determination of the plastic response of these plastically graded materials is essential to improve the RCF life of high performance bearings. However, it is extremely difficult to obtain the plastic response as a function of depth for a PGM due to the continuous gradation in microstructure or composition. Therefore new methods are needed to extract the flow curve of these types of materials.

Hardness measurements are relatively easy to perform and can be repeated multiple times on a relatively small specimen. They obviate the need for tedious procedures of creating tensile or compression test specimens to obtain the plastic response of a material. Tabor (1970) has shown that the hardness of a strain hardening material increases with plastic strain and can be related to the increase in yield strength (flow stress) of the plastically deformed material. The process of using indentation hardness measurements or other means to determine the stress–strain response of a material is often called a reverse (or inverse) analysis (Nakamura et al., 2000; Dao et al., 2001; Gu et al., 2003; Tho et al., 2004; Antunes et al., 2007). Conversely, a forward analysis utilizes the known plastic flow behavior of a material to predict the increase in hardness with plastic strain.

Many reverse analyses have been proposed since Tabor (1970) and most of these depend on instrumented indentation methods. Instrumented indentation essentially relates the load–displacement response during the indentation process to the material properties such as elastic modulus, strain hardening exponent, and yield strength. Dao et al. (2001) created a new set of dimensionless functions that relate the elastic and plastic material properties to instrumented indentation data; namely the loading curvature, the unloading curve, and the ratio of the elastic rebound depth to the maximum indentation depth. Chollacoop and Ramamurty (2005) showed how initial plastic deformation affects indentation loading curvature and that the method of Dao et al. (2001) can be used to predict flow curves using two different indenters on strain hardening materials. Bucaille et al. (2003) extended the method of Dao et al. (2001) to four different conical

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