Journal of Materials Processing Technology 216 (2015) 188–198

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Ultrasonic characterization of heat-treatment effects on SAE-1040 and -4340 steels

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ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form 4 September 2014
Accepted 5 September 2014
Available online 16 September 2014

Keywords:
Ultrasonic characterization
Sound velocity
Attenuation
Heat treatment of steel
Microstructural phases
Mechanical testing

ABSTRACT

In this work microstructural characterization and mechanical testing results were correlated with ultrasonic velocity and sound attenuation of steels SAE-1040 and SAE-4340. Both types were subjected to three types of heat treatment; the first was annealing at 850 °C, the second was austenitizing at 1000 °C followed by oil quenching and the third was similar austenitizing then water quenching. Treatments of SAE-1040 steel resulted in microstructures containing different ferrite and pearlite contents, different inter-lamellar spacing and also different grain size. Similar ferrite and pearlite content was obtained when annealing SAE-4340 whereas, oil and water quenching resulted into martensite. With SAE-1040, the sound velocity was reduced in the order of annealing–oil–water quenching due to the reduction of ferrite on the expense of pearlite. The same order in sound velocity reduction was also obtained with SAE-4340 due to the change in microstructural phases from pearlite to martensite. In comparison to pearlite, the martensite possessed higher crystal lattice distortion, higher dislocation density and lower elastic modulus all of which contribute in reducing sound velocity. Attenuation of SAE-1040 increased in the order of annealing–oil–water quenching because of higher pearlite content and the reduction in inter-lamellar spacing. Attenuation of SAE-4340 gave an opposite order due to the reduction of the extent of microstructural anisotropy. The mechanical properties and hardness were predominantly affected by the microstructural phases leading to the logical correlation with ultrasonic parameters.

1. Introduction

One of the prime objectives of non-destructive testing (NDT) is to certify that the component being examined is fit for the intended service. The most common way of doing so is by examining the component with NDT to detect flaws or discontinuities such as voids, inclusions, cracks, in materials or structures. Another parameter which is equally important to flaw detection is to assess the material properties. Among various NDT methods, ultrasonic testing (UT) was applied rather extensively in a variety of publications related to the correlation of ultrasonic measurements with microstructural phases of steel as conducted by Gür and Tuncer (2004), duplex stainless steel by de Albuquerque et al. (2010a,b), Ni-base super alloy by de Albuquerque et al. (2012), thermally aged Ni-base alloy by Nunes et al. (2013) and grain size as by Bouda et al. (2003). UT results were also correlated with mechanical properties as investigated by Vijayalakshmi et al. (2011) and de Albuquerque et al. (2010a,b), as well as residual stresses as by Chaki and Bourse (2009). Therefore, the utilization of ultrasonic techniques to indirectly determine the microstructural features and the mechanical properties can be useful for numerous industrial applications.

Plain carbon steels SAE-1020 and -1050 were heat treated by varying the austenitization temperature between 860 °C and 1060 °C, as well as the cooling rate was varied between furnace cooling, air cooling and oil quenching. These materials were characterized by ultrasonic velocity and attenuation measurements as reported by Gür and Keles (2003). Metallographic studies revealed that the amount of proeutectoid ferrite, the softer phase, in SAE-1020 was higher than that in SAE-1050. Ultrasonic results showed that sound velocities vary depending on the severity of cooling. The lowest sound wave velocity was found with the oil quenched SAE-1050 consisting of martensite, which possessed high dislocation density, distortion of crystalline lattice and maximum hardness among other specimens. On the other hand, the highest sound velocity was obtained with furnace cooled SAE-1020 which had the softest structure. It was also found that prior austenite grain size; and not the transformation products within it, as manifested

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http://dx.doi.org/10.1016/j.jmatprotec.2014.09.005
0924-0136/

Table 1
Chemical composition of steels SAE-1040 and -4340 in wt.%.

Steel grade SAE	C	Mn	P	S	Si	Cr	Mo	Ni
1040	0.41	0.6	0.04	0.05	0.3	–	–	–
4340	0.36	0.25	0.04	0.04	0.25	1.4	0.2	1.4

by the author, had the predominant effect on the attenuation values. The larger the prior austenite grain size the higher the sound attenuation. Slower cooling rates led to larger prior austenite grain size, larger amounts of soft ferrite and wider interlamellar spacing between cementite [Fe_3C] plates of pearlite.

Prasad and Kumar (1994) studied the influence of varying the grain size of cast steel on ultrasonic velocity and attenuation. Various grain sizes were achieved via hot upsetting at different percentages of height reduction. These samples were further heat treated through annealing, normalizing and hardening using oil quench followed by tempering. They reported that increasing the degree of deformation decreases the ultrasonic velocity. However, numerous research work concluded the fact that the longitudinal ultrasonic velocity varied from grain to grain because of misorientation of grains, which was related to the variation in the elastic constant as well.

The objectives of the present work were to correlate ultrasonic measurements namely; ultrasonic longitudinal sound wave velocity and ultrasonic attenuation with the microstructural and mechanical properties of two types of steel which were subjected to different heat treatments. These treatments were selected to obtain different microstructural phases as well as different grain size.

2. Materials and methods

Two types of steels, namely SAE-1040 (C-Mn steel) and SAE-4340 (Cr-Ni-Mo steel), supplied in the form of 50 mm diameters rods, from which both materials were cut into three equal pieces 100 mm long using hack saw with lubricant to avoid excessive heating. The selection of these steel types was based on their importance in various fields of industrial applications in which they are mainly characterized by durability. Steel 1040 is normally used in axels, crank shafts and gears, whereas, steel 4340 is used in air craft landing gears, power transmission gears and shafts. In addition, the types of heat treatment chosen were expected to result into different phases that were ought to significantly affect the microstructural, mechanical and ultrasonic characteristics. Table 1 presents the average chemical composition of these steels in wt.% after three runs for each type using spectroscopic chemical analyzer.

Both materials were subjected simultaneously to the same heat treatment type in an electric resistance furnace. The first treatment was austenitizing at 850 °C for 2 h followed by furnace cooling (full annealing). The second and third were austenitizing at 1000 °C for 3 h followed by oil and water quenching, respectively. The heat treated samples were sectioned into disks using hack saw with coolant to extract ultrasonic measurements samples [50 mm long], microstructural, hardness and tensile test samples. The microstructure was examined by secondary electron imaging using scanning electron microscopy (SEM), and electron back scattered diffraction (EBSD).

For SEM the samples were prepared according to standard metallographic sample preparation which includes grinding using SiC sand paper, polishing using diamond paste of 1.0 and 0.05 μm, and etched with 5% Nital to reveal the samples' microstructure. The microstructure for both materials was also studied by EBSD using Oxford HKL system incorporated on a field emission scanning electron microscope (FESEM) 7600 JEOL. These samples were polished with colloidal silica as a final step prior to imaging.

The ultrasonic measurement samples were machined using end milling then surface ground on both sides in order to ensure complete parallelism between faces. In order to eliminate roughness, visible irregularities and any oxides which might affect the ultrasonic measurements, the samples were further processed similar to the metallographic preparation steps. For ultrasonic measurements, the pulse-echo technique and direct contact method were applied to obtain ultrasonic velocities and attenuation coefficients using ultrasonic pulse-receiver equipment-Karl Deutsch (Model: Echograph-1085). Ultrasonic measurements for all samples were obtained by using commercial NDT ultrasonic-longitudinal wave transducers of 4 MHz. The coupling material Karl Deutsch-Ecotrace gel was used for the longitudinal wave measurements. During measurements a constant load was applied to the probe against the specimen surface so as to have a constant thickness of couplant layer at the interface between the specimen surface and the probe. Ultrasonic velocity was determined by dividing twice the specimen thickness by time of flight (TOF) obtained between zero crossing of the first and second back-wall echoes using Eq. (1) as applied by Vijayalakshmi et al. (2011). In order to check results repeatability, seven ultrasonic readings of each specimen were averaged to represent the data obtained, which gave an error of around ±0.5% with both types of steel.

$$\text{Velocity}\quad (\text{m/s}) = 2 \times \frac{\text{thickness}\quad (\text{m})}{\text{time}\quad (\text{s})} \tag{1}$$

During the same measurement, ultrasonic velocity was measured again using a function in the ultrasonic equipment which automatically calculates the ultrasonic velocity when locating two corresponding points on two successive echoes (first and second echoes) at the extreme sides of the screen with an error of less than the above mentioned one.

The ultrasonic attenuation values were calculated according to Eq. (2) which is based on the reduction of the amplitude of an ultrasound pulse, measured in decibels per millimeter (dB/mm). This equation appeared in several publications such that of Stella et al. (2009), Vijayalakshmi et al. (2011) and Freitas et al. (2011) and given in as:

$$\alpha = \frac{20}{2x} \log \frac{A_0}{A_1} \tag{2}$$

where α is the attenuation coefficient [dB/mm], x is the thickness of the sample measured in the test [mm], A_0 is the amplitude of the first echo in dB and A_1 is the amplitude of the second echo. The constant 2 is because the pulse-echo technique is used. For each sample, the measurements were repeated seven times with maximum error of ±0.1% with both steels.

Vickers macro-hardness tests were conducted using 10 kg force and were performed five times for each heat treated specimen and the average was taken. In order to evaluate the mechanical behavior of heat treated steels, tensile specimens were extracted from the center of the disk along its axis and were cut according to ASTM E-08. Tensile tests were conducted at room temperature and a cross-head speed velocity of 2 mm/min using Instron machine model 3385 H. The machine was equipped with a computer having software through which the load-elongation data were recorded. The tensile test for each type of steel and treatment was repeated three times and the average value was taken and presented hereafter.

3. Results and discussion

3.1. Microstructure

Fig. 1a–c shows the SEM microstructures obtained with the three different treatments applied on SAE-1040 steel. Fig. 1a shows