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Determination of constitutive response of plastically graded materials

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ABSTRACT

Plastically graded materials (PGMs) are frequently used in high-performance tribological components such as case-hardened gears and bearings for jet and rocket engines due to their superior resistance to rolling contact fatigue. These components can have a surface hardness as high as 9 GPa and a decreasing hardness gradient over a depth of approximately 2 mm. This hardness gradient is achieved by a gradient in carbon content. Proper design of such components requires the knowledge of the constitutive response with depth. In this manuscript, a coordinated experimental and numerical method is presented to extract the constitutive response of commercially available case-hardened Pyrowear 675 (P675) stainless steel. Utilizing the variation in micro-Vickers hardness with depth for both virgin and plastically deformed PGMs, representative plastic strain, and well established hardness-yield strength relationships, the constitutive response of the PGM is uniquely determined. It is shown that this specific PGM has a linear variation in yield strength, but a constant strain hardening exponent. The procedure developed here can assist in surface engineering a PGM with optimized hardness profiles to maximize tribological performance.

1. Introduction

Incorporation of gradients in material microstructure to tailor the functional properties of engineering materials has been in use since the iron-age (Smith, 1960). Such graded materials were heat treated to obtain a surface that is harder than its core for use in weapons such as swords, spears, and shields (Suresh and Mortensen, 1998; Miyamoto et al., 1999). Interestingly, these principles of heat treatment are still practiced throughout the steel industry even in today's advanced-technology applications. Plastically graded materials (PGMs) traditionally have constant elastic properties while the plastic response varies with depth (Cao and Lu, 2004; Choi et al., 2008a,b), whereas a variation in elastic modulus is also possible for some materials (Gu et al., 2003; Fischer-Cripps, 2003). The variation in plastic response can be achieved either by variation in material microstructure, material composition, or a combination of both. In many case-hardened steels the variation in plastic response with depth is accomplished by heat-treating the outer surface through carburizing, nitriding, or boriding (Boyer, 1987) to obtain a microstructure with high hardness on the surface and a gradual reduction in hardness with depth. Such materials are used for the manufacture of high-performance tribological components such as ball and roller bearing raceways and gears for aircraft and space propulsion turbine engines. The decreasing hardness profile of the case-carburized PGM with depth is designed to take advantage of the decreasing plastic strain amplitudes induced by rolling contact fatigue (RCF). The hardness gradient within the case layer can be indicative of complex variations in yield strength and work hardening behavior with depth. Determination of the monotonic and cyclic stress–strain response of such

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