The effect of plastic deformation on the temperature dependences of ultrasonic velocities in Al-Mg alloy

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Abstract. This work deals with an experimental investigation of the effect of damage resulting from plastic deformation on the temperature dependences of ultrasonic velocities in 93% Al - 6% Mg alloy. For samples with different degrees of plastic deformation, the velocities of shear and longitudinal waves linearly decrease with increasing temperature from 230 K to 320 K. For both shear and longitudinal waves, results showed the average value of the temperature-velocity factor varies linearly with plastic deformation. The discovered structural sensitivity of the temperature-velocity factor opens up new possibilities for nondestructive evaluation of metal alloys with accumulated damage, but requires further research.

1. Introduction
The further development of ultrasonic nondestructive evaluation techniques for early diagnosis of material with accumulated damage is of great scientific and applied interest. One of the promising ways is a technique based on the effect of damage on the temperature dependence of ultrasonic velocity.

Elastic constants and density of material vary significantly with temperature, which leads to the fact that the velocities of elastic waves depend on the temperature. It is known that elastic constants and density, and, accordingly, the ultrasonic velocities depend on the damage accumulated in the material during operation of structure. It can be assumed the temperature dependences of ultrasonic velocities are also sensitive to accumulated damage.

The previous results of [1-7] show that, in the metal alloys, the ultrasonic velocity linearly depends on the temperature in the range between 210 K and 320 K:

\[ V = V_0 + \frac{\partial V}{\partial T} (T - T_0), \]

where \( \frac{\partial V}{\partial T} \) is the temperature derivative of ultrasonic velocity known as a temperature-velocity factor, \( V \) is a current velocity, \( T \) is current temperature, \( V_0 \) is the velocity at room temperature \( T_0 \).

It is generally accepted that the temperature-velocity factor is a constant for a particular material. However, it is shown in [5-7] for aluminum alloy and stainless steel that the temperature-velocity factor depends on the degree of plastic deformation. Basically, the temperature dependences of the elastic constants and, accordingly, the velocities of elastic waves are due to anharmonicity of the crystal lattice, and are directly related to the coefficients of higher order terms in the strain energy function [8]. The effect of plastic deformation on the temperature dependence of elastic properties and,
accordingly, ultrasonic velocities can be explained by changes in the interatomic interaction as a result of accumulation of crystal structure defects.

The purpose of this work is to investigate the effect of plastic deformation on the temperature dependences of ultrasonic velocities in Al-Mg alloy.

2. Experiment
For this study, 93% Al and 6% Mg alloy widely used in the arctic and aerospace applications was chosen. Five sheet-type samples were prepared. The initial dimensions of working area were 100×20×6 mm. One sample was investigated as-received. Four samples were plastically deformed to elongation for 5, 10, 15 and 20% to produce various degrees of damage. For deformation of samples, the testing machine Tinius Olsen H100KU was used. The loading rate was 2 mm/min.

The straightforward and precise ultrasonic echo-method was used for evaluating the velocities of elastic waves depended on the temperature. During measurements at sub-zero temperatures, we cooled the sample in the chamber by dry ice. During measurements at elevated temperatures, we heated the sample in the chamber by a digitally controlled dryer. We monitored the temperature using a thermocouple and a digital thermometer. We carried out the ultrasonic experiments at the temperature from 250 to 350 K.

The ultrasonic measurements were performed in three zones on the sample. The wide band piezoelectric transducers V156 and V110 Panametrics-NDT (direct, integrated, center frequency 5 MHz, piezoelectric element diameter 6 mm) were used for generation and reception of shear and longitudinal ultrasonic waves propagated perpendicular to the surface of the sample. The ultrasonic flaw detector A1212 MASTER ACS was used to generate electrical pulses. The digital oscilloscope LA-n10USB with ADCLab software was used to obtain the amplitude-time diagram of signals from the piezoelectric transducer on the PC. The sampling rate of the digital oscilloscope was 100 MHz, and the time resolution was 10 ns. The times-of-flight of ultrasonic waves were measured between echo pulses reflected from the reverse surface. To measure the time-of-flight, the technique described in detail in [9] was used. The ultrasonic velocity $V$ was determined from the ratio of the path length $l$ to the time-of-flight $t$:

$$ V_{ls} = \frac{l}{t_{ls}}. $$

Here subscript $l$ or $s$ denotes shear and longitudinal waves respectively.

The path length was determined taking into account the thermal expansion:

$$ l = 2h_0[1 + \alpha(T - T_0)]. $$

Here $h_0$ is the thickness of the sample measured using a micrometer at the room temperature $T_0$, $\alpha$ is the linear thermal expansion coefficient, $T$ is current test temperature, $T_0$ is room temperature equal to 293 K. In the calculations, the linear thermal expansion coefficient $\alpha$ was assumed to be constant and equal to $24.7 \times 10^{-6}$ K$^{-1}$.

As a result of experiment the dependences of shear and longitudinal velocities on temperature were obtained for samples with degrees of plastic deformation 0, 5, 10, 15 and 20%. For example, figure 1 shows the curves for the temperature dependences of longitudinal wave velocity in one of the zones of as-received sample and in one of the zones of plastically damaged sample. Although dispersion between the temperature derivatives of ultrasonic velocity for the different zones is quite high, the average value varies linearly with plastic deformation for both shear and longitudinal waves as shown in figure 2. It should be noted that this effect has different signs for longitudinal and shear waves. Thus, it can be assumed that the temperature-velocity factor is sensitive to microstructural damage accumulated in the material. The physical mechanism of this can be explained by the fact that the accumulated crystal structure defects affect anharmonicity of the crystal lattice.
Figure 1. Example of temperature dependence of longitudinal wave velocity.

\[ \frac{\partial V}{\partial T} \text{ [m/s×K\(^{-1}\)]} \]

- \( V \) is velocity of wave,
- \( T \) is temperature

Figure 2. Temperature-velocity factors for shear and longitudinal waves.

Density of each sample was measured by hydrostatic weighing, and then damage resulting from plastic deformation was quantified as density reduction

\[ \psi = 1 - \frac{\rho}{\rho_0}, \]

(4)

where \( \rho \) is density of deformed sample, \( \rho_0 \) is density of as-received sample. A plot of dependence of density reduction on plastic deformation is shown in figure 3.
Figure 3. Dependence of density reduction on plastic deformation.

For non-destructive evaluation of material with accumulated damage, it is more convenient to use not the temperature-velocity factor $\partial V/\partial T$, but the relative change in the time-of-flight due to temperature $\partial \ln t/\partial T$. The use of this quantity allows not to measure the thickness of material $h_0$ and the linear thermal expansion coefficient $\alpha$. The relative changes in the time-of-flight and velocity due to temperature are related by follows

$$\frac{\partial \ln t}{\partial T} = \alpha - \frac{1}{V} \frac{\partial V}{\partial T}.$$  (5)

The plots of dependences of $\partial \ln t/\partial T$ on density reduction for longitudinal and shear waves are shown in figure 4. It is assumed that the change in quantity $\partial \ln t/\partial T$ is affected by microstructural damage accumulated during plastic deformation. The effect of crystallographic texture on the temperature dependence of ultrasonic velocity was not investigated in this work.

Figure 4. Dependence of temperature sensitivity of time-of-flight of ultrasonic wave on density reduction of material.
Table 1 summarizes all the results of the experiment.

| ε [%] | ρ [kg/m³] | ψ [%] | ∂V/L/∂T [m/s·K⁻¹] | ∂V/S/∂T [m/s·K⁻¹] | ∂ln t/L/∂T [K⁻¹] | ∂ln t/S/∂T [K⁻¹] |
|-------|-----------|-------|---------------------|---------------------|-------------------|-------------------|
| 0     | 2649      | 0     | −1.67±0.01          | −1.34±0.09          | 273±0             | 436±28            |
| 5     | 2644      | 0.18  | −1.60±0.21          | −1.43±0.11          | 265±30            | 460±33            |
| 10    | 2640      | 0.36  | −1.53±0.16          | −1.55±0.10          | 254±24            | 496±31            |
| 15    | 2635      | 0.54  | −1.38±0.02          | −1.63±0.17          | 233±2             | 520±48            |
| 20    | 2630      | 0.73  | −1.29±0.01          | −1.67±0.37          | 218±2             | 540±102           |

The use of temperature-velocity factor ∂V/∂T or relative change in the time-of-flight due to temperature ∂ln t/∂T opens up new possibilities for nondestructive assessment of damage accumulated in material. Such problem as high dispersion of values requires further investigations.

3. Conclusion

It is shown that the temperature dependences of velocities of longitudinal and shear waves in 93% Al and 6% Mg alloy vary with microstructural damage resulting from plastic deformation. This effect can be used for nondestructive evaluation.

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