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Analytical and Experimental Assessment of Ultimate Tensile Strength of a Hardened Layer on a Material Surface

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Abstract. Ultimate tensile strength of a hardened layer on a material surface is studied analytically and experimentally with the application of the finite element method and the rule of mixtures, when a specimen with a hardened surface layer is viewed as a composite material consisting of a matrix and hardening layer. It has been found that the application of both methods gives close ultimate tensile strength values for the hardened surface layer. Particularly, for a surface-hardened medium-carbon (0.51 wt% C) structural steel, the ultimate tensile strength of the hardened surface layer is 2700 MPa for the finite element method and 2671 MPa for the rule of mixtures. The obtained results testify to the possibility of determining the ultimate tensile strength of a hardened layer on a material surface by standard mechanical testing for uniaxial tension. The distribution of normal stresses has been determined in a bulk specimen and in a surface-hardened specimen. The presence of a 30 μm thick non-gradient hardened layer on a material surface is shown to cause a strong local stress concentration resulting from the effect of primary mesoconcentrators arising at the site of external load application and by the difference in the mechanical properties of the base material and the hardened surface layer.

INTRODUCTION

At present, new requirements to the reliability, durability, competitiveness of products, to specific conditions of the operation of machines and mechanisms are constantly established. In this connection, the application of advanced methods of hardening of metal materials by surface plastic deformation is an important line in the creation of durable products. Among them there may be ultrasonic impact and laser shock treatments, shot peening and frictional treatment, deep rolling, etc. The improvement of the complex of mechanical properties of metal materials by surface hardening is generally achieved by generating favorable residual compressive stresses in them and/or forming ultrafine grained and nanocrystalline structures.

To predict the fracture of materials with a hardened surface layer, it is necessary to determine the strength of this layer. However, as a rule, hardened surface layers with a submicro- or nanocrystalline structure have a small thickness (several tens of micrometers). Therefore, it is very difficult to make microspecimens, such as of bulk-hardened nanostructured materials, in order to perform mechanical testing. Structural alterations of the specimen, which may affect the results of mechanical testing, cannot be excluded. On the one hand, these problems can be successfully solved by computer simulation methods and allied methods for performing virtual mechanical testing [1]. On the other hand, if a specimen with a hardened surface layer is viewed as a composite material consisting of a matrix and a hardening layer, the ultimate tensile strength of the hardened surface layer can be determined by the results of standard mechanical testing for uniaxial tension, with the application of the rule of mixtures [2]. The aim of this paper is to evaluate the ultimate tensile strength of a hardened layer on a material surface with the application of the finite element method (FEM) and the rule of mixtures.

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EXPERIMENTAL PROCEDURE

The geometrical interpretation of the problem is presented in Fig. 1. The experimental characteristics necessary for the calculation were determined on a medium-carbon (0.51 wt% C) structural steel subjected to bulk heat treatment and combined strain-heat treatment, which forms a hardened surface layer with a nanocrystalline structure [3]. Mechanical testing for uniaxial tension was performed on an Instron 8801 servohydraulic machine with the use of 2.7 mm thick flat specimens with a 25×7 mm gauge length portion and an overall length of 80 mm. A bulk specimen and a surface-hardened specimen of an original design [2] were tested. The following parameters were specified in the calculation: the elastic modulus and Poisson's ratio of the base material, respectively, E_1 = 210 GPa and η_1 = 0.27. The plastic properties of the base material were specified according to the hardening curve obtained from the mechanical testing of the bulk specimen for uniaxial testing. The thickness of the hardened surface layer was determined by the effective hardening depth (the depth of intensive decrease in microhardness), which was t^{hl} = 30 μm [4]. The elastic-plastic properties of the hardened surface layer were assumed to be equal through its entire thickness (non-gradient layer) and specified according to the model of bilinear isotropic hardening with the elastic modulus E_2 = 210 GPa, Poisson's ratio η_2 = 0.27, yield stress σ_f, tangent modulus E_t = 0. For one of the specimen heads, the displacement of the lateral face, normal to the direction of tension, was assumed to be zero. The calculation was made in the Salome-Meca software environment with the Code_Aster solver for the bulk specimen and the surface-hardened specimen. The distribution of normal stresses σ_{xx} in the specimens was determined from the calculation. The difference between the experimental and calculated ultimate tensile strength values for the bulk specimen was assumed to be a calculation error. Different values of σ_f were specified in the calculation for the surface-hardened specimen. The value of σ_f for which the calculated ultimate tensile strength of the surface-hardened specimen differed from the experimental one by the value of the calculation error was taken as the ultimate tensile strength value for the hardened surface layer.

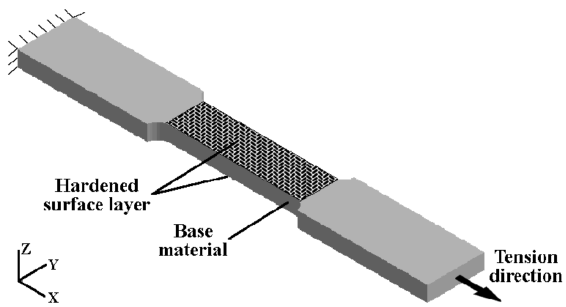

FIGURE 1. The geometrical interpretation of the problem of calculating the ultimate tensile strength of a hardened layer on a material surface

The ultimate tensile strength of the hardened surface layer was evaluated according to the rule of mixtures by the following formula [2]:

$$S_u^{hl} = \frac{S_u^{shs} - S_u^{bul} \cdot (1 - V^{hl})}{V^{hl}}, \quad (1)$$

where S_u^{hl} is the ultimate tensile strength of the hardened surface layer; S_u^{shs} is the ultimate strength of the surface-hardened specimen; S_u^{bul} is the ultimate tensile strength of the bulk specimen; $V^{hl} = (2 \cdot t^{hl})/t^{shs}$ is the volume fraction of the hardened surface layer; t^{hl} is the thickness of the hardened surface layer; t^{shs} is the thickness of the surface-hardened specimen.

RESULTS AND DISCUSSION

The results of the mechanical testing for uniaxial tension are presented in Fig. 2 (curves 1 and 3). The experimental ultimate tensile strength value is S_u^{bul} = 1546 MPa for the bulk specimen and S_u^{shs} = 1571 MPa for the surface-hardened specimen.

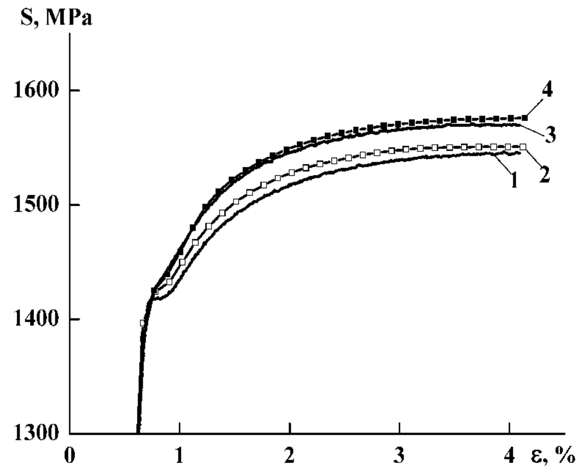

FIGURE 2. Experimental (1, 3) and FEM calculated (2, 4) the loading curves of the bulk specimen (1, 2) and the surface-hardened specimen for σ_f = 2700 MPa (3, 4) under uniaxial tension

The loading curve for the bulk specimen, obtained from the FEM calculation, is shown in Fig. 2 (curve 2). The difference between the calculated and experimental values of ultimate tensile strength for the bulk specimen is 1551 – 1546 = 5 MPa. This value is taken as the calculation error. In the calculation of the surface-hardened specimen with different values of σ_f, it was found that, for σ_f = 2700 MPa (Fig. 2, curve 4), the ultimate tensile strength was 1576 MPa, and this exceeds the experimental ultimate tensile strength value for the surface-hardened specimen by the value of the calculation error. Thus, the ultimate tensile strength of the 30 μm thick hardened surface layer is assumed to be S_u^{hl} = 2700 MPa.

The calculation with the use of Eq. (1) when S_u^{shs} = 1571 MPa, S_u^{bul} = 1546 MPa, t^{hl} = 30 μm and t^{shs} = 2.7 mm yields the ultimate tensile strength of the hardened surface layer S_u^{hl} = 2671 MPa. Consequently, the evaluation of the ultimate tensile strength of the hardened surface layer with the application of the finite element method and the rule of mixtures yields close values of the ultimate tensile strength of the hardened layer. The obtained results testify to the possibility of determining the ultimate tensile strength of a hardened layer on the surface of a material by standard mechanical testing for uniaxial tension, this being supported by the FEM calculation data.

Figure 3 shows calculated normal stresses σ_{xx} in the bulk specimen and in the surface-hardened specimen for σ_f = 2700 MPa. It is obvious from Fig. 3a, b that the stresses σ_{xx} are distributed fairly uniformly in the bulk specimen, except that on the specimen surface, at the transition from the gauge length portion to the heads, there is a slight local stress concentration. In the surface-hardened specimen (Fig. 3c, d), inside the hardened layer, near one of the specimen heads, there is a high local stress concentration caused by the effect of primary mesoconcentrators arising at the site of external load application [5, 6] and by the difference in the mechanical properties of the base material and the hardened surface layer. As is known, stress concentration may favor strain localization under plastic flow. However, the surface-hardened medium-carbon steel under study demonstrates uniform plastic flow under static and cyclic tension [3, 7]. This may be due to the gradient nature of the hardened layer on the steel surface [3, 4], this being ignored in the calculation.

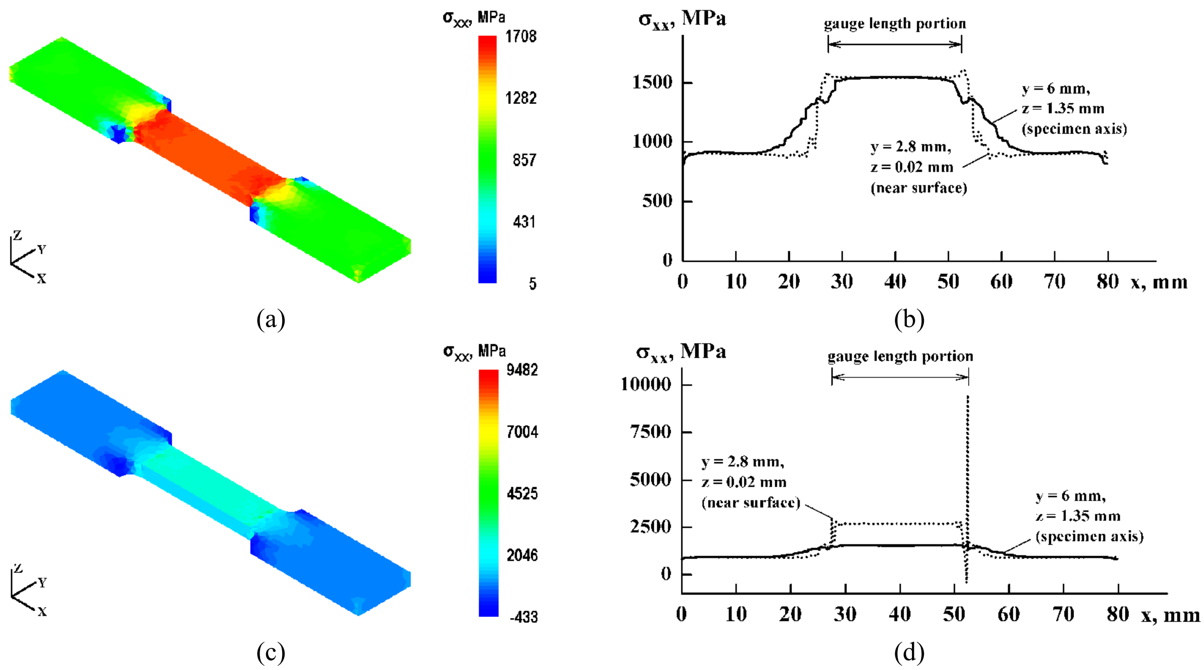

FIGURE 3. Distribution of calculated normal stresses σ_{xx} in the bulk specimen (a, b) and the surface-hardened specimen for σ_f = 2700 MPa (c, d) in the specimen volume (a, c) and along the x-axis at different distances from the surface (b, d)

Thus, the evaluation of the ultimate tensile strength of the hardened layer on the material surface by the finite element method and by the rule of mixtures gives close ultimate tensile strength values for the hardened surface layer. Hence, with the application of the rule of mixtures, it is possible to determine the ultimate tensile strength of a hardened surface layer by standard mechanical testing for uniaxial tension, this being supported by the FEM calculation data. The analysis of the distribution of normal stresses in the bulk specimen and the surface-hardened specimen has shown that the presence of a 30 μm non-gradient hardened layer on the material surface causes a high local stress concentration. This is attributed to the effect of primary mesoconcentrators arising at the site of external load application and to the difference in the mechanical properties of the base material and the hardened surface layer.

CONCLUSIONS

The ultimate tensile strength of a hardened layer on a material surface has been calculated experimentally and analytically with the application of the finite element method and by the rule of mixtures, when a surface-hardened specimen is viewed as a composite material consisting of a matrix and a hardening layer. It has been found that the application of both evaluation techniques gives close ultimate tensile strength values for the hardened surface layer. Particularly, for a surface-hardened medium-carbon (0.51 wt% C) structural steel, the ultimate tensile strength of the hardened surface layer is 2700 MPa in the calculation by the finite element method and 2671 MPa in the evaluation by the rule of mixtures. The obtained results testify to the possibility of determining the ultimate tensile strength of a hardened layer on a material surface by standard mechanical testing for uniaxial tension, this being supported by the FEM calculation data. Normal stress distribution has been determined in a bulk specimen and in a surface-hardened specimen. It has been demonstrated that the presence of a 30 μm thick non-gradient hardened layer on a material surface results in a high local stress concentration. This is caused by the effect of primary mesoconcentrators arising at the site of external load application and by the difference in the mechanical properties of the base material and the material of the hardened surface layer.

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