

Ultrasonic Technique and Device for Residual Stress Measurement

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ABSTRACT

One of the advantages of ultrasonic techniques for residual stress measurement is that they are non-destructive. Using such techniques, one can measure the residual stresses in the same points many times, studying, for instance, the changes of residual stresses under the action of service loading or effectiveness of stress-relieving techniques. An Ultrasonic Computerized Complex (UCC) for non-destructive measurement of residual and applied stresses was developed recently. The UCC includes a measurement unit with transducers and basic supporting software and an advanced database and an Expert System, housed in a laptop, for analysis of the influence of residual stresses on the fatigue life of welded elements. In general, the ultrasonic method allows one to measure the residual stresses in both cases: averaged through thickness or in surface layers. The present version of UCC allows measuring the averaged through thickness residual stresses in plates 2 - 150 mm thick. The advanced ultrasonic method, the equipment and some examples of residual stress measurement are discussed in this paper.

1. Introduction

In many cases, the residual stresses are one of the main factors, determining the engineering properties of materials, parts and welded elements. This factor plays a significant role in fatigue processes, especially for welded elements. For example, at a symmetric loading cycle, the effects of residual stresses on fatigue life of a butt weld and a fillet weld can be compared with the stress concentration effects [1,2]. For that reason, the residual stress analysis is a compulsory stage in the process of design and manufacturing of parts and structures and in the estimation of their reliability under the real service conditions.

Although certain progress has been achieved in the development of different experimental techniques, a considerable effort is still required to develop efficient and cost-effective methods of residual stress analysis [3]. The application of an ultrasonic non-destructive method for residual stress measurements had shown that, in many cases, this technique is very efficient and allows measuring the residual stresses both in laboratory conditions and in real structures for a wide range of materials [3-7].

An advanced ultrasonic method and a portable device for measurements of uni- and biaxial applied and residual stress in samples and real structure elements were developed, utilizing modern components and parts. In addition, supporting software for calculations of the effects of the measured residual stresses on fatigue life of welded elements was developed that takes into account the dependence of the residual stresses on the mechanical properties of the materials used, the type of welded joints and the parameters of cyclic loading.

2. Ultrasonic Method of Residual Stress Measurement

Ultrasonic stress measurement techniques are based on the acoustic-elasticity effect, according to which the velocity of elastic wave propagation in solids is dependent on the mechanical stress [3-6]. The relationships between the changes of the velocities of longitudinal ultrasonic waves and shear waves of orthogonal polarization under the action of tensile and compressive external loads in steel and aluminum alloys are presented in Figure 1. As can be seen from Fig. 1, the intensity and character of such changes could be different, depending on material properties.

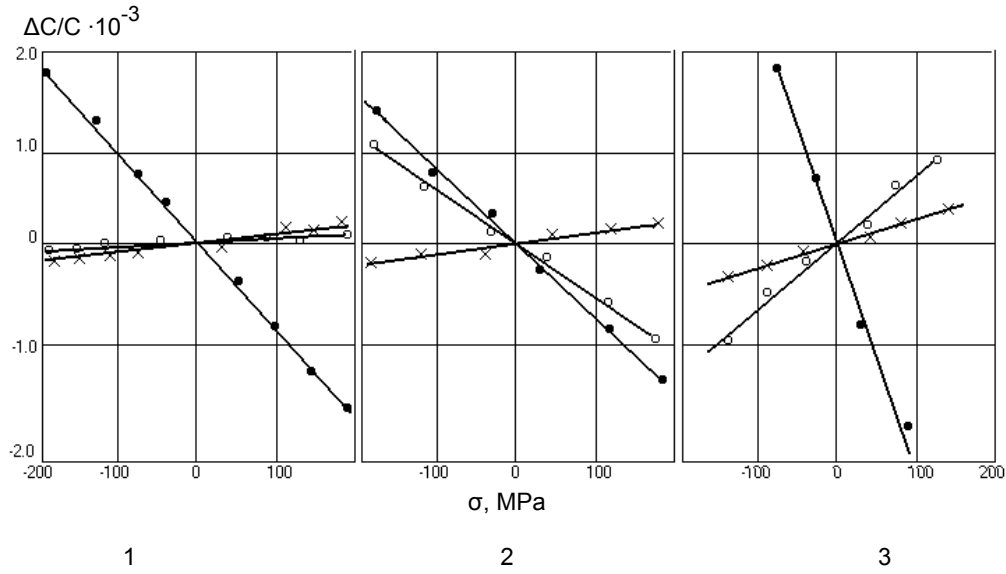


Figure 1. Change of ultrasonic longitudinal wave velocity (C_L) and shear waves velocities of orthogonal polarization (C_{SX3} ; C_{SX2}) depending on the mechanical stress σ in steel A (1), steel B (2) and aluminum alloy (3): ● - C_{SX3} ; ○ - C_{SX2} ; x - C_L

The acoustic relationships are at the basis of the theoretical grounds for the development of ultrasonic methods of stress measurement and in investigations of physical and mechanical properties of materials by means of ultrasound waves:

$$\begin{aligned}
 C_{Lx_1}^2 &= C_{Lx_1,0}^2 + C_{Lx_1}^2 \left[2 \frac{(a+b) \sigma_{\kappa\kappa}^0}{3K_0(\langle\lambda\rangle + 2\langle\mu\rangle)} + \left(\frac{2(\langle\lambda\rangle + \langle\mu\rangle) \sigma_{11}^0}{\langle\mu\rangle 3K_0(\langle\lambda\rangle + 2\langle\mu\rangle)} - \right. \right. \\
 &\quad \left. \left. - \frac{\langle\lambda\rangle(\sigma_{22}^0 + \sigma_{33}^0)}{3K_0(\langle\lambda\rangle + 2\langle\mu\rangle)} \right) (2b+c+4\langle\mu\rangle) + \frac{\sigma_{11}^0}{\langle\lambda\rangle + 2\langle\mu\rangle} \right]; \\
 C_{SX_2}^2 &= C_{SX_2,0}^2 + C_{SX_2}^2 \left\{ b \frac{\sigma_{\kappa\kappa}^0}{3K_0\langle\mu\rangle} + \left[\frac{\langle\lambda\rangle + 2\langle\mu\rangle}{3K_0\langle\mu\rangle} (\sigma_{11}^0 + \sigma_{22}^0) - \right. \right. \\
 &\quad \left. \left. - \frac{2\langle\lambda\rangle}{3K_0\langle\mu\rangle} \sigma_{33}^0 \right] \left(1 + \frac{c}{4\langle\mu\rangle} \right) + \sigma_{11}^0 \right\}; \\
 C_{SX_3}^2 &= C_{SX_3,0}^2 + C_{SX_3}^2 \left\{ b \frac{\sigma_{\kappa\kappa}^0}{3K_0\langle\mu\rangle} + \left[\frac{\langle\lambda\rangle + 2\langle\mu\rangle}{3K_0\langle\mu\rangle} (\sigma_{11}^0 + \sigma_{33}^0) - \right. \right. \\
 &\quad \left. \left. - \frac{2\langle\mu\rangle}{3K_0\langle\mu\rangle} \sigma_{22}^0 \right] \left(1 + \frac{c}{4\langle\mu\rangle} \right) + \sigma_{11}^0 \right\},
 \end{aligned}$$

where: C_{Lx_1} – is the longitudinal wave propagation velocity, C_{SX_2} and C_{SX_3} – are the polarized shear wave propagation velocities, σ_{11}^0 , σ_{22}^0 and σ_{33}^0 – are the residual stresses in the corresponding directions, and ρ , λ , μ , a , b , c and K_0 – are material constants.

In the proposed technique, the velocities of longitudinal ultrasonic wave and shear waves of orthogonal polarization are measured at a considered point to determine the uni- and biaxial stresses. The bulk waves are used to determine the stresses averaged over the thickness of the investigated elements. Surface waves are used to determine the uni- and biaxial stresses at the surface of the material. The mechanical properties of the material are represented by the proportionality coefficients, which can be calculated or determined experimentally under an external loading of a sample of considered material.

In general, the change in the ultrasonic wave velocity in structural materials under mechanical stress amounts only to tenths of a percentage point. Therefore the equipment for practical application of ultrasonic technique for residual stress measurement

should be of high resolution, reliable and fully computerized. For these purposes, the Ultrasonic Computerized Complex for residual stress analysis was recently developed.

3. Ultrasonic Equipment and Software for Residual Stress Measurement

The Ultrasonic Computerized Complex (UCC) for residual stress analysis was developed recently based on an improved ultrasonic methodology. The UCC includes a measurement unit with supporting software and a laptop with an advanced database and an Expert System (ES) for analysis of the influence of residual stresses on the service life of welded components. The developed device with gages for ultrasonic residual stress measurement is presented in Figure 2. The UCC allows determining uni- and biaxial applied and residual stresses for a wide range of materials and structures. In addition, the developed ES can be used for calculation of the effect of measured residual stresses on the fatigue life of welded elements, depending on the mechanical properties of the materials, type of welded element, parameters of cyclic loading and other factors.



Figure 2. The developed device with sensors for ultrasonic measurement of residual stresses

The developed equipment allows one to determine the magnitudes and signs of uni- and biaxial residual and applied stresses for a wide range of materials as well as stress, strain and force in various size fasteners. The sensors, using quartz plates measuring from 3×3 mm to 10×10 mm as ultrasonic transducers, are attached to the object of investigation by special clamping straps and/or electromagnets.

The main technical characteristics of the measurement unit:

- stress can be measured in materials with thickness 2 - 150 mm;
- error of stress determination (from external load): 5 - 10 MPa;
- error of residual stress determination: 0.1 σ_y (yield strength) MPa;
- stress, strain and force measurement in fasteners (pins) 25-1000 mm long;
- independent power supply (accumulator battery 12 V);
- overall dimensions of measurement device: 300x200x150 mm;
- weight of unit with sensors: 6 kg.

The supporting software allows controlling the measurement process, storing the measured and other data and calculating and plotting the distribution of residual stresses. The software also allows an easy connection with standard PC's.

An example of presentation of the residual stress measurement data, using the developed software, is shown in Figure 3. The software allows comparing different data on residual stress measurement and transferring selected data for further fatigue analysis. In Figure 3, the left side of the screen displays information on the measured ultrasonic wave velocities as well as other pertinent technical information on the sample. The right side of the screen displays the distribution of calculated residual stresses.

In the example presented in Figure 3, a plate made from low carbon steel, with a yield strength of 296 MPa, was heated locally, with the focal point of heating located approximately 50 mm from the left side of the plate. The distribution of both components of residual stresses in the specimen, as a result of this local heating are shown in the right side of Figure 3. As can be seen, in the heating zone, both residual stress components are tensile and reach the yield strength of the considered material. In the compression zone, located between the edge of the plate and the centre of the heating zone, the longitudinal component of residual stresses reaches – 140 MPa.

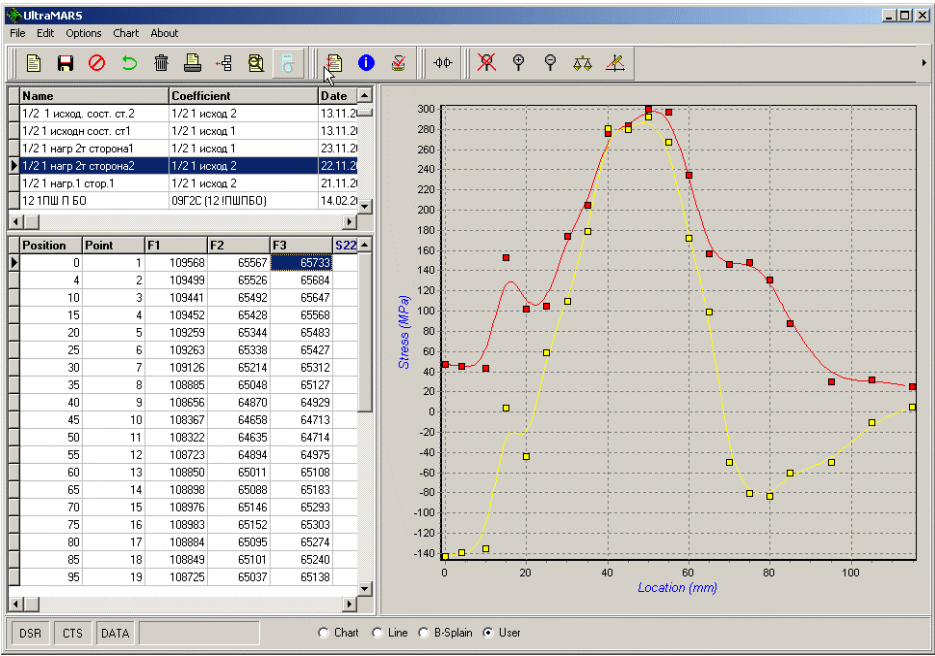


Figure 3. Example of the graphic presentation of the residual stress measurement data in a low carbon steel plate after local heating.

Using the Expert System (ES) it is possible to assess, through calculations, the redistribution of the residual stresses, under the effect of various improvement treatments and cyclic loading, and their influence on the service life of welded elements without having to perform time- and labor-consuming fatigue tests. The program package enables to calculate the fatigue life of welded components after application of improvement treatments directed at the redistribution of residual stresses, such as heat-treatment, vibration treatment, overloading, ultrasonic peening, etc.

As an example of using the ES for residual stress analysis, the results of computation of the residual stress effect on the fatigue life of a transverse loaded butt weld (made in shop in flat position, toe angle $\leq 30^\circ$, NDT), depending on the stress ratio R , are presented in Figure 4. The presence of tensile residual stresses causes a decrease in the fatigue strength of the welded joints: the lower are the R and the stress range – the higher is the influence of the welding residual stresses. For instance, the decrease of the limit stress range at $N=2 \times 10^6$ cycles in the case of $R=0$ is 42% and for $R=-1$ is 70%. The effect of the welding residual stresses is relatively low at $R \geq 0,5$.

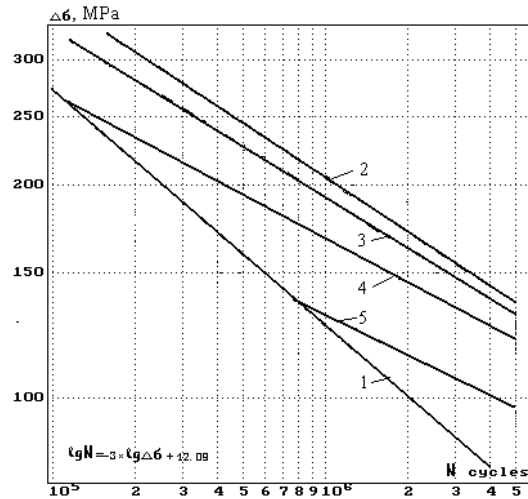


Figure 4. Fatigue curves of transverse loaded butt weld: 1 - with high tensile residual stresses for all levels of R; 2, 3, 4 and 5 - without residual stresses at R=-1, -0.5, 0 and 0.5

4. Examples of Residual Stress Measurements Using the Ultrasonic Method

One of the main advantages of the developed technique and equipment is the possibility to measure the residual and applied stresses in samples and real structure elements. Such measurements were performed for a wide range of materials. A few examples of the practical application of the developed technique and equipment for residual stress measurement in welded elements are presented below.

4.1. Specimen for Fatigue Testing

The residual stresses were measured in a 500x160x3 mm specimen made of an aluminum alloy ($\sigma_y = 256$ MPa, $\sigma_u = 471$ MPa) with a fatigue crack. The residual stresses were induced by local heating at the distance of 30 mm from the centre of the specimen. As can be seen from Figure 5, in the heating zone, both components of the residual stress are tensile. In the compression zones, the longitudinal component of residual stresses reaches – 130 MPa.

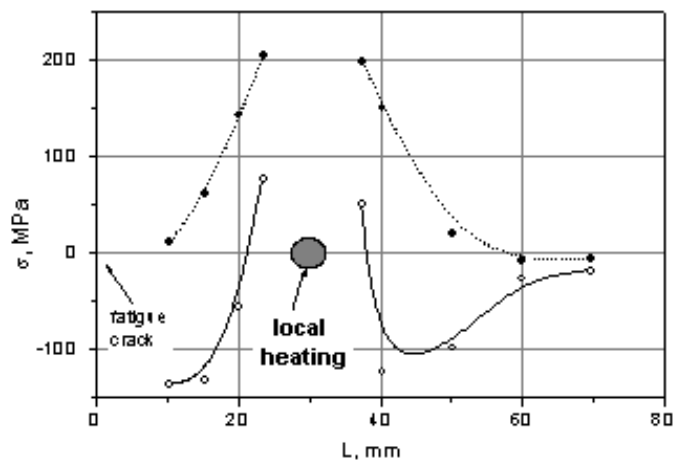


Figure 5. Distribution of residual stresses induced by local heating in a specimen made of an aluminum alloy ($\sigma_y = 256$ MPa, $\sigma_u = 471$ MPa) with a fatigue crack. (L – distance from the center of specimen)

4.2. Compound Pipes and Pipes with Surfacing

Another example of measuring the residual stresses is associated with compound pipes. Compound pipes are used in various applications and they are made by fitting under pressure one pipe with an outer diameter into a pipe with approximately the same inner diameter. For residual stress measurement, rings were cut-off from a number of such compound pipes. The width of the rings was 16 mm. Residual stresses were measured across the prepared cross-sections in three different locations at 120 degrees to each other as shown in Figure 6, with a subsequent averaging of the measurement results. Depending on the differences between the inner diameter D_1 of the outer pipe and the outer diameter D_2 of the inner pipe, the measurements were made in 3 to 5 points along the radius. The distribution of residual stresses as measured across the wall thickness of the compound pipe is presented in Figure 7.

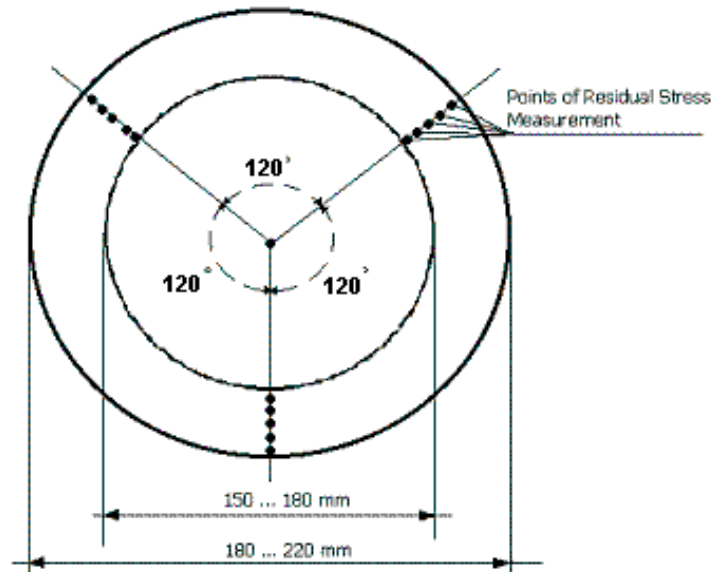


Figure 6. Schematic view of the ring cut-off from the pipe. The points on the ring cross-sections where the residual stress measurements were made are shown.

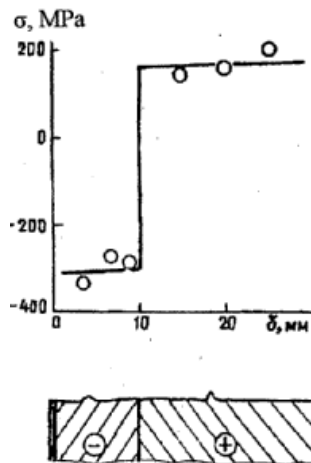


Figure 7. Residual stress distribution in a compound ring with the following dimensions:
inner ring: $D_1 = 160$ mm and $D_2 = 180$ mm;
outer ring: $D_1 = 180$ mm and $D_2 = 220$ mm.
(D_1 - inner diameter, D_2 - outer diameter, width of the ring – 16 mm)

The results of the residual stress measurement in rings cut-off from the pipes with inner surfacing are presented on Figure 8.

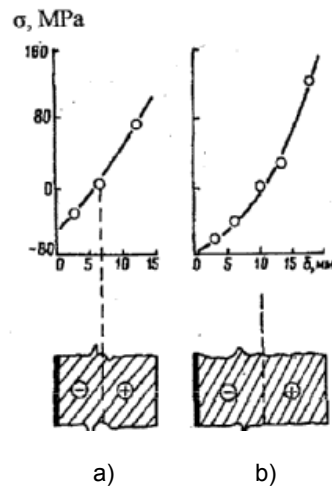


Figure 8. Residual stress distribution in rings with inner surfacing:
a) ring with $D_1 = 150$ mm and $D_2 = 180$ mm;
b) ring with $D_1 = 180$ mm and $D_2 = 220$ mm.
(D_1 - inner diameter, D_2 - outer diameter, width of the rings - 16 mm)

5. Conclusions

1. The developed advanced ultrasonic method, based on it portable instrument and the supporting software can be used for non-destructive residual stress analysis in laboratory samples and real structure elements in many applications for a wide range of materials. The developed technique may be used in construction industry, shipbuilding, railway and highway bridges, nuclear reactors, aerospace industry, oil and gas engineering and in other areas during manufacturing, in service inspection and repair of real structures.
2. The developed expert system allows analyzing, with sufficient for practical purposes accuracy, the effects of welding residual stresses and their redistribution under the effect of cyclic loading and various improvement treatments on the fatigue life of welded elements, depending on the level of residual stresses, mechanical properties of material used, type of joint and parameters of cyclic loading.

6. References

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