Residual welding stresses evaluation in the typical platform element of amphibious all-terrain vehicle by ultrasonic method

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Abstract. As part of solutions development for the technical diagnosis of the amphibious all-terrain vehicle platform, evaluation of residual stresses in a typical welded joint of the frame was carried out by the acoustic birefringence technique. The significant residual stresses were observed after welding, the largest in the heat affected zone. The intricate distribution of the residual stresses due to the complex boundary conditions was obtained. The state of the material was estimated using the hypothesis of maximum shear stress. The difference of the principal stresses was compared with the yield stress.

1. Introduction
Advanced efficient amphibious all-terrain vehicles developing for operation in the Arctic and Antarctic should have high reliability. The platform of such vehicles has a large number of welded joints. As part of the diagnosis of amphibious vehicles platform, determination of residual welding stresses has great importance considering their significantly affect strength, fatigue life and corrosion resistance of metal components [1].

Various ultrasonic techniques based on a theory of acoustoelasticity developed by Hughes and Kelly [2] are often used for nondestructive evaluation of residual welding stresses because of acceptable accuracy, convenience, easiness and low cost of measurements.

As a result of finite element analysis, it was found that some of the most loaded platform elements of developing amphibious vehicle are welded joints of frame. A feature of frame made of rectangular pipes, angle bars and channel bars is that many elements have small thickness. Generally, ultrasonic measurements in thin materials and their application to stress assessment become a challenge.

The aim of this work is experimental evaluation of residual stresses in the typical welded joint of amphibious all-terrain vehicle frame using ultrasonic method.

2. Theoretical background
The existing engineering techniques of stress determination using ultrasound are based on the acoustoelastic effect, which manifests as the change in the propagation velocity of ultrasonic wave due
to elastic deformation. The acoustoelastic effect in structural materials is well studied theoretically and experimentally. In practice, it is preferable to use relative values rather than velocities.

Acoustic birefringence measurement is the most often using among numerous ultrasonic techniques for quantitative evaluation of the residual stresses averaged over the thickness. One of its advantages is that measurements can be carried out with one-sided access to the testing object when the thickness of the material is unknown. Another is that the measure results do not depend on temperature.

Acoustic birefringence can be determined by the times-of-flight of two orthogonally polarized shear waves [3]

$$ B = 2 \frac{(t_2 - t_1)}{(t_2 + t_1)}, $$

Here $t_1$ and $t_2$ are the times-of-flight of shear elastic waves propagating through the thickness and polarized in the principal stresses directions coincided with the material symmetry directions. If the principal stresses directions are coincided with the material symmetry directions, relationship between the acoustic birefringence and the principal stresses is described by following equation [4]

$$ B = B_0 + m_1 (\sigma_1 + \sigma_2) + m_2 (\sigma_1 - \sigma_2), $$

Here $B_0$ is initial acoustic birefringence due to texture; $\sigma_1$ and $\sigma_2$ are the principal stresses, $m_1$ and $m_2$ are acoustoelastic coefficients.

For a slightly textured material $m_1 \ll m_2$, for an isotropic material $m_1 = 0$, so the difference between the principal stresses can be determined almost without loss of accuracy as

$$ \sigma_1 - \sigma_2 = k (B - B_0), $$

where $k$ is the stress-acoustic constant determined experimentally from a uniaxial tensile test.

Thus the use of the relative value $B$ avoids the error associated with measuring of material thickness and allows achieving the required accuracy of biaxial stresses evaluation.

Although the acoustic birefringence technique allows only evaluating the difference of the principal stresses, the obtained information will be valuable for determining the material state. The difference of the principal stresses is used in one of the main hypotheses of material failure – the hypothesis of maximum shear stress.

According to the hypothesis of maximum shear stress formulated in terms of the principal normal stresses, failure will occur if the difference of the principal stresses exceeds failure stress under uniaxial tension $\sigma_f$ [5]

$$ |\sigma_1 - \sigma_2| \geq \sigma_f, $$

Comparison the difference of the principal stresses with its critical value, for example, yield stress, provides important information about the state of the material.

3. Experimental procedure

In Figure 1, you can see the typical welded joint of the frame at the prototype of amphibious all-terrain vehicles developing for operation in the Arctic and Antarctic. For laboratory investigation, we manufactured from a channel bar and a rectangular pipe the inclined tee-welded joint shown in Figure 2, which simulated the typical welded joint of the frame. The material was carbon steel 1020 ASTM. The wall thickness of the channel bar was 3.8 mm, the transverse profile was 60×60 mm. The wall thickness of the rectangular pipe was 2 mm, the transverse profile was 40×40 mm. The tee joint was made by electric arc welding. The width of the weld bead was about 5 mm. The angle between the pipe guide and the vertical axis was 10 degrees. On the surface of the channel bar, we marked the zones in which we carried out ultrasonic measurements before and after the welding.
Figure 1. Typical welded joint of frame.

Figure 2. Inclined tee-welded joint made from channel bar and rectangular pipe.

We used the pulsed echo-method for measuring times-of-flight of two shear elastic waves by a specially designed measuring and computing experimental device shown in Figure 3. We employed a V156 Panametrics-NDT wide band piezoelectric transducer for generation and reception of shear elastic waves propagating perpendicular to the surface. The central frequency of the piezoelectric transducer was 5 MHz, the diameter was 6 mm. We used an epoxy resin without a hardening agent as the contact liquid. We carried out testing at room temperature. To generate electrical pulses, we employed an A1212 MASTER ACS ultrasonic flaw detector. To obtain the time scan of signals from the piezoelectric transducer, we used a LA-n10USB digital oscilloscope and ADCLab software. The sampling rate of the digital oscilloscope was 100 MHz, and the time resolution was 10 ns. We processed the saved data using MathCAD. Each file contained about 100 amplitude-time diagrams. To improve the measurement accuracy, we interpolated the data with splines. After processing, the time resolution was 0.1 ns.
Figure 3. Experimental device.

We measured the time-of-flight between echo pulses reflected from the reverse surface. The absolute experimental error of time measurement was no more 2 ns. After that we determined acoustic birefringence by formula (1). The absolute experimental error of acoustic birefringence measurement was no more 2×10⁻⁴. Then we evaluated residual stresses by equation (3). Previously, we obtained the acoustoelastic coefficient \( m_2 = -9.1 \pm 0.8 \) TPa⁻¹ for carbon steel 1020 ASTM [6]. So we used the stress-acoustic constant \( k = -110 \pm 10 \) GPa, inverse value of the acoustoelastic coefficient, to calculate the difference of the principal stresses by equation (3).

4. Results and discussion

First, we obtained the distributions of acoustic birefringence in the channel bar near the welded joint before and after welding, then the distribution of the difference of the principal residual stresses. Figure 4 shows the distributions of acoustic birefringence and of difference of the principal stresses in the channel bar along the middle line perpendicular to the weld.

Figure 4. Distributions of acoustic birefringence and of difference of principal stresses.
Figure 5 shows the field of residual stresses. The principal stress $\sigma_1$ direction is perpendicular to the weld. The principal stress $\sigma_2$ direction is parallel to the weld.

Ultrasonic testing detected that after welding, the significant residual stresses appeared in the channel bar. The largest difference of the residual stresses, about 300 MPa, is observed in the heat affected zone. Due to the complex boundary conditions, the obtained distribution of residual stresses is very different from the classical distribution of residual stresses in the welded plate described in the literature [7, 8]. Nevertheless, the residual stresses rapidly decrease with distance from the weld.

For analysis of the material state, it is valuable to compare the largest difference of the principal stresses with the failure stress taking advantage of the hypothesis of maximum shear stress. The failure stress depends on the conditions under which the material loses its ability to perform its functions. For example, if plastic deformation of a design element is unacceptable, the failure stress is equal to the yield stress. The yield stress for fine grained steel 1020 ASTM is about 300 MPa. So the difference of the residual stresses observed in the heat affected zone is approximately equal the yield stress $\sigma_1 - \sigma_2 \approx \sigma$. Since the stresses $\sigma_1$ and $\sigma_2$ singly can’t exceed the yield point, that in the heat affected zone, the stress $\sigma_1$ may be from 0 to 300 MPa and the stress $\sigma_2$ may be from $-300$ to 0 MPa.

Figure 6 shows a graphical representation of the hypothesis of the maximum shear stress. The state of the material in the heat affected zone is described by the bold solid line.

It should be noted that usually after welding, the microstructure in the heat affected zone changes in comparison with the microstructure of the parent metal. It leads to a change in the elastic properties, in particular, the parameters of the acoustoelastic effect. This in turn increases the inaccuracy of the residual stress evaluation by the ultrasonic method [9].
5. Conclusion
The results of ultrasonic testing of the typical welded joint of amphibious all-terrain vehicle frame showed that the significant residual stresses appeared after welding, which must be taken into account for analysis the design strength. It was established that the largest residual stresses arose in the heat affected zone. The state of the material in the heat affected zone was analyzed in terms of hypothesis by of the maximum shear stress.

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