Ultrasonic Measurement of Residual Stresses in Welded Elements and Structures

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Abstract. The objective of the study described in this paper is to identify the residual stress distribution and relaxation in standard welded specimens as well as in a large-scale welded panel imitating the critical, from the fatigue point of view, zones of ship structure. The residual stresses were measured after welding and in the process of fatigue loading of welded elements by the UltraMARS system that is based on using ultrasound. The measurements had shown that the maximum residual stresses near the welds (4-5mm away from the weld) reach levels 290-320 MPa that are close to the yield strength of considered material both in welded specimens and in the large scale panel. Analysis of residual stress relaxation in the welded panel under the action of cyclic loading confirmed the fact that within the interval of applied stress ranges corresponding to the multi-cycle region of loading of the welded joints, the relaxation of residual stresses occurs mainly during the first cycle. The results of residual stress measurements in welded elements were compared with the results of computation based on advanced finite element model.

Introduction

Residual stresses (RS) can significantly affect engineering properties of materials and structural components, notably fatigue life, distortion, dimensional stability, corrosion resistance, brittle fracture [1]. Systematic studies had shown that, for instance, welding RS might lead to a drastic reduction in fatigue strength of welded elements [2]. In multi-cycle fatigue ($N>10^6$ cycles of loading), the effect of RS can be compared with the effect of stress concentration. Figure 1 illustrates one of the results of these studies. The butt joints in low-carbon steel were tested at symmetric cycle of loading (stress ratio R=-1). There were three types of welded specimens. The relatively small specimens (420x80x10 mm) were cut from a large welded plate. Measurements of RS revealed that in this case the specimens after cutting had a minimum level of RS. Additional longitudinal weld beads on both sides in specimens of second type created in the central part of these specimens tensile RS close to the yield strength of material. These beads did not change the stress concentration of the considered butt weld in the direction of loading. In the specimens of third type longitudinal beads were deposited and then the specimens were bisected and welded again. Due to the small length of this butt weld the RS in these specimens were very small and approximately the same as those within the specimens of first type [2].

Tests showed that the fatigue strength of specimens of first and third types (without RS) is practically the same with the limit stress range 240 MPa at $N=2\cdot10^6$ cycles of loading. The limit stress range of specimens with high tensile RS (second type) was only 150 MPa. In all specimens the fatigue cracks originated near the transverse butt joint. The reduction of the fatigue strength in this case can be explained only by the effect of welding RS. These experimental studies showed also that at the level of maximum cyclic stresses close to the yield strength of base material the fatigue life of specimens with and without high tensile RS was practically identical. With the decrease of the stress range there is corresponding increase of the influence of the welding RS on the fatigue life of welded joint.

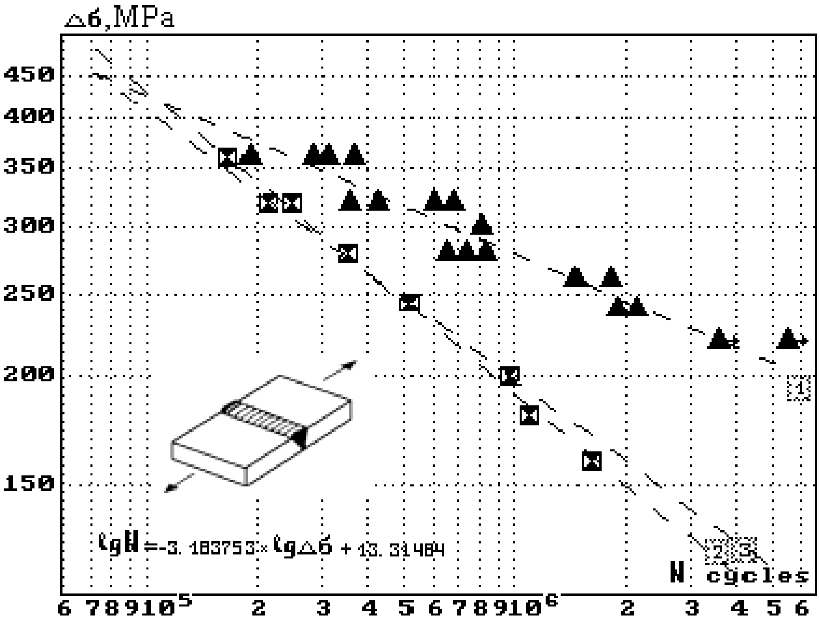


Fig.1. Fatigue curves of butt welded joint in low-carbon steel: 1 - without residual stresses; 2, 3 - with high tensile residual stresses (fatigue testing and computation).

The effect of RS on the fatigue life of welded elements is more significant in the case of relieving of harmful tensile RS and introducing of beneficial compressive RS in the weld toe zones. The beneficial compressive RS with the level close to the yield strength of material are introduced at the weld toe zones by, for instance, ultrasonic impact treatment/ultrasonic peening (UIT/UP) [1, 3].

The RS, therefore, are one of the main factors determining the engineering properties of materials, parts and welded elements and this factor should be taken into account during the design and manufacturing of different products. 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 [1, 4]. 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 in field for a wide range of materials [4-10].

The objective of the study described in this paper is to identify the residual stress distribution and relaxation in a number of different welded specimens as well as in a large-scale welded panel imitating the critical, from the fatigue point of view, zones of ship structure. The residual stresses were measured after welding and in the process of fatigue loading of welded elements using the UltraMARS system [9]. The RS were measured in a total of 303 points with 21 residual stress profiles studied.

Specimens and Welded Panel for Residual Stress Measurements. The measurements of welding residual stress were performed for 8 and 15 mm thick specimens with longitudinal attachments welded from both sides. The main plate dimensions are 700x115 mm and 600x70 mm for 15 mm and 8mm thick specimens, respectively. The process of residual stress measurement in 15 mm thick specimen by using the UltraMARS system is shown in Fig. 2. The residual stresses were also measured in as-welded condition and during fatigue testing after 1, 2, 10 and 2010 cycles in the large scale welded panel. The welded panel main dimensions were 2000x900x535 mm.

From the fatigue point of view, the critical zones in specimens and welded panels are zones at the ends of longitudinal welded stiffener. Residual stress measurements were carried out for these locations.

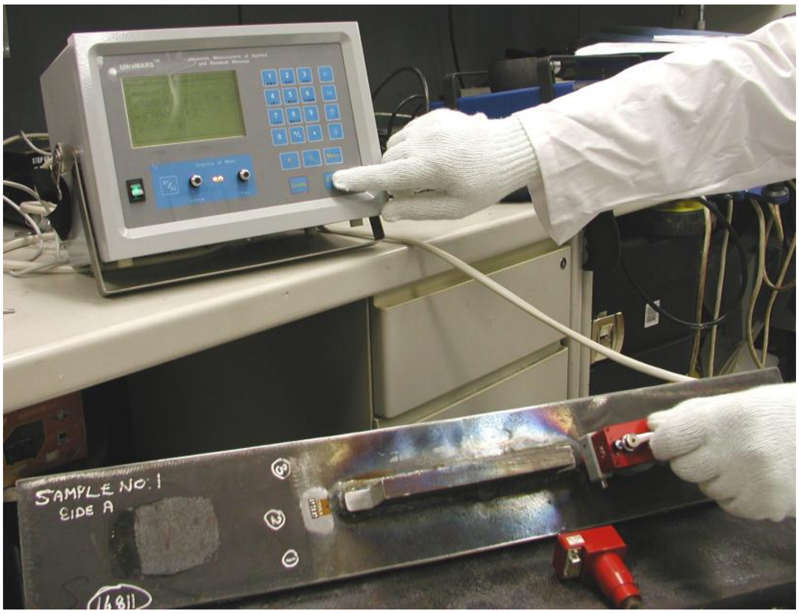


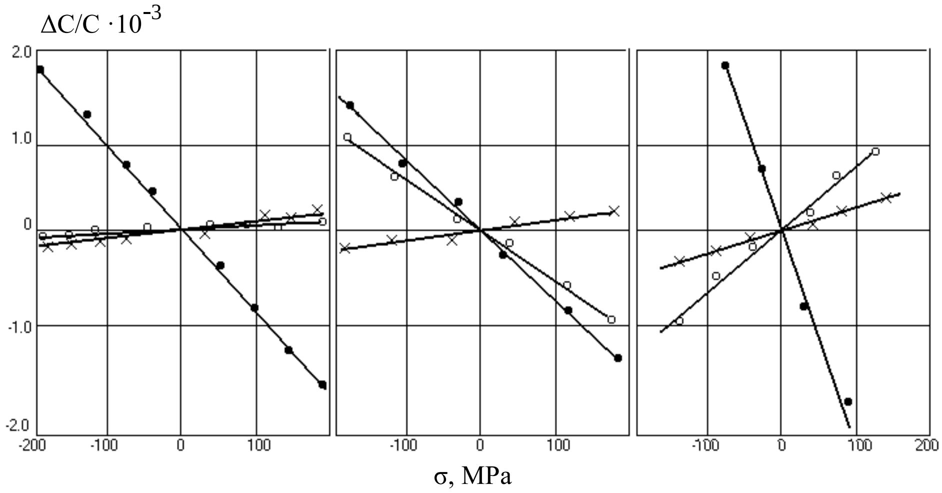
Fig.2. Process of measurement of residual stresses in a welded specimen using the UltraMARS system.

The portable, semi-automatic device for Ultrasonic Measurements of Applied and Residual Stresses UltraMARS was used in the present work [9]. The device is designed for non-destructive measurement of averaged through-thickness and surface residual and applied stresses in samples, parts, welded elements and structures.

Ultrasonic Measurement of Residual Stresses

Ultrasonic Method of Residual Stress Measurement. One of the promising directions in development of non-destructive techniques for residual stress measurement is application of ultrasound. 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. 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 Fig. 3. As can be seen from Fig. 3, the intensity and character of such changes could be different, depending on material properties.

Different configurations of ultrasonic equipment can be used for residual stress measurements. In each case, waves are launched by a transmitting transducer, propagate through a region of the material and are detected by a receiving transducer as shown in Fig. 4. The technique when the same transducer is used for excitation and receiving of ultrasonic waves is often called pulse-echo method (Fig. 4a). This method is effective for analysis of residual stresses in the interior of material. In this case the through-thickness average of residual stresses is measured. In the configuration shown in Fig. 4c, the residual stress in a surface/subsurface layer is determined.



1 2 3

Fig.3. 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

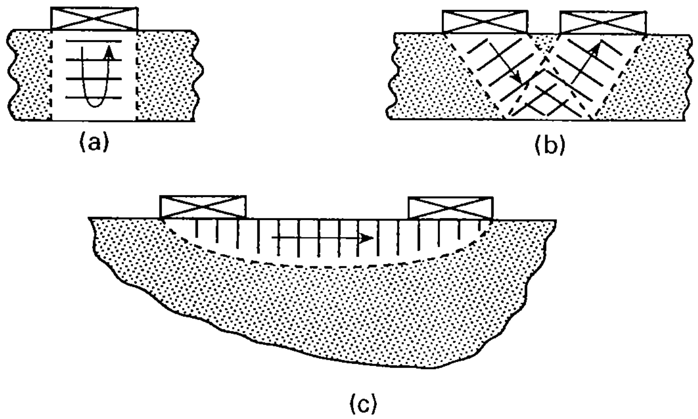


Fig.4. Schematic view of ultrasonic measurement configurations:
(a) through-thickness pulse-echo, (b) through-thickness pitch-catch and (c) surface pitch-catch.

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 biaxial residual stresses. 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.

Results of Residual Stress Measurement. Stress in direction of longitudinal attachment is denoted as σ_{33}, stress normal to the direction of longitudinal attachment is denoted as σ_{22}. Distributions of residual stress in as-welded condition along the welded stiffener in 8 mm thick specimen are presented in Fig. 5.

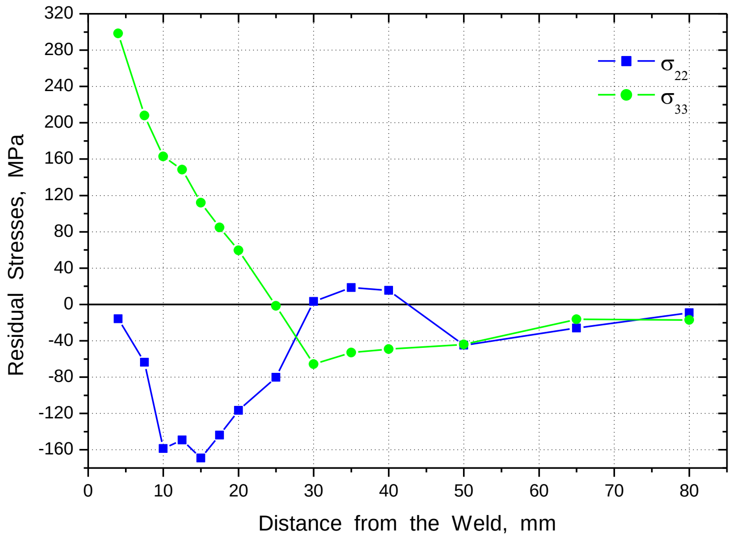


Fig.5. The distribution of residual stresses along the welded stiffener in the 8 mm thick welded sample

Fig. 6 shows the distribution of residual stress in as-welded condition along the welded stiffener in welded panel. It can be seen from Fig. 3 and 4 that the maximum residual stress near the welds (4-5 mm away from the weld) acting in the direction of longitudinal attachment and applied load reach levels 290-320 MPa that are close to the yield strength of considered material both in specimens and in the panel.

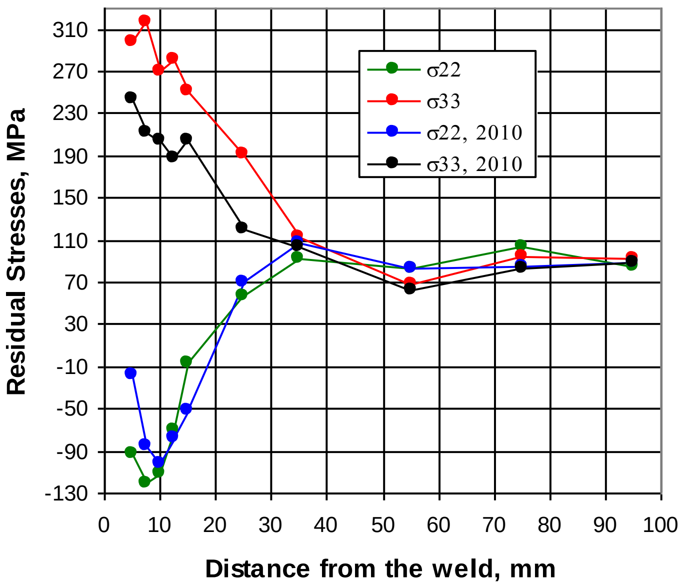


Fig.6. The distribution of residual stress along the welded stiffener in welded panel before and after 2010 cycles of loading

Relaxation of Residual Stress in a Welded Panel. After installation of the welded panel in the testing machine, ultrasonic gauge was placed as close as possible to the critical weld at a distance of 4.5 mm from the weld toe. The residual stresses at this point were measured before testing and after 1, 2 and 10 cycles of constant amplitude loading (between 51[kN] and -21[kN]). After 10th cycle, 2000 cycles of variable amplitude spectrum was applied to the panel and residual stresses were measured again. Fig. 6 demonstrates the distribution of residual stress along the welded stiffener in welded panel after 2010 cycles of loadings.

Fig.7. Measurement of residual stresses using UltraMARS system in large-scale welded panel in as-welded condition and during the fatigue loading of the panel

The results of residual stress measurements at a distance of 4.5 mm from the weld toe after 1, 2 and 10 and 2010 cycles of fatigue loading are presented in Fig. 8.

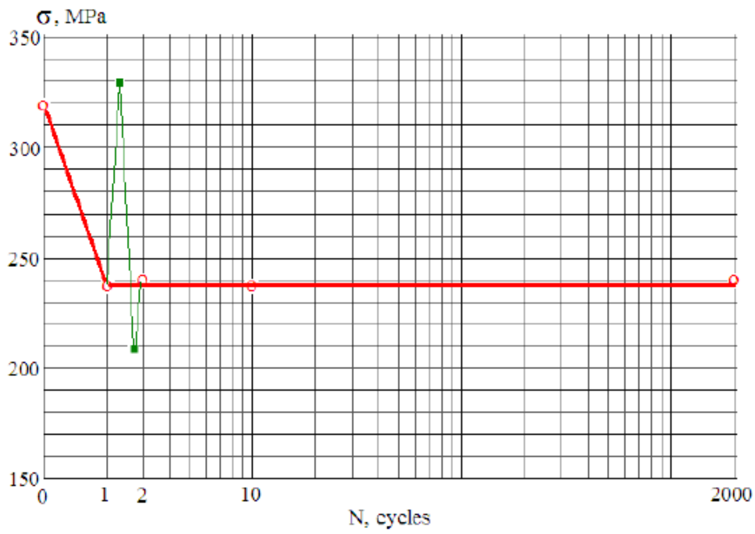
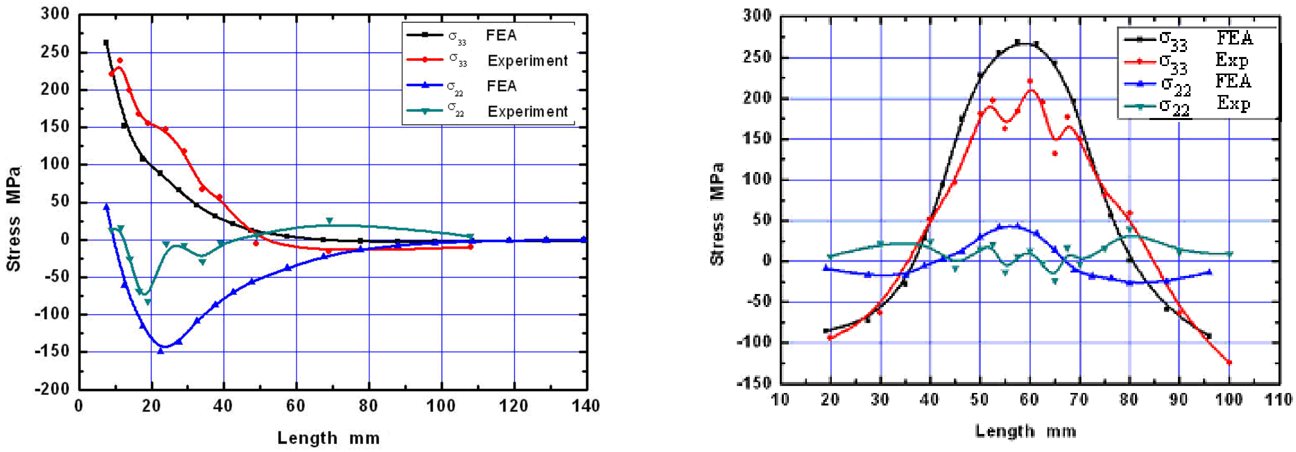


Fig.8. The relationship between the level of residual stresses and number of cycles of loading (red line) and max/min stresses during second cycle of loading (green line).

Comparison of Experimental and Numerical Results. The results of residual stress measurement were compared with results of numerical simulation [10]. The distributions of the initial welding residual stresses in the 15 mm plate specimen are presented in Fig. 9. As can be seen from Fig. 9, the numerical and experimental profiles of the residual stresses are close to each other both in longitudinal and transversal directions of stress, and both the numerical and experimental results of residual stresses show relatively small differences in the maximum values.



a) b)

Fig.9. The distribution of residual stresses in 15 mm thick welded sample obtained experimentally and through FEA: a) along the welded stiffener, b) in direction perpendicular to the welded stiffener.

A comparison of residual stresses determined by measurements using the ultrasonic method and by numerical simulations showed a reasonable agreement both for standard welded specimens and the large welded panel.

Summary

1. The objective of the project described in this report was the measurement of residual stresses, using an ultrasonic method, in standard welded samples and a large-scale welded panel, all designed for fatigue testing. The residual stress distributions were studied in the zones that are critical from the fatigue point of view in two types of welded samples and the panel. The relaxation of residual stresses in the welded panel under the effect of cyclic loading was also analyzed. The residual stresses were measured in a total of 303 points with 21 residual stress profiles studied.

2. The measurements had shown that the maximum residual stresses in 8 mm thick welded sample near the welds (4-5 mm away from the weld) reach levels 290-320 MPa that are close to the yield strength of considered material both in specimens and in the panel.

3. Analysis of residual stress relaxation in the welded panel under the action of cyclic loading confirmed the fact that within the interval of applied stress ranges corresponding to the multi-cycle region of loading of the welded joints, the relaxation of residual stresses occurs mainly during the first cycle. For the welded panel the relaxation of residual stress was around 25% of initial residual stress for applied hot spot stress range of 200 MPa and mean stress of 42 MPa.

4. The comparison of residual stresses determined by ultrasonic method and numerical simulation showed reasonable agreement both for standard welded specimens and for the large welded panel.

5. The developed advanced ultrasonic method, based on it portable instrument and the supporting software can be used for non-destructive measurement of applied and residual stresses in laboratory samples and real parts and structural elements in many applications for a wide range of materials. The developed ultrasonic technique was successfully applied 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 welded elements and structures.

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