Use of acoustic parameter measurements for evaluating the reliability criteria of machine parts and metalwork

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Abstract

A new method for non-destructive evaluation of the mechanical properties of structural materials has been developed. This is based on measurements of the ultrasound propagation velocity in deforming materials. Preliminary investigations were carried out in order to relate the ultrasound propagation velocity to the mechanical characteristics of the deforming material. A detailed description of suitable devices intended for ultrasound propagation velocity measurement to a high accuracy is presented. Using Zr base alloys as an example, it is shown that the method can be used for monitoring zirconium billets from which nuclear reactor fuel cladding is fabricated by cold rolling.

Keywords: Ultrasound propagation, nondestructive, stress-strained state, monitoring

1. Experimental justification of the method

It was established previously [1, 2] that the ultrasound propagation rate measured directly for tensile metal specimens would depend on total deformation (see Fig. 1 obtained for the tested brass specimen), flow stress and material structure. Similar data were obtained also for small total strains by M. Kobayashi [3]. However, our attention was focused in particular on the form of ultrasound rate dependence on flow stress obtained (Fig. 2). This consists of three linear sections that can be described [1] by the following equation

\[ V_S = V_0 + \xi \sigma, \]  

were the empirical constants \( V_0 \) and \( \xi \) have different values for the different stages of the flow process. From Fig. 1 follows that \( \xi \) can be both positive and negative. However, the proportionality \( V_S \sim \sigma \) is always fulfilled within a single stage with the correlation coefficient being \( \sim 0.9 \).

The goal of the present study is to verify that Eq. 1 can be used for the evaluation of mechanical characteristics of materials, using the non-destructive method developed. To elucidate the issue, the dependence \( V_S(\sigma) \) was obtained for various kinds of alloys (see Table). Using the method of sound pulses autocirculation, the propagation rate of Rayleigh waves was measured directly for flat tensile specimens.

The dependencies \( V_S(\sigma) \) obtained for all the test materials have a similar shape. One can easily establish the general form of this dependence (Fig. 2), using the dimensionless
variables $V_s/V_s^*$ and $\sigma/\sigma_B$, were $V_s^*$ is the rate of ultrasound propagation in the undeformed material and $\sigma_B$ is the strength limit of the material.

The above normalization permits pooling of the data obtained for all the materials tested; stages 1 and 2 of the dependence $V_s(\sigma)$ are given by

$$V_s/V_s^* = \kappa_i + \alpha_i \cdot \sigma/\sigma_B. \quad (2)$$

Here $i = 1, 2$ is stage number; the empirical constants $k_i$ and $\alpha_i$ are independent of the kind of material. It is found that the respective values for stages 1 and 2 are as follows: $k_1 = 1.0 \pm 2.10^{-3}$ and $k_2 = 1.03 \pm 10^{-3}$; $\alpha_1 = 6.5 \cdot 10^{-3} \pm 4.7 \cdot 10^{-4}$ and $\alpha_2 = 3.65 \cdot 10^{-2} \pm 3.2 \cdot 10^{-3}$.

From Eq. (2) follows

$$\sigma_B = \frac{\alpha_i \sigma}{V_s/V_s^* - \kappa_i}. \quad (3)$$

This can be used for the estimation of strength limit at small total plastic strains long before specimen failure. To do this, the ultrasound propagation rate, $V_s$, is measured for stresses in the range $\sigma_{0.2} < \sigma < 0.6 \sigma_B$ (here $\sigma_{0.2}$ is proof stress) $\Box\Box$, which initiates small plastic deformation only.

The strength limit values obtained from Eq. (3) ($\sigma_B^*$) are matched against those derived conventionally from the curves $\sigma - \varepsilon$ ($\sigma_B$) in Fig. 3. The rate, $V_s$, was measured at the deformation $\varepsilon \Box \Box \approx 1\%$ for the flow stress $\sigma \approx 0.1 \sigma_B$. The values $\sigma_B$ and $\sigma_B^*$ are practically equal, i.e. $\sigma_B = 0.96 \sigma_B^*$. The correlation coefficient is $\approx 0.96$. 

### Table. Chemical composition of the alloys investigated.

<table>
<thead>
<tr>
<th>N</th>
<th>Material</th>
<th>Symbol</th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>Mg</th>
<th>Mn</th>
<th>Li</th>
<th>Cr</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Pb</th>
<th>Zr</th>
<th>Ti</th>
<th>Sn</th>
<th>Nb</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Steel</td>
<td>▼</td>
<td>0.12</td>
<td>–</td>
<td>0.8</td>
<td>2.0</td>
<td>–</td>
<td>17.0</td>
<td>9.0</td>
<td>0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>Steel</td>
<td>□</td>
<td>&lt;0.12</td>
<td>0.008</td>
<td>0.5</td>
<td>1.3</td>
<td>1.7</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>3</td>
<td>Steel</td>
<td>△</td>
<td>&lt;0.12</td>
<td>0.008</td>
<td>0.8</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
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<td>0.12</td>
<td>–</td>
<td>0.4</td>
<td>0.65</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>Duralumi n</td>
<td>◊</td>
<td>–</td>
<td>–</td>
<td>0.5</td>
<td>1.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.35</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>6</td>
<td>Al-Mg</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>0.25</td>
<td>5.8</td>
<td>6.2</td>
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<td>0.25</td>
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<td>2.2</td>
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<td>–</td>
<td>–</td>
<td>0.1</td>
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<tr>
<td>7</td>
<td>Al-Li</td>
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<td>–</td>
<td>0.15</td>
<td>–</td>
<td>–</td>
<td>1.8</td>
<td>2.0</td>
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<td>3.2</td>
<td>–</td>
<td>–</td>
<td>0.12</td>
<td>0.12</td>
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<td>–</td>
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<tr>
<td>8</td>
<td>Brass</td>
<td>●</td>
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<td>–</td>
<td>&lt;0.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.8</td>
<td>0.8</td>
<td>4.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>Zr-Nb</td>
<td>★</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>99.0</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>Zr-Nb</td>
<td>●</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>97.5</td>
<td>1.0</td>
<td>1.0</td>
<td>–</td>
</tr>
</tbody>
</table>

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Fig. 2. The generalize dependence $V_s/V_s^*(\sigma/\sigma_B)$ obtained for steels.
The above testifies the efficiency of the proposed method for strength limit evaluation in structural materials, which deform at small total plastic strains long before specimen failure. Thus, it is a promising method for structural integrity monitoring of metalwork and machine parts. The nature of the above relation might be addressed on the assumption that material hardening is determined by the internal stress fields, which inhibit dislocation motion [4]. On other hand, with increasing internal stresses, the ultrasound propagation rate would decrease [1, 2]. Thus, the above two values are defined by the same factor; therefore, they are found to be closely related.

2. Equipment designed for ultrasound method application

The units designed for ultrasound method implementation are Acoustic Strain Tester Rapid (ASTR) and Acoustic Non-Destructive Analyzer (ANDA), which are meant for structural integrity inspection of metals and alloys in metalwork and machine parts during long-term service in both regular and severe conditions; the units are made in small lots. The general principle of operation of the units is measurement of Rayleigh wave pulse frequency, using an auto-circulation method [3]. They are simple in operation; frequency measurement is performed to an accuracy of \( \sim 3 \times 10^{-5} \).

The technique of auto-circulation of pulses is based on the excitation of the ultrasonic vibrator by a pulser, which is synchronized by pulses passing through the analyzed medium. The pulse repetition frequency assumes a steady-state value, which is determined by the running time of the pulse in the medium analyzed. Evidently, due to a fixed distance between the piezo-transducers, the pulse repetition frequency would be directly proportional to the ultrasound propagation rate. The pulse repetition frequency is commonly called auto-circulation frequency. A device based on the principle of auto-circulation makes use of longitudinal, transverse or surface (Rayleigh) waves. In the present work Rayleigh surface waves having frequency of 2.5 MHz are used.

The excitation of surface waves in the specimen investigated is performed with the aid of a piezoelectric transducer, which features a waveguide having the shape of a truncated prism, a piezoelectric element and a damper. The piezoelectric transducers, both the excitation source and the receiving one, are installed on a common base and thus form a gage head. The separation between the piezo-transducers is fixed and is taken to be the gage length. To take measurements, the waveguides are pressed firmly to the object tested so as to provide for good contact. Transformer oil is used as contact medium for ultrasonic transmission. However, the space between the transducers should remain free of the contact medium.

3. Use of the ultrasound method to evaluate residual internal stress level

The applications of the proposed method include the estimation of stressed state in zirconium billets used for the manufacture of nuclear reactor fuel cladding. During the cold rolling of Zr-Nb alloy tubes, an intricate distribution of residual internal macro-stresses would form in the worked billet, which enhances the probability of its failure at one of the process stages. When tackling the problems of process optimization, one has to take into account the level and distribution of residual internal macrostresses in worked billets. On account of their
large size, however, this is hardly feasible with the aid of conventional methods, e.g. X-ray techniques [5], very much so under process conditions.

The present investigation was carried on using the ASTR unit to determine internal stress levels for worked billets. The measurements were made in a wide range of internal stresses for the deforming specimens of Zr-Nb alloy 9 (see the Table) in order to relate the internal stresses to the propagation rate of acoustic waves. The most significant results were obtained for the worked billets in which internal stresses varied over a wide range. The present work is aimed at development of non-destructive methods for the determination of residual stresses in thin-wall Zr tubes manufactured by cold rolling [6]. This would help improve the technologies currently employed for tube production. The investigation was carried on for a wide range of specimens, i.e. tubes and round billets made from Zr based alloys 9 and 10. The lifetime of materials and constructions is in many ways affected by material uniformity and by the stressed state of end products manufactured from the same material.

Therefore, the investigation of residual macro-stresses was performed using the traditional X-ray technique as well the acoustic method developed; the two sets of data obtained by the above two techniques were matched.

It has been found that the magnitude of macro-stresses $\sigma_1 + \sigma_2$ is linearly related to the frequency of auto-circulation $f$ in alloy 9, i.e.

$$\sigma_1 + \sigma_2 = \sigma_0 - b f,$$

where $\sigma_0 = 420$ MPa and $b = 0.42$ MPa·s are the constants. The correlation coefficient is $\sim 0.7$, which allows one to conclude that the above relationship is close to a functional one. Therefore, auto-circulation frequency can be safely converted to stresses using Eq. (4). On the base of the above results, a technique has been developed which is intended for internal stress measurement in Zr alloy tubes.

![Fig. 4. The distribution of internal stresses in the pipe billets tested.](image)

The macro-stresses, i.e. residual stresses resulting from rolling, were measured with the aid of X-ray technique for round zirconium billets $\varnothing 14.8 \times \varnothing 9.5$ mm. The macro-stresses in the specimens of alloy 10 (see the Table) are found to vary from 400 to 900 MPa (Fig. 4), especially so in the area between a small diameter and a larger one. It should be noted that regions removed far enough from the above area reveal sufficiently smooth and uniform distributions of macro-stresses. The level of stresses in alloy 9 is found to be considerably lower relative to alloy 10. The low stress jumps in Fig. 4 suggest that alloy 9 worked by rolling is in a more homogeneous state relative to alloy 10, which might be due the former alloy having greater ductility. The use of appropriate die profile enabled one to reduce considerably the stress jumps in the worked material. To measure the stresses accurately, the test objects shall conform to the following requirements: absence of surface defects, the occurrence of equidistant points marked over the tube envelope and availability of reference sample.
The stress distributions in tubes were determined using a specially designed attachment. This features a stage with two guides, which allow the sample to be aligned in both the beam plane and relative to the goniometer axis. The scanning was performed manually every 20 mm, using the marks over the tube envelope. Figure 5 illustrates the variation in the macro-stresses $\sigma_1$ over the tube made from alloy 9.

It can be seen that homogeneous distributions are observed in the range of 200 MPa. To obtain more detailed distribution patterns, recording was performed for four equidistant points marked over the tube envelope. The measurements were made for the ends and middle lengths of the tubes. As is seen from Fig. 5, more uniform distributions of stresses are observed for the middle lengths of the tubes relative to the tube ends where stresses may be due partly to material non-uniformity and partly to the tube deformation by cutting.

4. Conclusion

Thus, the method designed for estimation of mechanical characteristics facilitates considerably residual stress measurement in real objects. This is based on the relation between the ultrasound rate and the level of residual internal macro-stresses in tubes and round billets. The modern applications of the ultrasound method also include:

- analysis of stress-strained state of heavily loaded large-sized metalwork;
- evaluation of the remaining lifetime of water-tube boiler parts and pipelines;
- estimation of residual stresses in steels and alloys by welding;
- monitoring of cumulative fatigue damages;
- analysis of chemical heat-treatment (carburizing, nitriding, hydrogen saturation);
- monitoring and evaluation of the remaining lifetime of railway transport parts.

References