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Ultrasonic studies of texture inhomogeneities in pressure vessel steel subjected to ultrasonic impact treatment and shock compression

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ABSTRACT

Specimens of Cr-Ni-Mo-V pressure vessel steel 15Kh2NMFA were cut from the achieve wall of the WWER-1000 reactor and were then deformed either using ultrasonic impact treatment (UIT) inducing low energy multiple impacts or by drop-hammer inducing high energy shock compression (HESC). With the aim of texture evaluation comprehensive ultrasonic measurements and X-ray texture analysis were carried out in different sections of the deformed specimens. A nondestructive quantitative analysis of the crystallographic texture in various layers of the deformed specimens was performed on the base of precise measurements of the bulk-wave ultrasonic velocities (v_{ij}) by means of the pulse-echo method using a home-made automated apparatus. The mass densities (ρ) of the deformed specimens and their cut sections were also precisely measured. The obtained data allowed calculating orientation distribution coefficients (W_{4i0}) of crystallites and to construct ultrasonic pole figures for different specimen layers and cut sections. The ultrasonic pole figures correlate well to the X-ray pole figures registered in the cut sections of the specimens. It is found that maximal pole intensities ($\Delta I_{[ijk]}$) and spatial inhomogeneities of these textures depend on the used regimes of UIT and HESC. The revealed peculiarities of the texture formation correlate well to the depth distributions of microhardness and strain extents. The higher the strain extent or the longer the treatment time, the more intensive texture is registered and the deeper the textured layer is observed. The ultrasonic method applied is shown to be useful and efficient for non-destructive examination of elastically heterogeneous systems, particularly the materials with mechanically treated surfaces.

1. Introduction

Mechanical surface treatments are widely used to improve physico-mechanical properties of metallic components. This improvement is usually supported by the modified microstructure, grain refinement, texture, formation of compressive residual stresses and work hardening in subsurface layers of certain thickness, which often become determinative with regard to the enhancement of overall operational characteristics of the components.

A number of these treatments, such as shot peening [1], SMAT [1,2], UIT [3] and cavitation impact [4], use multiple impact loads to induce severe plastic deformation, and they often result in the formation of gradient microstructures coupled with the gradient depth distributions of the accumulated strain [1–5], which depends on the impact energy used [5]. The top near-surface layers of finite thickness, which underwent impact loads, accumulate the most of strains, while the deeper layers are considered to be strained to much lower extent. The thickness of the work-hardened layer produced by UIT was reported to be approx. 30…200 μm in different metallic materials. The UIT process, which is believed to induce both alternating dynamic stresses $\sigma_{\sim}$ and unidirectional static stresses $\sigma_{=}$ in the treated material [6], leads to redistribution/relaxation of residual macro-stresses in the work-hardened and underneath surface layers [7,8]. Ultrasonic finishing treatment was shown to enhance the impact toughness of the pressure vessel steel 15Kh2NMFA and to reduce its susceptibility to the radiation cracking at low temperatures [9]. Additionally, UIT was reported to prolong the fatigue life of welded joints [10–12] and smooth specimens [13] owing to the increased fracture toughness.

The strain induced crystallographic texture is one of the important features of deformed materials, which can be a crucial characteristic in the sense of hardening, fatigue and anticorrosion performances. Thus, ultrasonically assisted surface straining was shown to change texture characteristics in aluminum [14] or copper [15] or in the UIT processed Zr-1Nb [16] and Zr-2,5Nb [17] alloys, which demonstrated a significant increase in intensity of the (0002) and (0004) diffraction lines. The basal texture formed was one of the main factors that provided enhancement in microhardness and corrosion resistance of these hcp alloys. Conversely to the Zr-Nb alloys, which were initially anisotropic, the reactor steel 15Kh2NMFA addressed in this work is almost isotropic [18] and has relatively high strength and ductility [19]. Thus it is a good candidate to examine the strain induced texture evolution at the impact loads of different types.

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It is of great importance to know the texture characteristics not only at the specimen surface but also in the bulk of the material. In contrast to the EBSD and XRD methods, which respectively allow to accurately analyze only the top surface and the near-surface layers of tens of micrometers thick [20,21], ultrasonic texture analysis based on the precise measurements of bulk-wave ultrasonic velocities accompanied with subsequent theoretical calculations using well-developed models [22, 23] can give the information with regard to the bulk texture and elastic properties of materials without their destruction [24–26]. Moreover, the ultrasonic texture analysis is less time consuming and cheaper albeit slightly less accurate than such a powerful method as neutron diffraction analysis [27]. The ultrasonic method is based on analytical connection between effective elastic coefficients of anisotropic polycrystalline aggregate (C'_{ij}), corresponding bulk-wave ultrasonic velocities (v_{ij}) in orthogonal directions and the orientation distribution coefficients (ODC) W_{ij0} of crystallites that determine the orientation distribution functions of the crystallites by means of the analytical expressions [22, 27] described in the next section.

The aim of this study is to examine crystallographic texture in different layers/sections of the specimens of pressure vessel steel 15Kh2NMFA deformed with UIT or with high energy shock compression (HESC). Basic procedure used for texture characterization included the following steps: precise measurements of bulk-wave ultrasonic velocities (v_{ij}) in perpendicular direction to the shock load direction; precise measurements of mass densities (ρ) of specimens; calculations of ODC W_{ij0}; and reconstruction of pole figures (PF) and maximal poles intensities ($\Delta I_{[ijk]}$) for the main crystallographic directions. Then the results of nondestructive ultrasonic texture analysis are compared with the X-ray texture data registered on the cut sections of the deformed specimens.

2. Theoretical bases for ultrasonic texture analysis

The theoretical bases of the ultrasonic method for texture analysis of anisotropic polycrystals are described in details in [20,22–26]. The method is based on the interpretation of a textured polycrystalline aggregate as a quasi single-crystal with lower crystallographic symmetry. To explain the used model a scheme shown in Fig. 1 represents the rolled specimen of cuboid shape positioned in an orthogonal coordinate system. Axes along the rolling (RD), transverse (TD) and normal (ND) directions are denoted with the Arabic numerals 1, 2 and 3, respectively. The ND direction was coincided to the deformation (impact) direction in this study. Six transversal ultrasonic velocities (v_{ij}) ($i,j = 1,2,3$) can be measured (Fig. 1). The first subscript in the v_{ij} indicates the propagation direction of the ultrasonic wave, and the second one specifies the direction of polarization vector of the ultrasonic wave. Three longitudinal ultrasonic velocities along the orthogonal directions can be measured as well.

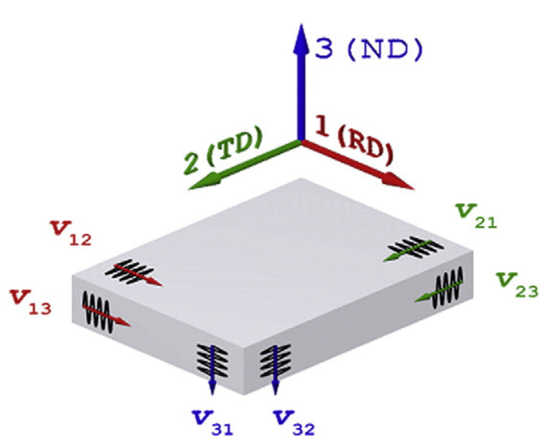

Fig. 1. Schematic view of a rolled specimen of cuboid shape for measurement of bulk-wave ultrasonic velocities and texture analysis of anisotropic polycrystals.

Expressions for effective elastic coefficients C'_{ii} for cubic polycrystals can be written in the matrix form as follows:

$$C'_{ii} = K + \frac{4}{3}\mu - 2C^a\left(\delta_i - \frac{1}{5}\right) \quad with \quad i = 1,2,3 \tag{1}$$

$$C'_{ii} = \mu + C^a\left(\delta_i - \frac{1}{5}\right) \quad with \ i = 4,5,6 \tag{2}$$

$$C'_{23} = K - \frac{5}{3}\mu + C'_{44} \tag{3}$$

$$C'_{13} = K - \frac{5}{3}\mu + C'_{55} \tag{4}$$

$$C'_{12} = K - \frac{5}{3}\mu + C'_{66} \tag{5}$$

where K and μ are the bulk and shear modulus of isotropic polycrystal, respectively; δ_i are the components of linear combination of three independent orientation distribution coefficients (ODC) W_{400}, W_{420}, W_{440}; C^a is the anisotropy factor, which is calculated using the elastic coefficients of crystallites (single crystals), C_{ij}. Superscript a denotes the method used for averaging and described by the following formula – Eq. (6) averaging by Voigt ($a = V$), Eq. (7) by Reuss ($a = R$) and Eq. (8) by Voigt–Reuss–Hill ($a = H$). The latter one was used in this work.

$$C^V = C_{11} - C_{12} - 2C_{44} \tag{6}$$

$$C^R = \frac{50(C_{11} - C_{12} - 2C_{44})(C_{11} - C_{12})C_{44}}{[3(C_{11} - C_{12}) + 4C_{44}]^2} \tag{7}$$

$$C^H = 1/2\left(C^V + C^R\right) \tag{8}$$

Expressions used in this work for calculation of ODC W_{4j0} comprise the measured magnitudes of ultrasonic velocities v_{ij} and density ρ:

$$W_{400} = \frac{35\sqrt{2}}{64C^a\pi^2}\left[\rho\left(v_{11}^2 + v_{22}^2 + 2v_{12,21}^2\right) - 2\left(K + \frac{7}{3}\mu\right)\right] \tag{9}$$

$$W_{420} = \frac{7\sqrt{5}\rho}{32C^a\pi^2}\left(v_{22}^2 - v_{11}^2\right) \tag{10}$$

$$W_{440} = \frac{\sqrt{35}}{64C^a\pi^2}\left[\rho\left(v_{11}^2 + v_{22}^2 - 6v_{12,21}^2\right) - 2\left(K - \frac{5}{3}\mu\right)\right] \tag{11}$$

It is important that the expressions (9)–(11) do not contain the ultrasonic velocities in the normal direction (ND) denoted with the 3 numeral (the straining direction at the UIT or HESC processes). It allows performing the layer-to-layer texture analysis of the deformed specimens without possible strain-induced uncertainties. Additionally, another essential peculiarity of these expressions seem to be the averaging of the transversal ultrasonic velocities by symmetric indexes: $v_{12,21} = (v_{12} + v_{21})/2$.

Generally, the inequality $\nu_{ij} \neq \nu_{ji}$ indicates the presence of the operating (σ_A) or residual (σ_R) macrostresses in the tested material. Therefore, the averaged magnitudes ν_{ij}, ν_{ji} as well as the results of the ultrasonic texture analysis used them, become independent on the influence of the residual macrostresses. It is also important that the contribution of macrostresses to the anisotropy of ν_{ij} in metals is much lower than that of crystallographic texture, and this discrepancy was shown to be of more than the order of magnitude (see the results of our previous studies [18] or other literature data [26]). For instance, the 30% upsetting of 15Kh2NMFA steel was reported to lead to the formation of maximum residual stress along the straining direction of $\sigma_R = 167.2$ MPa, which resulted in negligible anisotropy of transversal sound velocity