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Experimental observation and numerical modeling of formation of local plastic zones in hardened surface layers due to contact overloading

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ABSTRACT

The problem of formation of plastic zones in case-hardened metallic bodies due to contact overloading is studied both experimentally and numerically. Metallic materials exposed to surface hardening demonstrate spatial variation of the material hardness and yield strength with a decreasing profile with depth and belong to the class of so-called plastically graded materials. The presented experimental program employs micro-Vickers hardness tests to map the variation in material hardness and corresponding yield strength for both virgin and loaded case-hardened specimens made of a chromium tool steel. It is shown that, depending on the profile of the yield strength in the near-surface zones and contact parameters, a plastic deformation can originate underneath the hardened layer. The distribution of the effective plastic strain extracted from the micro-hardness increment measurements are found in good agreement with the results of finite element simulations of a plastically graded material subjected to similar loading conditions. Numerical analysis reveals significant perturbations in the stress field distribution within the hardened layer due to formation of a closed-shaped plastic zone in the gradient layers, including development of a tensile stress on the boundary between the elastic and plastic zones as well as an overall increase in the effective stress intensity. It is shown that the hardened layer behaves similar to an elastic beam on a compliant foundation. These stress field perturbations in the hardened layers with low deformation capacity can greatly affect the durability and serviceability of surface treated mechanical parts.

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1. Introduction

Surface or case hardening is commonly used to improve the wear resistance of mechanical parts or structural elements subjected to contact loading. Case hardening creates a non-uniform spatial distribution of hardness and consequently the yield strength of the material in the treated surface layers. Typically surface treatments, such as carbonitriding, carburizing, flame or induction hardening, etc. create a high hardness on surface and a decreasing hardness profile with depth. Elastic properties can usually be assumed constant. These materials are commonly called *plastically graded (PG) materials.*

Over the last few decades PG materials have attracted much attention in the research community in an attempt to characterize the treated surface by its effective response to indentation. During indentation a high contact pressure created by a sharp or spherical indenter forms a plastic

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zone directly under the indenter and nonlinear dependence of the indentation depth on the contact load is typically the goal of numerical and experimental studies on PG materials (Suresh, 1997; Suresh et al., 1997; Giannakopoulos, 2002; Gu et al., 2003; Choi et al., 2008a; Choi et al., 2008b; Branch et al., 2011; Klecka et al., 2011; Moussa et al., 2012; Yuan et al., 2012; Klecka et al., 2013).

Although understanding the effective response of PG materials to indentation is extremely important from the tribological point of view, in practical applications an abnormal increase in the loads between hardened contacting parts can occur that does not necessarily lead to development of plastic zones on the contact surface, but nevertheless significantly affects the parts' durability.

Contacting mechanical parts are typically designed such that the stresses at any point of contact and adjacent areas do not exceed 50–90% of the elastic limit of the material (e.g. see Serensen et al., 1975; Roberts, 1978). This creates a situation where the values of the resultant non-uniformly distributed stresses acting in the near-contact zones are below the *local* elastic limit of the hardened material. In most cases, the elastic modulus of the material in the zones close to contact stays practically unchanged and the near-contact area can be considered as homogeneous elastic (although a variation in elastic modulus is also possible for some materials (e.g. Gu et al., 2003)). This ensures long-term operation of the strengthened parts without development of damage and failure. This situation is relevant under the condition that the parts work in a regular pre-designed regime.

However, the situation changes significantly when in some areas of the contact region the operating stress exceeds the *local* elastic limit and the material transfers into the elastic–plastic state. As an example, a very common issue in the steel industry is when the rolled sheet folds in the deformation zone between the rolls due to sheet breakage or non-uniform deformation of the sheet across its width, which can occur for several technological reasons. Practical research has established an unequivocal relationship between local overloading and subsequent damage in the case hardened rolls in the area of local overloads (Devyatchenko et al., 1982; Tsun, 1985). Analysis showed that the contact stresses increase three to five times when folds of strip with threefold or more thickness pass through the deformation zone, and the total forces increase even more rapidly (up to eight times) (Tsun, 1985). Nevertheless, these loading conditions are significantly milder than during the indentation tests mentioned above; case hardened rolls do not usually show any surface damage due to a single overloading, but demonstrate significant degradation in performance and high sensitivity to further loading resulting in premature, typically brittle, failures. High sensitivity of a roll's serviceability to a cyclic and even single overloading is directly related to the stress field redistribution in the core of the PG material due to formation of plastic zones in the gradient transition zones.

According to the energetic strength theory (von Mises plasticity criterion), the transition of the material into a plastic state occurs when the intensity of shear stresses (effective stress) σ_i – reaches the value of material yield strength σ_s. At the contact area between convex bodies, when the length of the contact is much smaller than the bodies' size, the distribution of σ_i as well as the distribution of the maximum shear stresses along the depth direction exhibits a maximum. In the simplest case, when there is no shear stress at the contact between the parallel cylinders and the diagram of normal contact pressure is symmetrical, the peak of the distribution is located on the axis of symmetry at depth 0.4–1.0 of half the contact length, depending on the contact pressure distribution (0.785 in Hertz contact problem with elliptical distribution of contact pressure). The maximum value of the distribution is mainly determined by the maximum value of the contact stresses and the depth depends on the contact length. When tangential (for example, frictional) forces are operating at the contact the distribution maximum is shifted closer to the surface (Johnson, 1987).

Fig. 1 schematically shows the distribution of the yield strength along the depth of hardened zone *y* (curve 1) and the values of σ_i on the symmetry axis of the loading area (curve 2), corresponding to regular work conditions.

Due to an overloading the contact stress and hence the effective stresses σ_i increase significantly (curve 3). In some depths σ_i becomes greater than the local yield stress (shaded area), which leads to a transition of the region to the plastic state. At this moment the original linear problem of loading of the elastic homogeneous body turns into a nonlinear problem of deformation of a PG body, i.e. deformations of an elastic body with a pliant elastic–plastic inclusion with evolving boundaries influenced by the boundary conditions at the contact.

In this paper the problem of plastic zone formation in the gradient subsurface layers is addresses both experimentally and numerically. In Section 2 a systematic experimental program is described, that targets the hardness map and the corresponding yield stress map in the hardened surface layers in both the virgin and contact loaded disks, made of a case hardened chromium tool steel. The experimentally estimated distribution of the yield stress with depth is used in Section 3 for numerical FE analysis of a PG half-plane with a stress field perturbation due to

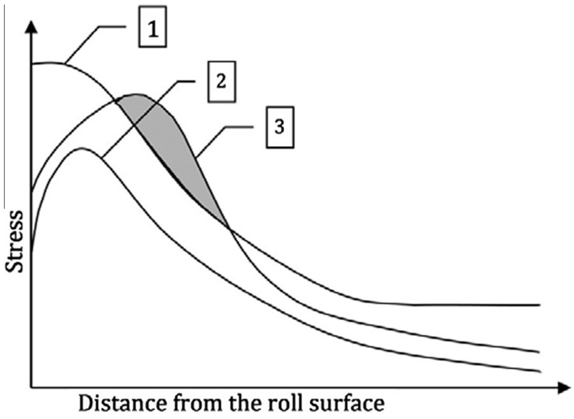

Fig. 1. Location of the plastic zone along the depth of hardened layer of the roll. 1 – distribution of the yield stress of the material; 2 – distribution of effective stresses under normal rolling conditions; 3 – distribution of the effective stress in rolling of folds of the rolled strip.

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