Broadband ultrasonic pulse-echo method for estimation of local density of tungsten samples

Kravcov A.1, Dudchenko O.L.2, Svoboda P.1, Ivanov P.N.2, Sizikov M.V.2, Belov O.D.2 and Gapeev A.A.2

1. Department of Construction Technology, Faculty of Civil Engineering in Prague, Thákurova 7/2077, Prague 6 - Dejvice, 166 29, Czech Republic
2. Moscow Mining Institute, the National University of Science and Technology MISiS, Leninskii Prospect 4, Moscow 119991, Russia

Corresponding author: kravtale@fsv.cvut.cz

Abstract. Current paper describes an application of laser ultrasonic time-of-flight measurement method for estimation of local density of pure tungsten sample. Formulas for estimation of density from speed of sound are derived. Experimental maps of sample density are presented. Accuracy of estimations is up to $37 \frac{kg}{m^3}$.

Keywords: laser ultrasound, time-of-flight measurements, distribution of density, tungsten

1. Introduction
Measurement of volume distribution of material density is an important problem for a number of industrial and scientific applications, as this parameter determines various properties of materials. To this end, in current study we show an ability of laser ultrasonic pulse-echo structuroscopy to estimate local density of tungsten sample with a very high acoustic impedance. Laser ultrasonic method is being intensively developed for solution of such problems of applied physics, as inspection of welds [1], estimation of residual stresses in metal structures [2], detection of micro-cracks in carbon fiber composites [3], measurement of local elastic modules [4,5], local porosity [4], visualization of filaments in liquids and gases [7], defectoscopy of samples manufactured by selective laser sintering [7], laser ultrasonic tomography [8,9]. Nowadays creation of more elaborated laser ultrasonic apparatus allowed experimental measuring of local density of alloys.

2. Method and Material
Laser ultrasonic structuroscope was used for experimental time-of-flight measurements. A principle of operation of laser ultrasonic apparatus is based on laser thermo-optical excitation of wideband nanosecond ultrasonic pulses of longitudinal bulk acoustic waves in special opto-acoustic transducer [10, 11, 12]. Duration of probe pulses is 70 ns, 0.1 MPa, and diameter of acoustic beam is 1 mm [13, 14]. Waves propagate through volume of the sample, undergo reflection or scattering by crack or bottom of the sample, travel back the same path. They are recorded by polymeric piezoelectric film (0.1–10 MHz), digitized by analog-to-digital converter and transferred to personal computer for further treatment. Speed of sound is calculated in the unilateral-access mode from measurements of thickness of the sample and time of flight of laser ultrasonic pulse, which is the difference of arrival
times of pulses reflected from top and bottom surfaces. Note, that obtained values of speed are mean values along path of acoustic beam in every measurement point. Experimentally achievable precision of speed of sound measurements by laser ultrasonic apparatus is 0.1 %.

Speed of longitudinal acoustic waves in metal can be calculated by well-known relation

\[ c_l = \sqrt{\frac{K}{\rho}}, \]

where \( K \) is elastic modulus, given by combination of Young’s and Poisson’s ration, and \( \rho \) is material density. This formula can be used to derive an estimation for relative error of measurement of speed of sound

\[ \frac{\Delta c_l}{c_l} = \frac{1}{2} \sqrt{\left(\frac{\Delta K}{K}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2}, \]

where \( K, c_l \) are mean values of elastic modulus and speed of sound of longitudinal waves, \( \rho = M/V \) is mean density of material, \( M \) is sample mass, \( V \) is sample volume, which are obtained by simple hydrostatic weighing, \( \Delta c_l, \Delta K, \Delta \rho \) – absolute errors of measurements of corresponding values. Variations of elastic modulus \( K \) over sample volume depend on state of material and its density. However, these variations for \( K \) are lower than that of density \( \rho \) for the case of tungsten sample, and we write limitation for variation of density in material in the following form:

\[ 2 \left| \frac{\Delta c_l}{c_l} \right| \geq \left| \frac{\Delta \rho}{\rho} \right|. \]

Therefore, we obtain a formula for an upper limit of local sample density (the same can be written for lower limit of sample density):

\[ \rho_{\text{est}} = \rho \left(1 + 2 \frac{\Delta c_l}{c_l}\right). \]

Approbation of provided estimations was done for tungsten sample with cylindrical shape (diameter – 200 mm, thickness – 28 mm). Variations of sample thickness were lower than 50 \( \mu \)m. Measurements by laser ultrasonic structuroscope were carried out in raster-scanning mode with 1-mm step. Speed of sound was calculated from formula

\[ c_l = \frac{2L}{\Delta t}, \]

where \( L \) is sample thickness, \( \Delta t \) is time of flight. And estimations of density are calculated from formula for upper limit of local sample density.

3. Results

In Fig. 1 you can see the distribution of estimation of mean density in \( \text{kg/m}^3 \) units over flat surface of the sample with size of \( 20 \times 20 \text{ mm} \).
Figure 1. Distribution of local mean density over tungsten sample surface. Images are calculated from C-scan data over two parts of the sample.

The relative difference between maximum and minimum density values of the scanned area is 0.8%. This significantly exceeds error of speed-of-sound measurements (~ 0.1 %), caused by thickness variations. Maximal density is 18720 kr/m$^3$, minimal is 18510 kr/m$^3$. Therefore, we estimate density of scanned parts of the sample as

$$\rho = 18650 \pm 110 \text{ kg/m}^3.$$ 

Special software uses recorded signals (A-scans) to build B-scans and C-scans. Digital treatment of these scans are used to visualize cracks and internal sample structure in different cross-sections of the sample. Fig. 2 shows XY (sample surface) and YZ (vertical) cross-sections with image of pore with diameter ~ 0.3 – 0.5 mm at depth of ~ 5 mm.

Figure 2. Cross-sections of tungsten sample: a - XY, b - YZ cross-section with pore.
4. Conclusions

Estimations and experimental results on measurement of local density of tungsten sample provided in the current paper show, that

1. The acoustic beam with 1 mm width provides measurement of local speed of longitudinal waves with 1 mm step over plane metal surface. Hence, step of measurement of density distribution is the same;

2. Relative error of density estimations is twice as relative error of measurement of speed of longitudinal waves. Precision of measurements by laser ultrasonic structuroscope is up to 0,1%, and precision of density measurements is up to 0,2% ($\sim 37 \text{ kg/m}^3$);

3. Application of laser ultrasonic structuroscopy allows both determining local characteristics of metal and visualizing its internal structure for detection of pores, micro-cracks with precision of 100 $\mu$m.

Therefore, laser ultrasonic structuroscopy is promising method for inspection of wide range of properties of different materials, which provides higher resolution of measurements and better image quality compared to standard ultrasonic methods.

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