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Influence of temperature on mechanical characteristics of 1018 low carbon steel estimated by ultrasonic non-destructive testing method

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The temperature dependence of ultrasonic velocities propagated in low carbon steel 1018 has been investigated by the A-scan mode of the ultrasonic non-destructive testing method. Experimental results show that these velocities are linearly dependent on temperature of the carbon steel sample in the range of 0 to 50 °C. Based on the experimental velocities of the longitudinal wave and the shear one, mechanical characteristics of this carbon steel including Poisson's ratio (υ), Young's modulus (E), shear modulus (G), and bulk modulus (K) have been calculated. These mechanical characteristics have also been linear response with respect to the increase of sample's temperature. By using linear fitting approach, the temperature dependence coefficients of these mechanical characteristics have been analyzed and estimated to be 9.76×10^{-6} / °C, −0.057 GPa/°C, −0.023 GPa/°C, and −0.038 GPa/°C for v, E, G, and K, respectively. It is concluded that the influence of the temperature on the mechanical properties of the carbon steels is necessary determined due to the improved accuracy of the ultrasonic testing method.

Keywords: Nondestructive testing methods, Ultrasonic testing methods, Ultrasonic velocity, Poisson's ratio

1 Introduction

Non-destructive testing methods (NDT) are widely used to evaluate the properties of materials and also to define the components of a systems without damaging of testing samples. The most common application of NDT is to check the apperance of defects inside a testing sample. When defects are detected, their location, dimension, orientation, and shape could be determined in detail. Nowadays, there are several non-destructive techniques, such as X-ray images[1], thermographic imaging[2] and ultrasonic testing methods[3], etc. Among these NDT techniques, the ultrasonic testing method is widely ultilized to analyze and characterize the important properties of materials such as microstructure, mechanical properties of materials, thermal damage, molecular interaction of liquid mixtures, etc.[4-13], because of its advantages for example low-cost, high safety, good accuracy, and ease of operation.

Carbon steels are alloys of steel in which carbon is main element. These steels have good properties such as good strength, good toughness and ductility. Therefore, they have many applications in different fields, for examples ship building, goods fabrication, home appliances, low carbon wire, etc[14]. In order to guarantee the quality of carbon steel products, investigating mechanical properties of the carbon steels is of hight importance. Up to date, various researches have been showing that the ultrasonic non-destructive testing is an useful method to analyze and characterize properties of the carbon steels. Ruiz *et al.*[8] used this ultrasonic method for early detection of thermal damage in steel. Freitas *et al.*[15] showed that the nondestructive characterization of microstructures and determination of elastic properties of the carbon steel can be utilized by ultrasonic method. In addition, Yan *et al.*[16] and Zenghua *et al.*[17] reported the dependences of the ultrasonic properties of steels on temperature.

The main aim of this work is to evaluate the dependence of the mechanical properties of the 1018 low carbon steel on sample's temperatures which were estimated by the ultrasonic non-destructive testing. By using the pulse echo technique and a direct contact method of the A-scan mode of the ultrasonic non-destructive testing, velocities of longitudinal ultrasonic wave and shear one could be characterized when the sample's temperature increased from 0 to 50 °C. Instantaneously, the dependences of mechanical properties of this 1018 low carbon steel

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*Corresponding author (E-mail: phamvanthanh@hus.edu.vn) on temperature were also determined in detail such as Poisson's ratio (υ), Young's modulus (E), shear modulus (G) and bulk modulus (K).

2 Experimental Methods

Type 1018 low carbon steel was used in this study with the following chemical composition in %wt: 0.17 C, 0.816 Mn, 0.01 P, 0.005 S, 0.07 Ni, 0.06 CR, 0.01 Mo, 0.2 Cu, 0.022 Al and 0.01 N. The mass density of this steel type is 7800 kg/m^3. The shape and the dimensions of this steel sample were shown in Fig. 1(a) with mm unit for each dimension; this sample separates into two parts: one for ultrasonic longitudinal wave measurement and other for ultrasonic shear wave measurement.

Figure 1(b) shows the schematic diagram of the experimental set-up. In this diagram, the ultrasonic flaw detector AND 3213EX was used as a pulser/receiver ultrasonic system. The pulse-echo technique and direct contact method were used to characterize the ultrasonic velocities. A single transducer with 5 MHz center frequency was used to generate an ultrasound and then received echo of the ultrasonic longitudinal wave measurements; otherwise, a single 70° angle transducer with 5 MHz center frequency was used for ultrasonic shear wave measurements. Motor oil was used as a coupling material layer between transducers and steel sample. The temperature of testing sample was controlled by a temperature controller FOX2005 and Peltier chips with ± 0.5 °C of temperature variation. The temperature of sample changed in the range from 0 to 50 °C with 5 °C for each raising step. The waiting time for each step is about 20 min in order to obtain stability of temperature. The temperature of sample must be kept smaller than 55 °C because the ultrasonic transducers could be damaged at high temperature[18].

To minimize error of the experimental ultrasonic velocities, the positions of ultrasonic transducers were kept the same for all steps of temperature change. The time of ultrasonic wave propagation was measured between the first two echoes of pulse-echo technique. The propagation distances were measured at transducers' position by vernier caliper with accuracy of ± 0.02 mm. To keep steady pressure applied to the transducers, a metal cylinder was positioned on the transducers; the weight of this cylinder is about 200 g. By using these experimental setups, the errors of experimental velocities were estimated about ± 0.5 m/s.

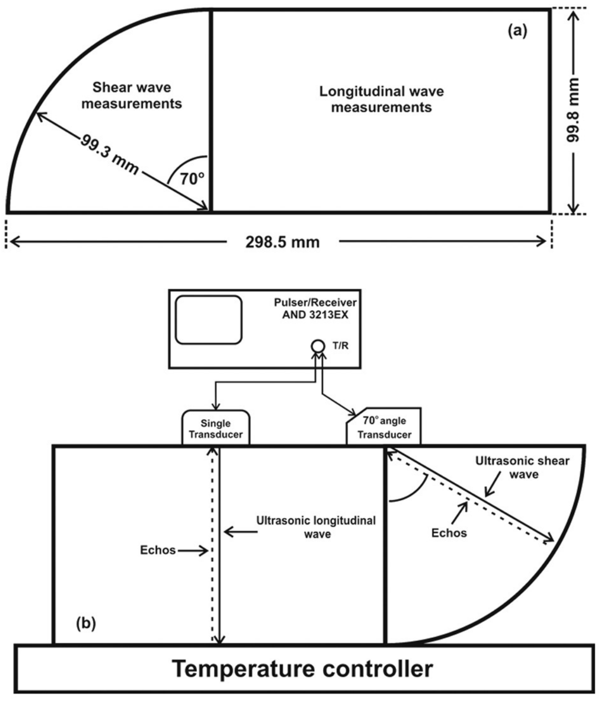

Fig. 1 — (a) Dimensions of the 1018 low carbon steel sample and (b) the experimental set-up

3 Temperature Dependence of Ultrasonic Wave Propagation

The mechanical properties and dimensions of a steel sample will change because of its temperature dependence. A linear dependence of each property on temperature is assumed as the following equation[17,19,20]:

$$P(T) = P(T_0) + \frac{\partial P(T)}{\partial T}\Delta T \qquad \ldots (1)$$

where P is one of the mechanical properties of the sample, such as Young's modulus (E), Poisson's ratio (ν), shear modulus (G), and bulk modulus (K). T is sample's temperature. T_0 is reference temperature. And $\partial P(T)/\partial T$ is temperature dependence coefficient, i.e., sensitivity of the material property of sample to temperature. The dependence of ultrasonic wave velocities on sample's temperature can be obtained by the following relations[15,20]:

$$C_l = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad \ldots (2)$$

$$C_t = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \qquad \ldots (3)$$

where C_l and C_{t} are velocities of ultrasonic longitudinal wave and one of ultrasonic shear wave, respectively, ρ is mass density of material.

The values of Poisson's ratio (υ), Young's modulus (E), and shear modulus (G) of material could be expressed as following[15]:

$$\nu = \frac{C_l^2 - 2C_{\mathrm{t}}^2}{2\left(C_l^2 - C_{\mathrm{t}}^2\right)} \qquad \ldots (4)$$

$$E = \frac{\rho C_t^2\left(3C_l^2 - 4C_{\mathrm{t}}^2\right)}{C_l^2 - C_{\mathrm{t}}^2} \qquad \ldots (5)$$

$$G = \rho C_{\mathrm{t}}^2 \qquad \ldots (6)$$

For an isotropic material, bulk modulus K of material could be obtained as[21]:

$$\frac{1}{3K} = \frac{3}{E} - \frac{1}{G} \qquad \ldots (7)$$

It is mean that if the values of ultrasonic velocities could be affected by sample's temperature, the values of υ, E, G, and K could be also affected by the sample's temperature[14,21]. Notably, the thermal expansion α of carbon steel is as small[22] as of 1.2×10^{-5}/°C; therefore, the temperature dependence of mass density ρ of the 1018 carbon steel sample will be ignored and considered as a constant value of 7800 kg/m^3 within a range of temperature from 0 to 50 °C in this study[14,17].

4 Results and Discussion

Firstly, the effect of the prolongation of propagation distance due to the temperature on the measurement of propagation velocity is considered. The length change of propagation distance in steel sample of ultrasonic waves is linear with temperature and can be expressed as[17,22]:

$$\Delta l = l_{\mathrm{T}} - l_{\mathrm{T_0}} = \alpha\left(T - T_0\right) l_{\mathrm{T_0}} \qquad \ldots (8)$$

where l_{To} and l_{T} are reference and final length for temperature changing from T_{o} to T, respectively. For example, with temperature raising from the room temperature 23 °C to 50 °C the prolongation of propagation distance was calculated to be about 0.03 mm. This prolongation is much smaller than the propagation distances of 99.8 and 99.3 mm for longitudinal and shear wave measurements, respectively. Therefore, the effect of temperature on the length change of propagation distance could be considerably ignored.

Based on Eqs (1) and (2), it is clearly indicated that the velocity of ultrasonic longitudinal wave strongly depends on the temperature of the sample. By using A-scan of pulse/echo method of the ultrasonic non-destructive testing[3], the experimental velocities C_l of the ultrasonic longitudinal were obtained and shown as line (a) in Fig. 2; these velocities increased in the range of 5893.6 to 5931.6 m/s when the temperature of 1018 carbon sample decreased from 50 down to 0 °C. By using linear fitting approach, the coefficient temperature dependence of these experimental velocities[10] was obtained to be -0.76 m/s.°C. Simultaneously, based on Eqs (1) and (3), the ultrasonic shear velocities C_{t} are also clearly dependent on the sample's temperature. The experimental velocities of the ultrasonic shear wave were obtained in the range of 3214.2 to 3237.2 m/s by using A-scan mode of pulse/echo method and shown as line (b) in Fig. 2 with sample's temperature decreasing from 50 down to 0 °C. By using the linear fitting approach of these experimental shear velocities, their coefficient temperature dependence was estimated to be −0.47 m/s.°C. The experimental values of the longitudinal ultrasonic velocities and the shear ones propagated in this 1018 carbon steel sample are comparable with ones of other researches for the carbon steels[8,15-17]. Notably, the temperature dependence coefficients of this 1018 carbon steel are smaller than -0.94 m/s.°C and - 0.64 m/s.°C for longitudinal velocities and shear ones of the steel strand, respectively, which were reported by Zenghue *et al.*[17]. Therefore, it is necessary to consider the

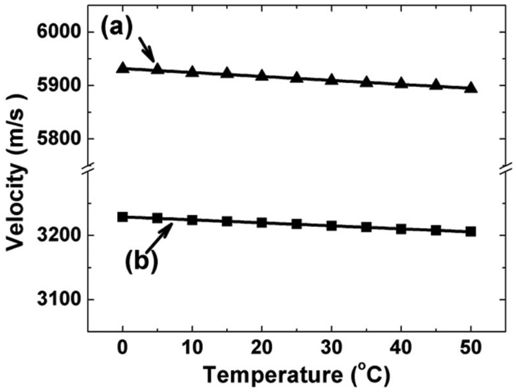

Fig. 2 — Experimental values of (a) longitudinal ultrasonic velocities C_l and (b) shear ultrasonic ones C_{t} versus sample's temperature

temperature effect on the ultrasonic velocities propagated not only in this 1018 carbon steel but also in the other carbon steels in order to improve the accuracy of the ultrasonic non-destructive testing method.

From Eq. (4), it is clearly shown that Poisson's ratio (υ) of this 1018 carbon steel is affected by temperature. Based on the measured values of the longitudinal velocities and the shear ones, values of Poisson's ratio of this carbon steel sample was investigated and shown as Fig. 3. The calculated values of v were in the range of 0.288 to 0.289. The coefficient temperature dependence of this υ was estimated to be 9.76×10^{-6} /°C by using linear fitting approach with temperature increasing from 0 to 50 °C. These values were very close to 0.29 of Poisson's ratio of the typical steels[14].

In addition, based on Eq. (5) and the experimental ultrasonic velocities, Young's modulus (E) of this steel sample were obtained in the range of 207.224 to 210.118 GPa that were shown as Fig. 4(a). This Young's modulus (E) is linear with sample's temperature shift, and its rate of change is about −0.057 GPa/°C estimated by using linear fitting approach. This rate is close to one of −0.06 GPa/°C of the low carbon steel with the sample's temperature below 360 °C obtained by American Society for Metals[14]. The shear modulus (G) of this 1018 steel sample could be also investigated by Eq. (6). The values of G were calculated in the range of 80.372 to 81.528 GPa and shown as Fig. 4(b); it is also clearly seen that the shear modulus (G) is linearly dependent on the sample's temperature. By using linear fitting approach, the coefficient temperature dependence of this shear modulus (G) was determined to be −0.023 GPa/°C. Whereas, based on the calculated values of Young's modulus (E) and shear modulus (G), the bulk modulus (K) of this carbon sample could be determined by using Eq. (7). The estimated values of K were in the range of 163.803 to 165.675 GPa and shown as Fig. 4(c), they are also linear dependence of sample's temperatures with −0.038 GPa/°C of its temperature dependence coefficient. Notably, the obtained values of G and K are very close to 78 GPa and 159 GPa, respectively, which were investigated by previous literatures[14,23,24].

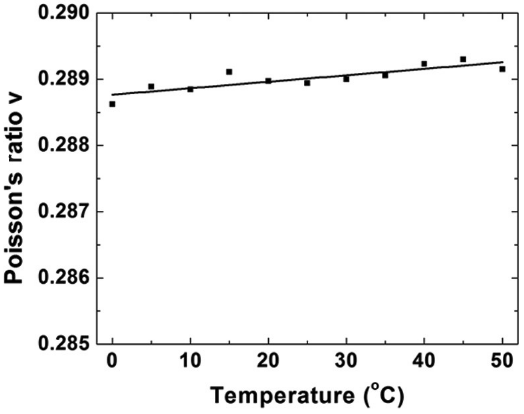

Fig. 3 — Poisson's ratio (υ) of 1018 steel sample versus temperature

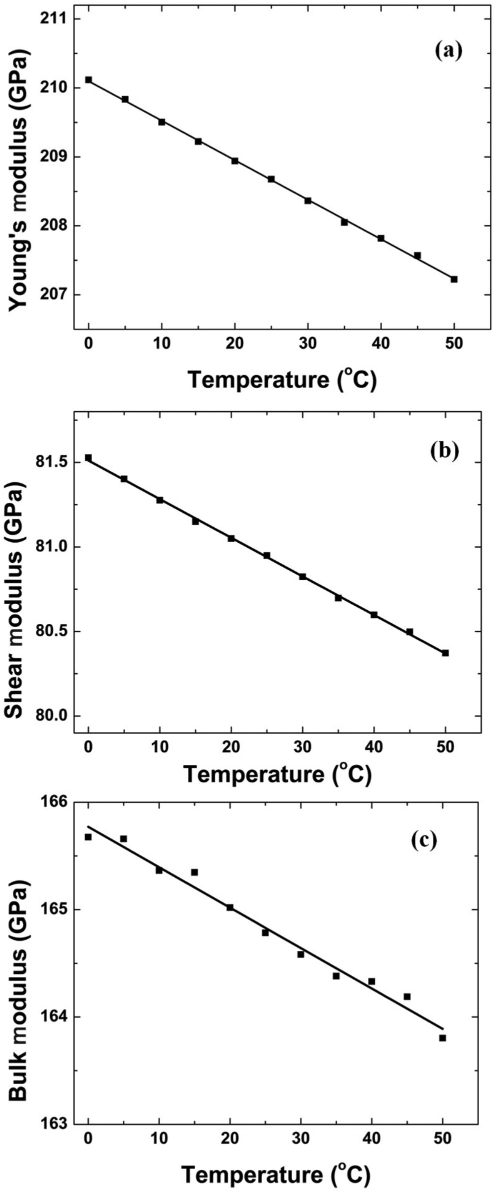

Fig. 4 — (a) Young's modulus (E), (b) shear modulus (G), and (c) bulk modulus (K) of 1018 steel sample versus temperature of sample

5 Conclusions

In this research, the dependences of ultrasonic velocities including longitudinal velocities and shear ones propagated in the 1018 low carbon steel sample on temperature were determined. When the temperature increased from 0 to 50 °C, it was seen that the velocities of the ultrasonic longitudinal wave and the ultrasonic shear one were decreased. The experimental temperature dependent coefficients of these ultrasonic longitudinal velocities and ultrasonic shear ones were estimated to be -0.76 and -0.47 m/s.°C by using linear fitting approach, respectively. Furthermore, the mechanical characteristics of this 1018 carbon steel sample including Poisson's ratio (v), Young's modulus (E), shear modulus (G), and bulk modulus (K) were investigated. It is reconfirmed that these mechanical characteristics are linear with temperature shift with the temperature dependence coefficients of v, E, G, and K being 9.76×10^{-6} /°C, −0.057 GPa/°C, −0.023 GPa/°C, and −0.038 GPa/°C, respectively. From the dependences of the experimental ultrasonic velocities and the estimated mechanical properties of the 1018 low carbon sample on the temperature shift, it is concluded that the temperature effects strongly not only on ultrasonic measurements but also on stress measurements of the low carbon steel materials. Therefore, it is necessary to consider it as one of the main factors which effect on the accuracy of these measurements.

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