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Application of ultrasonic waves in measurement of hardness of welded carbon steels

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Abstract

The ultrasonic contact impedance technique and ultrasonic wave velocities have been widely used for non-destructive hardness measurement. Ultrasonic wave velocity shift provides through the thickness average hardness, however, the correlations are performed according to surface hardness. In order to accept this technique as a particular non-destructive method for determination of hardness, it is necessary to test it with industrial applications. A widely used joining (welding) technique is selected for this purpose. Samples of carbon steels with three different carbon contents, but similar composition, are annealed in order to obtain the softened samples with different hardness values. Rockwell B scale hardness of heat treated samples, which are assumed to be isotropic, are determined and correlated with ultrasonic wave velocity shifts. Effect of welding process on hardness is investigated using ultrasonic wave velocity shifts, and the results are verified with destructive hardness measurements.

Keywords: Ultrasonic wave velocity; Average bulk hardness; Welding; Steel carbon content

1. Introduction

Hardness is a measure of the resistance of materials against the changing effects of external shape. The magnitude of this property is related to yield strength, tensile strength and modulus of elasticity of materials. Accordingly, the investigation and measurement of hardness have vital importance. During the decades, various destructive and non-destructive hardness test methods have been developed. The non-destructive methods are portable and can be used on materials at the service, but a widely accepted non-destructive hardness test method, the ultrasonic contact impedance technique, is limited to measure the surface hardness. The pulse echo ultrasonic waves can be used to investigate the internal hardness variations. These waves travel through the thickness of material and give the average magnitude of hardness within the bulk volume. However, some production methods, such as welding process, cause the irregular deformations of the interior crystal structure of materials. Different sections of materials can have different hardness, and so the reliability of this technique for the welded structures should be investigated.

Ultrasonic wave velocity can be correlated with the measurements of an accepted hardness test technique for the materials with different hardness values. For this purpose, heat treatment techniques, such as annealing, should be used to obtain the samples of a material. Time and temperature are the main variables of annealing process, which should be determined carefully in order to obtain the materials with desired hardness. Some studies have been conducted to investigate the behaviors of materials under different annealing conditions. During these studies, the annealing treatments were performed with different parameters to investigate their effect on hardness. Li et al. [1] investigated the annealing softening behavior

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of cold-rolled low-carbon steel. The annealing behavior and mechanical properties of severely deformed interstitial-free steel were studied by Gazder et al. [2]. The annealing behavior of martensitic steel was investigated by Kimura et al. [3]. Fargas et al. [4] investigated the effect of annealing temperature on the mechanical properties of hot-rolled duplex stainless steel. Euh et al. [5] studied the effect of temperature on hardness improvement in vanadium carbide coated steels. Irani et al. [6] studied the effect of forging temperature on the hardness of low carbon steel gears. The effect of annealing temperature on properties of stainless steels was investigated by Negm [7]. Kang et al. [8] investigated the effects of recrystallization annealing temperature on the mechanical properties of twinning induced plasticity steels. The effect of annealing temperature on microstructure, phase composition and mechanical properties of thixo-cast 100Cr6 steel was studied by Rogal et al. [9]. Liu et al. [10] investigated the decrease in hardness during the isothermal process at 700 °C for Fe−24Mn-0.7Si-1.0Al TWIP steel.

Various correlations between ultrasonic parameters and material properties have been proposed. Bibliographies and detailed explanations of previous studies were discussed in the handbook of the American Society of Nondestructive Testing [11]. Effect of hardness on ultrasonic waves was investigated by various authors. Kleesattel et al. [12] developed a correlation for measurement of surface hardness and proposed the ultrasonic contact impedance hardness test method in 1961. Rosen et al. [13] presented a relation between ultrasonic attenuation and hardness of aluminum−copper alloys by varying the age hardening processes. Another correlation between ultrasonic wave velocity and hardness was developed by Rosen et al. [14], for hardness prediction of aged aluminum alloy 2024.

Ultrasonic waves propagate in materials at a constant velocity. This behavior allows them to be used for non-destructive investigation purposes. Different studies were conducted to determine the hardness of various materials using the velocity variations of ultrasonic wave. Tariq et al. [15] correlated the material properties, including hardness, of selected aluminum alloys with ultrasonic wave velocity variations. Bouda et al. [16], Lukomski, et al. [17], Chou et al. [18] and Rayes et al. [19] developed the correlations between ultrasonic wave velocity and steel hardness to determine the thickness average hardness. These studies showed that the velocity measurements of pulse-echo ultrasonic wave provide average hardness through the thickness of materials, but the correlations were performed using surface hardness. Isotropic materials were used in these studies, and it was assumed that the inner hardness of samples was consistent with surface hardness. However, these correlations were not tested in industrial applications. This study aims to investigate the feasibility of through-thickness average hardness investigation method using a widely used industrial method. For this purpose, welding process, which causes the formation of irregularities in the material, is selected, and the hardness variations after welding of three different types of materials are investigated. Results of the ultrasonic method are verified by the widely used destructive surface hardness measurement method.

2. Methodology

Ultrasonic technique for investigation of average hardness through the thickness has some restrictions. Correlations can only be performed using destructive surface hardness measurement methods which cause suspicion on the accuracy of the results. Accordingly, the ultrasonic waves for average hardness measurement have not been widely used for industrial purposes. This study aims to propose the reliability of ultrasonic waves for average hardness investigation using a real industrial application on three different types of steels.

Welding is a complicated process that causes the irregular changes in the grain structure of materials. Rapid heating and cooling cycles of the welding process cause the formation of hardened zones around the weld beam. Variation of hardness during this process differs at different sections of a material related to distance from those at weld center and heat input. For this purpose, the welding process is selected as an industrial application for investigation of the reliability of ultrasonic bulk hardness measurement method in the conditions of non-homogeneous hardness. In addition, the most common variable in the composition of steels is carbon content so that the carbon steels with different carbon contents are used in order to observe the success of this method for different materials.

In order to investigate the feasibility of ultrasonic waves for hardness measurement, the low alloy steels with similar composition but different carbon contents are used. Ultra low-carbon interstitial free steel (IF steel) is used as a carbon free steel sample. Low carbon and medium carbon steels with 0.092 weight % and 0.478 weight % carbon contents are other steel types with higher carbon content. Samples of each steel type are prepared with dimensions of 20 mm × 20 mm × 10 mm. Each sample is annealed at varying temperatures from 100 °C to 1150°°C. The samples are heated to the annealing temperature, kept at this temperature for 2 h and then cooled down to room temperature in the oven.

The Rockwell hardness test is a simple hardness measurement technique which can be applied to a wide variety of materials [20]. The depth of a prescribed load is determined, and converted to a hardness value [21] in this technique. Eq. (1) [22] is used to calculate Rockwell hardness,

$$HR = N - \frac{h}{S} \tag{1}$$

where HR is Rockwell hardness; N is numerical constant; h is remaining depth of penetration; and S is scale division. There are various Rockwell scales that are marked by additional capital letter to HR. HRB scale is used for soft and middle hardness steel, aluminum, and brass. Carbon steels with carbon content lower than 0.5 weight % are classified as soft and middle hardness steels, and consequently, HRB scale is used