Use of Acoustic Parameter Measurements for Evaluating the Reliability Criteria of Machine Parts and Metalwork

L.B. ZUEV, B.S. SEMUKHIN, Institute of Strength Physics and Materials Science, SB RAS, Tomsk, Russia
A.G. LUNEV, S.Yu. ZAVODCHIKOV, Chepetsky Mechanical Plant, Glazov, Russia

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. Preliminarily 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 with high accuracy is presented. Using Zr-based alloys as an example, it is shown that the method can be used for the monitoring of zirconium billets from which nuclear reactor fuel cladding is fabricated by cold rolling.

1. Introduction. Experimental justification of the method

It was established previously [1, 2] that the ultrasound propagation rate measured directly for metal specimens tested in tension would depend on material structure, total deformation and flow stress. Similar data were obtained for small total strains in [3]. Of particular interest is the form of ultrasound propagation rate dependence on flow stress obtained for the tested pure aluminum specimen (Figure 1). This consists of three linear parts that can be described [1] by the equation

$$V_S = V_0 + \xi\sigma . \tag{1}$$

Here the empirical constants V_0 and ξ have different values for the different stages of the flow process.

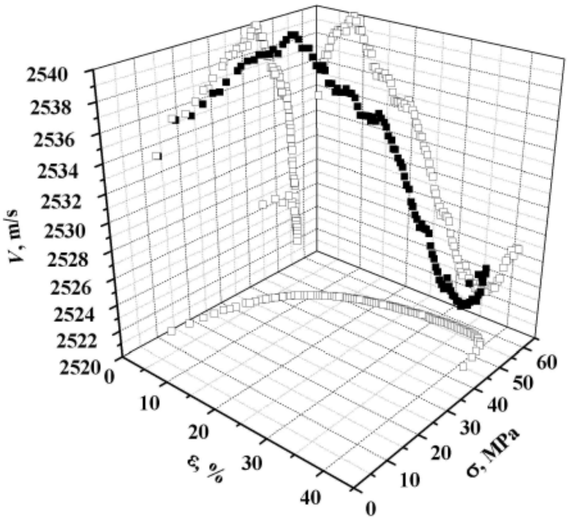

Fig. 1 – The ultrasound propagation rate dependence on flow stress and deformation obtained for the tested aluminum specimen

From Figure 1 follows that ξ can be either positive or negative. However, the proportionality $V_S \sim \sigma$ is always fulfilled within a single stage with the correlation coefficient $|\rho| \geq 0.9$.

The goal of the present study is to verify that Eq. 1 can be used for the evalu-ation of mechanical characteristics of materials by the non-destructive method developed. To elucidate the issue the dependence $V_S(\sigma)$ was obtained for various kinds of alloys (see Table). The propagation rate of Rayleigh waves was measured directly for flat specimens tested in tension by the method of sound impulses self-circulation, which is described in detail below.

The dependencies $V_S(\sigma)$ obtained for all the materials above have a similar shape. Using the dimensionless variables V_S/V_S^* and σ/σ_B (V_S^* is the rate of ultrasound propagation

Table 1. Chemical composition of the alloys investigated

N	Material	Symbol	C	N	Si	Mg	Mn	Li	Cr	Cu	Ni	Zn	Pb	Zr	Ti	Sn	Nb
1	Steel	▽	0.12	–	0.8	–	2.0	–	17.0-19.0	0.3	9.0-11.0	–	–	–	0.5-0.8	–	–
2	Steel	■	<0.1	0.008	0.5-0.8	–	1.3-1.7	–	<0.3	<0.3	<0.3	–	–	–	–	–	–
3	Steel	▲	<0.1	0.008	0.8-1.1	–	0.5-0.8	–	0.6-0.9	0.4-0.6	0.5-0.8	–	–	–	–	–	–
4	Steel	◆	0.14-0.22	–	0.12-0.3	–	0.4-0.65	–	<0.3	<0.3	<0.3	–	–	–	–	–	–
5	Duralumin	⊗	–	–	<0.5	1.5	–	–	–	4.35	<0.1	<0.3	–	–	–	–	–
6	Al-Mg	+	–	–	0.25	5.8-6.2	0.1-0.25	1.8-2.2	–		–	–	–	0.1	–	–	–
7	Al-Li	×	–	–	0.15	–	–	1.8-2.0	–	2.8-3.2	–	–	–	0.12	0.12	–	–
8	Brass	●	–	–	<0.1	–		–	–	–	–	38.0-41.0	0.8-1.9	–	–	–	–
9	Zr-Nb	★	–	–	–	–	–	–	–	–	–	–	–	99.0	–	–	1.0
10	Zr-Nb	⬢	–	–	–	–	–	–	–	–	–	–	–	97.5	–	1.0	1.0

in the material before the deformation and σ_B is the strength limit of the material), one can easily establish the general form of this dependence (Figure 2). 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

$$\frac{V_S}{V_S^*} = \kappa_i + \alpha_i \cdot \frac{\sigma}{\sigma_B}. \tag{2}$$

Here i is stage number 1 or 2; the constants κ_i and α_i are independent of the kind of material and are evaluated experimentally. It is found that the respective values for stages 1 and 2 are as follows: $\kappa_1 = 1 \pm 2.7 \cdot 10^{-4}$ and $\kappa_2 = 1.03 \pm 3 \cdot 10^{-3}$; $\alpha_1 = -6.5 \cdot 10^{-3} \pm 4.7 \cdot 10^{-4}$ and $\alpha_2 = -3.65 \cdot 10^{-2} \pm 3.2 \cdot 10^{-3}$.

From Eq. (2) follows

$$\sigma_B = \frac{\alpha_i \sigma}{V_S / V_S^* - \kappa_i}, \tag{3}$$

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

The strength limit values obtained from Eq. 3 (σ_B^S) are matched against those derived conventionally from the curves $\sigma - \varepsilon$ (σ_B) in Figure 3. The rate, V_S, was measured at

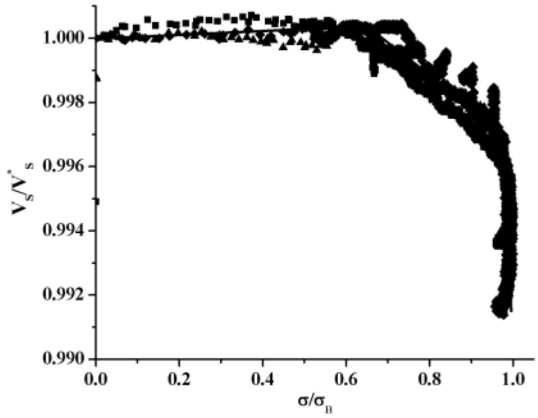

Fig. 2. The generalize dependence $V_S / V_S^* (\sigma/\sigma_B)$ obtained for steels

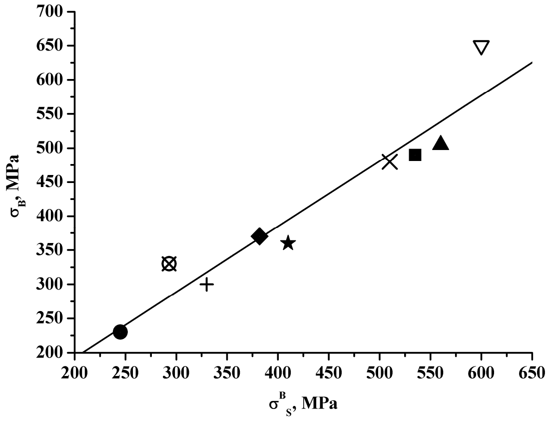

Fig. 3. The correlation between countered σ_B^S and experimental obtained σ_B

the deformation $\varepsilon \approx 1\%$ (flow stress $\sigma \approx 0.1\sigma_B$). The values σ_B and σ_B^S are proportional

$$\sigma_B = 0.96\sigma_B^S. \tag{4}$$

The correlation coefficient is ~ 0.96. The above testifies the efficiency of the proposed method for strength limit evaluation in structural materials, which deform at small total plastic strains precluding 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 magnitude of internal stress fields, which moving dislocations have to overcome [4]. On other hand, with increasing internal stresses, the ultrasound propagation rate decreases [1, 2]. Thus, the above two values are defined by the same factor; therefore, they are closely correlated.

2. Equipment designed for ultrasound method application

The units designed for ultrasound method implementation and made in small lots are Acoustic Strain Tester Rapid (ASTR) and Acoustic Non-Destructive Analyzer (ANDA). These 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 general principle of operation of the units is self-circulation frequency measurement of Rayleigh wave impulses [3]. They are simple in operation and allow the ultrasound rate to be measured to an accuracy of $\sim 3 \cdot 10^{-5}$.

The technique of self-circulation of impulses (see Figure 4) is based on the excitation of the ultrasonic vibrator by a pulser, which is synchronized by impulses passing through the medium analyzed. The impulse repetition frequency assumes a steady-state value determined by the impulse running time in the medium analyzed. Evidently, due to a fixed spacing between the piezo-transducers, the impulse repetition frequency would be directly proportional to the propagation rate of ultrasound in the medium. Impulse repetition frequency is commonly called self-circulation frequency. A device based on the principle of self-circulation makes use of longitudinal, transverse or surface waves. In the present work Rayleigh surface waves having frequency of 2.5 MHz are used.

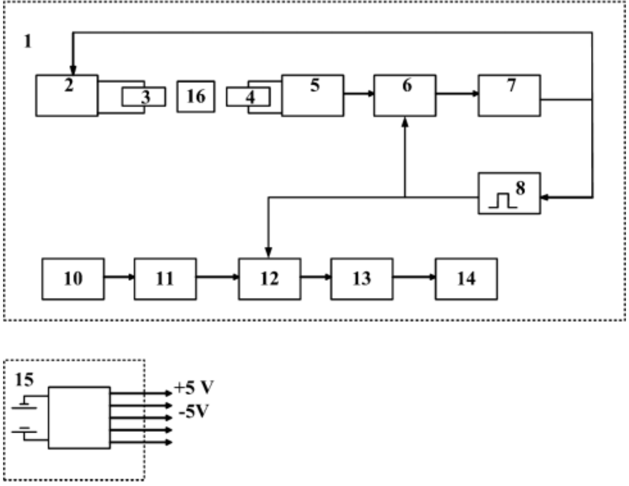

Fig. 4. Structural scheme of the device based on self-circulation technique

Surface wave excitation in the specimen investigated is effected by a piezo-electric transducer, which features a wave-guide having the shape of a truncated prism, a piezo-electric element and a damper. The piezo-electric transducers, both the excitation source and the receiving one, are installed on a common base and thus form a gage head. The piezo-transducer separation is fixed and is taken to be the gage length. To take measurements, the wave guides are pressed to the object tested so as the areas in contact should be minimal. Transformer oil is used as contact medium for ultrasonic transmission. However, the space between the transducers should remain free of the contact medium. The chart diagram of the ASTR is shown in Figure 4. The device features a self-circulation unit **1**, a trigger and display unit **9** and a supply unit **15**. A sounding pulse duration shaper **2** comprises in addition to the shaper proper also a power amplifier and No-And Circuit (NAND). The impulse produced has definite duration. This is amplified in the power amplifier and then fed to the source piezo-transducer **3** to be transmitted to an article tested **16**. A Rayleigh wave, which has passed over the base of an article **16,** arrives at a piezo-transducer **4** to be fed to the input of an amplifier **5**. The resulting amplified signal enters the first input of a comparator **6**, while to the second input of the same comparator variable-voltage reference is applied. From the comparator output the signal arrives at a counter **7**, which is pre-set to be triggered by a chosen active front number. The countdown of active front number over, on the counter output forms a short negative impulse, which arrives via the NAND simultaneously at the pulse shaper **2** and a univibrator **8**. The univibrator, in turn, produces an impulse, which causes the comparator operation to be suspended for a length of time, which is slightly less than the expected time of ultrasound vibration passage over the specimen tested.

The output signal of the counter **7** also arrives at the trigger and pulse-skipping display unit **9**. In the absence of self-circulation, i.e. in case no signal is generated from the output of the counter **7**, units **10**, **11** and **12** will form trigger (sound) impulses having much lower frequency relative to the self-circulation. In case the signal from the output of the counter **12** decays or at least one impulse is skipped, a signal of impulse skipping is generated. The pulse-skipping signal arrives at a display unit **14** where a sound impulse forms and arrives at the NAND of the former **2**. The output signal of the univibrator **8** is an input signal of the frequency meter (units **12** and **13**), which transmits the self-circulation frequency data to the display unit **14**. A supply unit **15** comprises a storage battery, a mains voltage converter and a rectifier with a stabilizer as an assembly.

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 therefore has to take into account the level and distribution of residual internal macro-stresses 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, very much so under process conditions.

The present investigation was carried on using the ASTR unit to determine internal stress level for finished product samples and worked billets. The measurements were made in a wide range of internal stresses for the deforming Zr-Nb alloy **9** specimens in order to relate the internal stresses to the propagation rate of acoustic wave. These were performed using a head having base length L_b = 30 mm for the same points and in accordance with the same scheme as that of an X-ray technique. The measured self-circulation frequency was converted to ultrasound rate. 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, which form in thin-wall Zr tubes manufactured by the process of cold rolling [5]. This would help improve the technologies currently employed for tube production. The investigation was made 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 worked material uniformity and by the stressed state of end products manufactured from the same material. Therefore, the investigation of residual macro-stresses was performed by both traditional (X-ray) and non-conventional (acoustic) methods; the two sets of data obtained by the above two techniques were matched.

The X-ray investigation was conducted using an X-ray diffractometer. The measurements were performed in Cu K_α radiation using a diffracted monochromatic beam. The X-ray examination allows one to distinguish in the worked material lattice certain regions characterized by variations in the interplanar spacing, which can be measured with a sufficient degree of accuracy. In the case of plane stressed state, one of the principal normal stresses is equal to zero and the sum of the remaining two is given [6] by

$$\sigma_1 + \sigma_2 = \frac{E}{\nu}(\theta_1 - \theta_0)\cot\theta_0, \qquad (5)$$

where θ_1 and θ_0 are the Bragg angles determined for the stressed and unstressed (reference) samples on the base of X-ray data; E is the Young modulus and ν is the Poisson ratio. A 30-mm length of tube made from alloy 9 (after re-crystallization annealing) was used as reference sample. The sample investigated was moved along the X-ray beam (scanned) and the local stresses were thus defined for the various points of the generatrix. Then the sample was rotated through $\pi/4$ and scanned over the other generatrix. Thus the local residual stresses were measured and mapped and then matched with the ultrasound rate data.

It has been found that the magnitude of macro-stresses $\sigma_1 + \sigma_2$ is linearly related to the frequency of self-circulation f in alloy **9** (see Figure 5), i.e.

$$\sigma_1 + \sigma_2 = \sigma_0 - \beta f\ , \qquad (6)$$

where $\sigma_0 = 420$ MPa and $\beta = 0.42$ MPa·s are the constants and the correlation coefficient is ~0.7. The high value of the correlation coefficient allows one to conclude that the relationship is a functional one, so that the self-circulation frequency can be safely converted to stresses using Eqn (6). On the base of the above results, a technique has been developed which is intended for internal stress measurement in Zr alloy tubes. In what follows, two sets of data on residual stresses are discussed. These were obtained for round billets and finished items with the aid of the above two techniques.

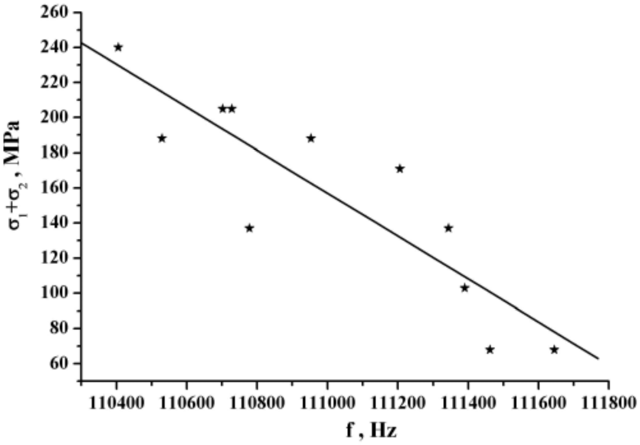

Fig. 5. The correlation between the ultrasound rate and the level of stresses in alloy **9**

The macro-stresses, i.e. residual stresses resulting from rolling, were measured with the aid of X-ray technique for round zirconium billets ∅14.8×∅9.5 mm. The macro-stresses in alloy **10** specimens are found to vary over a wide range from 400 to 900 MPa (Figure 6), especially so near the transition area from the smaller to the larger diameter. It should be noted that regions removed far enough from the transition 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 small height of the stress jumps suggests that alloy **9** worked by rolling is in a more homogeneous state, which might be due its greater ductility relative to alloy **10**. The use of appropriate die profile enabled one to reduce considerably the jump of stresses in the worked material. To measure the stresses accurately the test objects shall conform to the following requirements:

- absence of surface defects,
- equidistant points marked over the tube envelope,
- 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 7 illustrates the variation in macro-stresses σ_1 over the length of tubes 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 Figure 7, 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 the material non-uniformity and partly to the tube deformation by cutting.

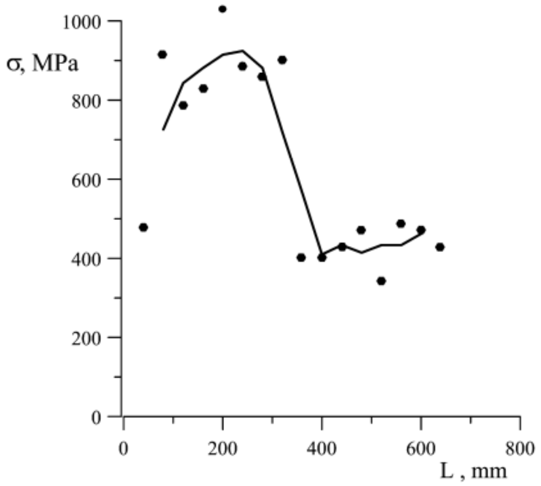

Fig. 6. The distribution of internal stresses in the pipe billets tested

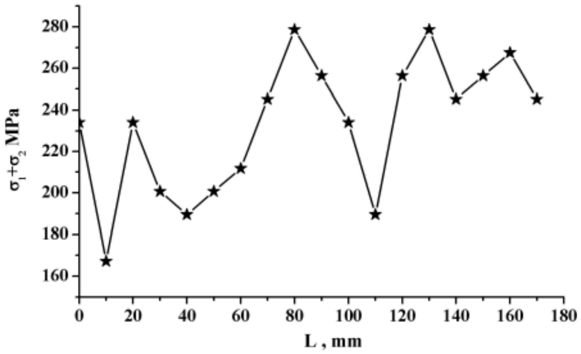

Fig. 7. The macrostresses distributed over the length of pipe from alloy **9**

4. Conclusion

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

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

It should also be noted that over fifty sheds in Russia are equipped with ASTR units for the inspection of metal state of locomotive trolleys during of their reconditioning and overhaul.

References

[1] Zuev L.B., Semukhin B.S., Bushmelyova K.I., Zarikovskaya N.V. On the acoustic properties and plastic flow stages of deforming Al polycrystals. Mater. Lett. 2000. V. 42. No. 1-2. P. 97-101.

[2] Kobayashi M., Tang S., Miura S., Iwabushi K., Oomori S., Fujika H. Ultrasonic nondestructive material evaluation method and study on texture and cross slip effect under simple and pure shear states. Int. J. Plasticity. 2003. V. 19. No. 4. P. 771-804.

[3] Truel R., Elbaum C., Chick B. Ultrasonic Methods in Solids State Physics. Academic Press, New York, 1969.

[4] Honeykombe R.W.K. The Plastic Deformation of Metals. Edward Arnold Publ. Ltd., New York, 1968.

[5] Zuev L.B., Zavodchikov S.Yu., Poletika T.M. *at al.* Phase composition, structure and localization of plastic deformation in Zr1%Nb alloys. Proc. 14-th Int. Symp. on Zr in the Nuclear Industry. ASTM International. STP 1467. 2005. West Conshohocken, USA. P. 264-275.

[6] Taylor A. X-Ray Metallography, J. Wiley and Sons, New York, 1961.