



INTERNATIONAL INSTITUTE OF WELDING
A world of joining experience

Canadian Delegation

IIW Document XIII-2339-10

Measurement of Residual Stresses in Welded Elements and Structures by Ultrasonic Method

Y. Kudryavtsev and J. Kleiman

Structural Integrity Technologies Inc., Markham, Ontario, Canada

E-mail: info@sintec.ca

ABSTRACT

Residual stresses (RS) can significantly affect engineering properties of materials and structural components, notably fatigue life, distortion, dimensional stability, corrosion resistance. RS play an exceptionally significant role in fatigue of welded elements. The influence of RS on the multi-cycle fatigue life of butt and fillet welds can be compared with the effects of stress concentration. Even more significant are the effects of RS on the fatigue life of welded elements in the case of relieving harmful tensile RS and introducing beneficial compressive RS in the weld toe zones.

Different methods exist to measure the RS. One of the advantages of ultrasonic techniques for RS measurement is that they are non-destructive. Using such techniques, one can measure the RS in the same points many times, studying, for instance, the changes of RS 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 RS on the fatigue life of welded elements. In general, the ultrasonic method allows one to measure the RS in both cases: averaged through thickness or in surface layers. The advanced ultrasonic method, the equipment and some examples of RS measurement in welded elements and structures are discussed in this paper.

Keywords: *residual stresses, welding, measurement of residual stresses, ultrasonic method*

1. 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]. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures. For that reason, the RS analysis is a compulsory stage in the design of parts and structural elements and in the estimation of their reliability under real service conditions.

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 at 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].

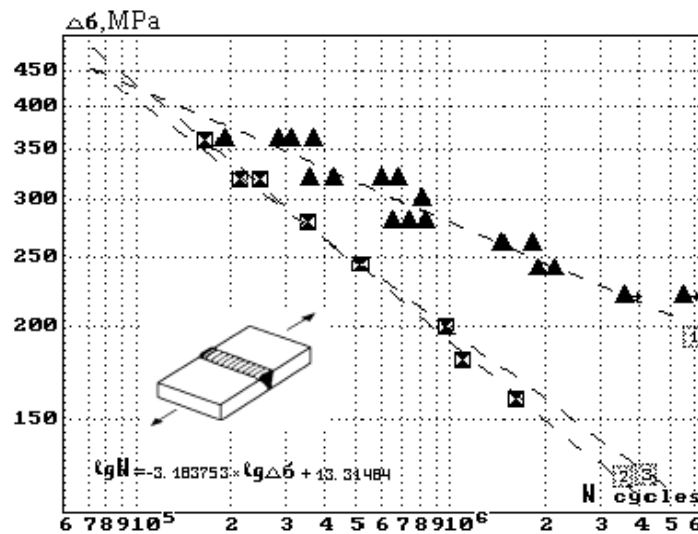


Figure 1. Fatigue curves of butt welded joint in low-carbon steel: 1 - without residual stresses; 2, 3 - with high tensile residual stresses (fatigue testing and computation)

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 $N = 2 \cdot 10^6$ 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.

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, the ultrasonic peening (UIT/UP) [1, 3]. The results of fatigue testing of welded specimens in as-welded condition and after application of UIT/UP are presented in Figure 2. The fatigue curve of welded element in as-welded condition (with high tensile RS) was used also as initial fatigue data for computation of the effect of the UP. In case of non-load caring fillet welded joint in high strength steel ($\sigma_y = 864$ MPa, $\sigma_u = 897$ MPa), the redistribution of RS resulted in approximately two times increase in limit stress range and over 10 times increase in the fatigue life of the welded elements.

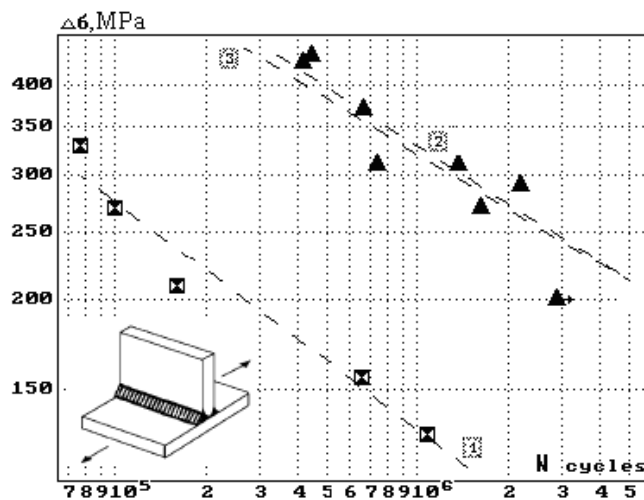


Figure 2. Fatigue curves of non-load caring fillet welded joint in high strength steel: 1 - in as-welded condition; 2, 3 - after application of ultrasonic peening (fatigue testing and computation)

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. The efficient approach to the problem of RS includes, at least, stages of determination, analysis and beneficial redistribution of residual stresses. The combined consideration of the above-mentioned stages of the RS analysis and modification gives rise to so called Residual Stress Management (RSM) concept approach [4, 5]. The RSM concept includes the following main stages:

- Stage 1. Residual Stress Determination:
 - Measurement: Destructive, Non-destructive
 - Computation
- Stage 2. Analysis of the Residual Stress Effects:
 - Experimental Studies
 - Computation
- Stage 3. Residual Stress Modification (if required):
 - Changes in Technology of Manufacturing and Assembly
 - Application of Stress-Relieving Techniques

Over the last few decades, various quantitative and qualitative methods of RS analysis have been developed [4]. In general, a distinction is usually made between destructive and non-destructive techniques for RS measurement. The first series of methods is based on destruction of the state of equilibrium of the RS after sectioning of the specimen, machining, layer removal or hole drilling. The most common destructive methods are:

- the hole drilling method,
- the ring core technique,
- the bending deflection method,
- the sectioning method, etc.

The application of the destructive or so-called partially-destructive techniques is limited mostly to laboratory samples.

The second series of methods of RS measurement is based on the relationship between the physical and the crystallographic parameters and the RS and does not require the destruction of the part or structural elements and could be used for field measurements. The most developed non-destructive methods are:

- the X-ray and neutron diffraction methods,
- the ultrasonic techniques,
- the magnetic methods etc.

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 [4, 6]. 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 [4-11].

2. ULTRASONIC MEASUREMENT OF RESIDUAL STRESSES

2.1. 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 Figure 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 Figure 4 [6]. The technique when the same transducer is used for excitation and receiving of ultrasonic waves is often called pulse-echo method (Figure 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 Figure 4c, the residual stress in a surface/subsurface layer is determined.

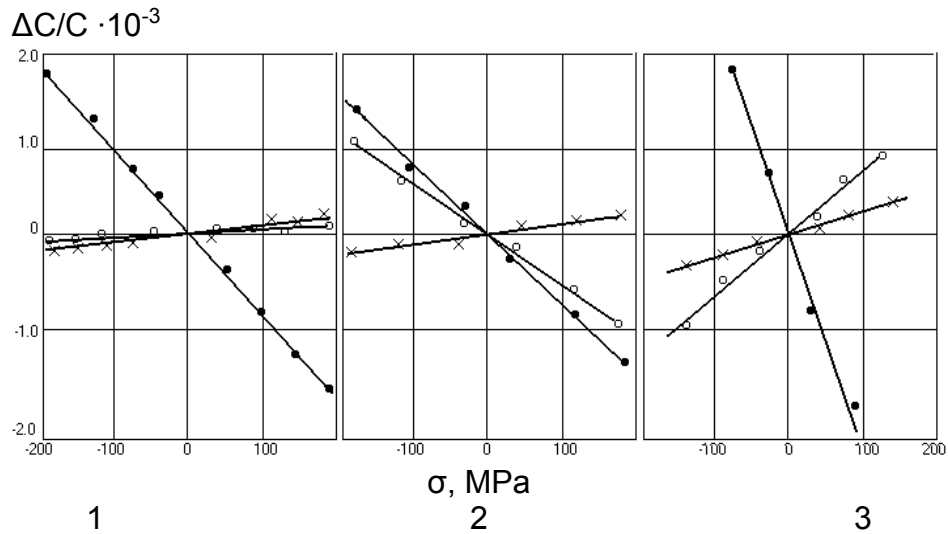


Figure 3. Change of ultrasonic longitudinal wave velocity (C_L) and shear waves velocities of orthogonal polarization (C_{SX3} ; C_{SX2}) depending on the mechanical stress σ in steel A (1), steel B (2) and aluminum alloy (3) [10]: ● - C_{SX3} ; ○ - C_{SX2} ; x - C_L

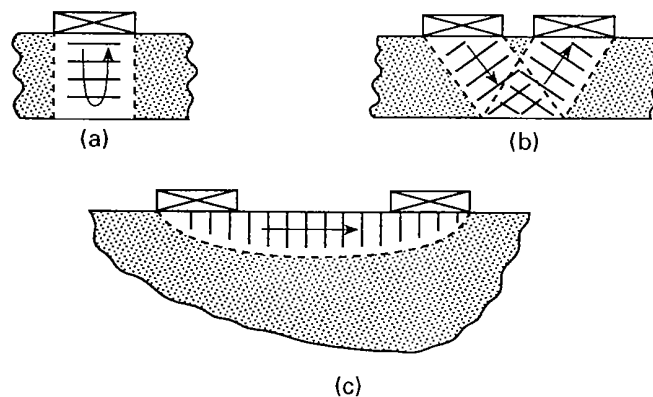


Figure 4. Schematic view of ultrasonic measurement configurations: (a) through-thickness pulse-echo, (b) through-thickness pitch-catch and (c) surface pitch-catch

The depth of this layer is related to the ultrasonic wavelength, often exceeding a few millimeters, and hence is much greater than that obtained by X-ray method. Other advantages of the ultrasonic technique are the facts that the instrumentation is convenient to use, quickly to set up, portable, inexpensive and free of radiation hazards.

In the proposed in [7, 9, 10] 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 residual stresses. The bulk waves in this approach 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.

2.2. 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 [7-10]. 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 fatigue life of welded components. The developed device with gages/transducers for ultrasonic residual stress measurement is presented in Figure 5. 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 5. The Ultrasonic Computerized Complex for measurement of residual and applied 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 (see Figure 5) 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 6. The software allows comparing different data on residual stress measurement and transferring selected data for further fatigue analysis. In Figure 6, the left side of the screen displays information on the measured ultrasonic wave velocities as well as other technical information on the sample. The right side of the screen displays the distribution of calculated residual stresses.

In the example of residual stress measurement presented in Figure 6, a plate made from low carbon steel, with 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 6. 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 minus 140 MPa.

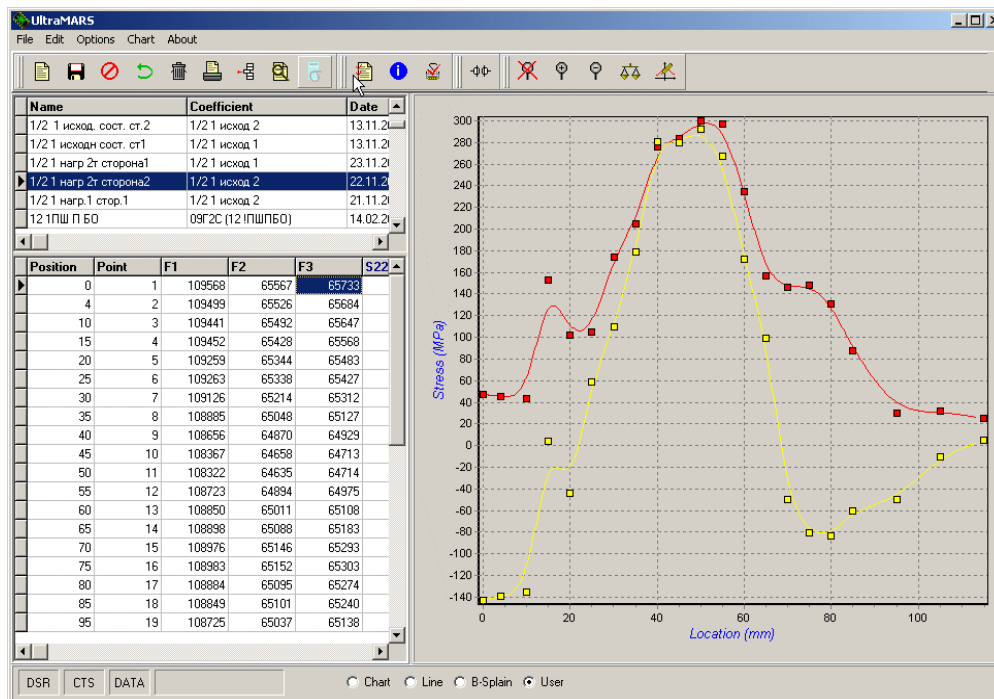


Figure 6. Distribution of residual stresses in a low carbon steel plate after local heating [10].

2.3. 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, parts and structures. A few examples of the practical application of the developed technique and equipment for residual stress measurement based on using of the ultrasonic technique are presented below.

2.3.1. 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 a distance of 30 mm from the centre of the specimen. As can be seen from Figure 7, in the heating zone, both components of the residual stress are tensile. In the compression zones, the longitudinal component of residual stresses reaches minus 130 MPa.

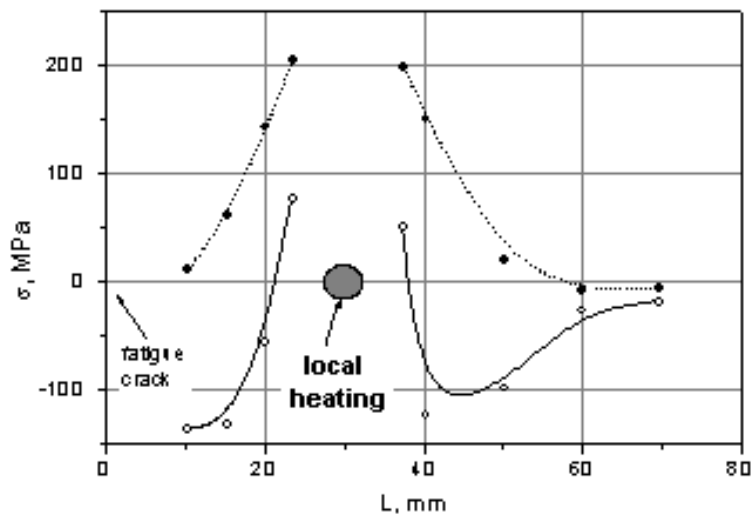


Figure 7. Distribution of residual stresses induced by local heating in a specimen made of an aluminum alloy with a fatigue crack: L – distance from the center of specimen [10]

2.3.2. Compound Pipes and Pipes with Surfacing

Another example of measuring the residual stresses by ultrasonic method 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 compound pipes of different diameters. 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 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 8.

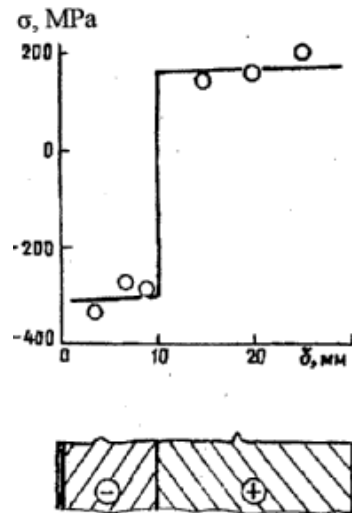


Figure 8. Residual stress distribution in a compound ring with the following dimensions [10]:
 inner ring: $D_1 = 160\text{mm}$ and $D_2 = 180\text{mm}$; outer ring: $D_1 = 180\text{mm}$ and $D_2 = 220\text{mm}$
 (D_1 - inner diameter, D_2 - outer diameter, width of the ring – 16 mm)

The results of the residual stress measurement by using ultrasonic method in rings cut-off from the pipes with inner surfacing are presented in Figure 9.

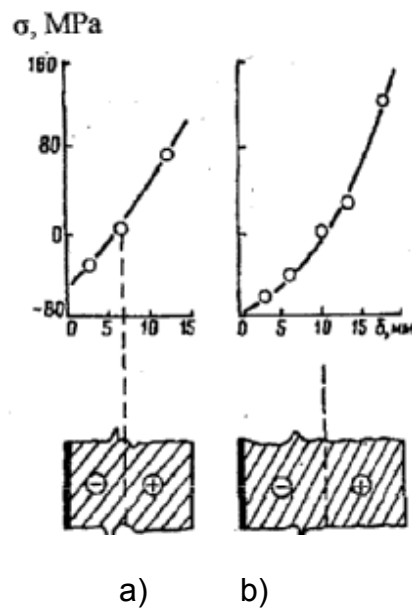


Figure 9. Residual stress distribution in rings with inner surfacing [10]:
 a) ring with $D_1 = 150\text{mm}$ and $D_2 = 180\text{mm}$;
 b) ring with $D_1 = 180\text{mm}$ and $D_2 = 220\text{mm}$.
 (D_1 - inner diameter, D_2 - outer diameter, width of the rings - 16 mm)

2.3.3. Measurement of Residual Stresses in Welded Samples

The residual stresses were measured in a specimen measuring $1000 \times 500 \times 36\text{ mm}$, representing a butt-welded element of a wind tunnel. The distribution of biaxial residual stresses was investigated in X (along the weld) and Y directions after welding and in the process of cyclic

loading of the specimen [7]. Figure 10 represents the distribution of longitudinal (along the weld) and transverse components of residual stresses along the weld toe. Both components of the residual stress reached their maximum levels in the central part of the specimen: longitudinal - 195 MPa, transverse - 110 MPa.

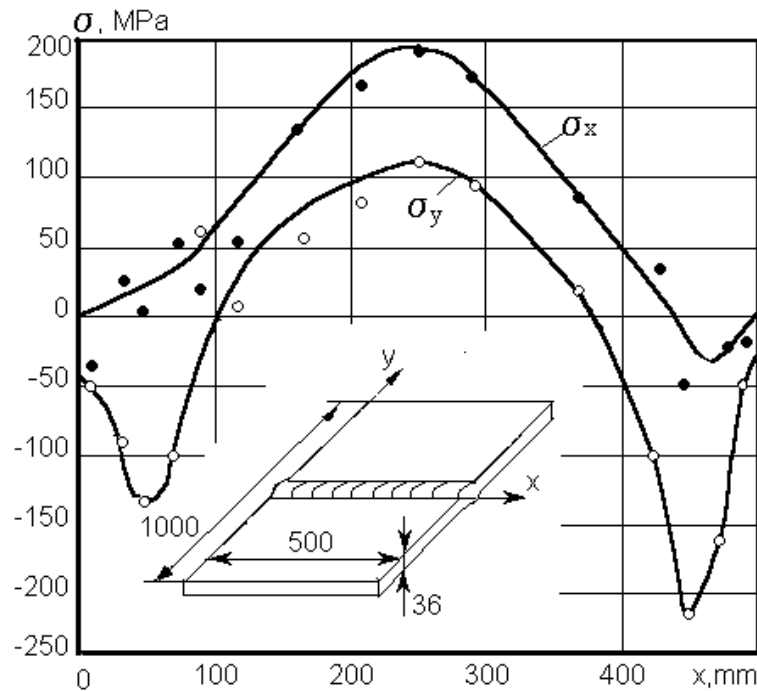


Figure 10. Distribution of longitudinal (along the weld) and transverse components of residual stresses along the butt weld toe [7]

The ultrasonic method was applied also for residual stress measurement in a specimen measuring 900x140x70 mm and made of low-alloyed steel, representing the butt weld of a structure [8]. The distribution of residual stress components in X₃ (along the weld) and X₂ (perpendicular to the weld) directions as well as through the thickness of the specimen near the weld (X₁direction) are presented on Figure 11.

2.3.4. Measurement of Residual Stresses in Welded Structures

The developed ultrasonic equipment could be used for RS measurement for both laboratory/factory and field conditions.

The residual stresses were measured by the ultrasonic method in large-scale welded panels in as-welded condition and during the fatigue loading of the panels [11]. The objectives of the study were to identify the residual stress distribution and relaxation in specimens with welded longitudinal attachment and welded panel that represent large scale models of ship structural detail, and compare the results of experimental and numerical analyses. During the fatigue testing the residual stresses were measured after 1, 2, 10 and 2010 cycles of loading. Figure 12 shows the process of residual stress measurement after certain number of cycles of loading. Figure 13 illustrates the distributions of the residual stress in large-scale welded panel near the weld that is critical from the fatigue point of view in as-welded condition and after 2010 cycles of loading.

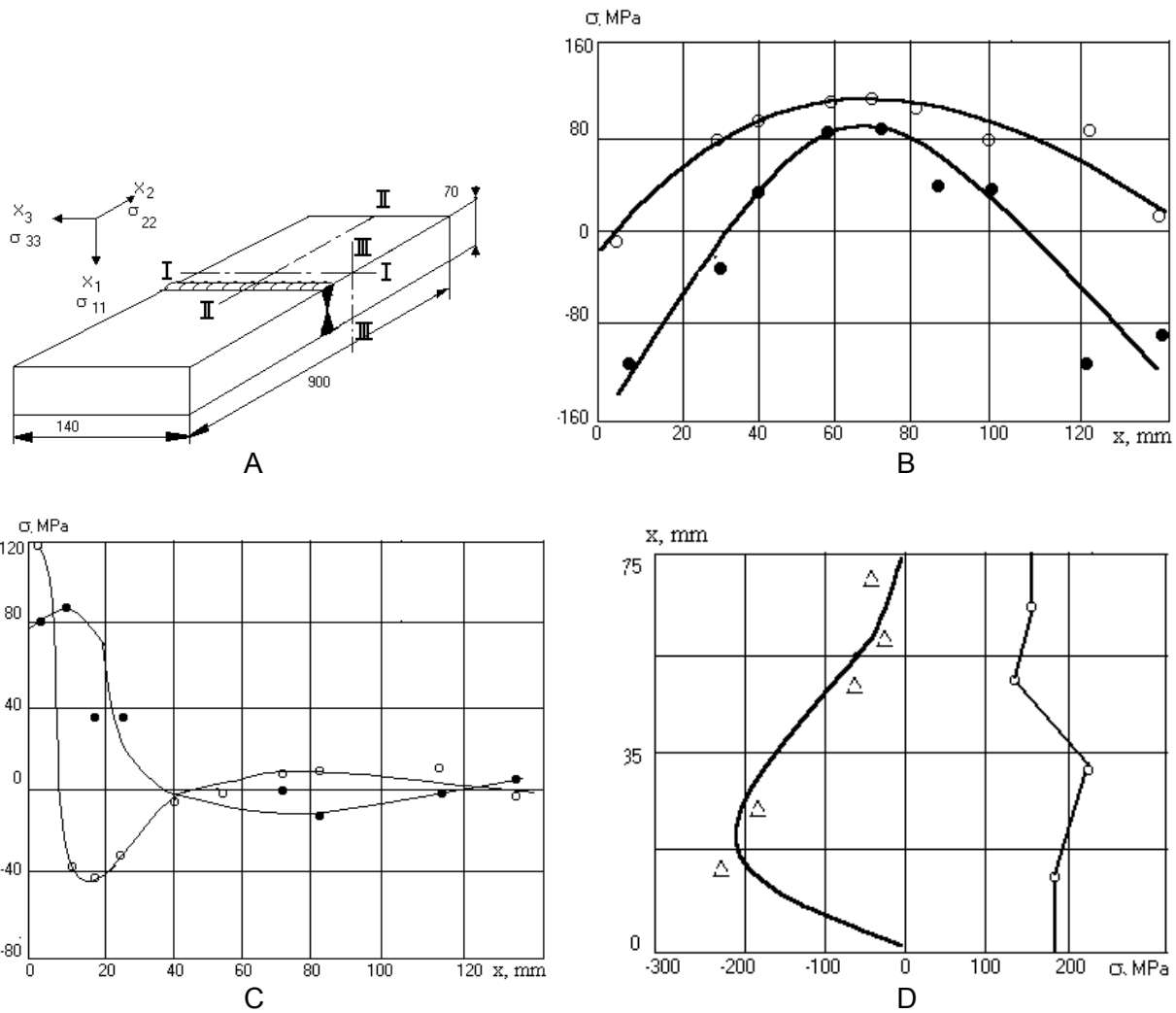


Figure 11. Welded specimen (A) and distribution of the residual stresses along the butt weld I-I (B), perpendicular to the weld II-II (C) and through the thickness near the weld III-III (D) [8]:
 ● - σ_{22} ; ○ - σ_{33} ; △ - σ_{11} .



Figure 12. Measurement of residual stresses using UltraMARS system in large-scale welded panel in as-welded condition and during the fatigue loading of the panel

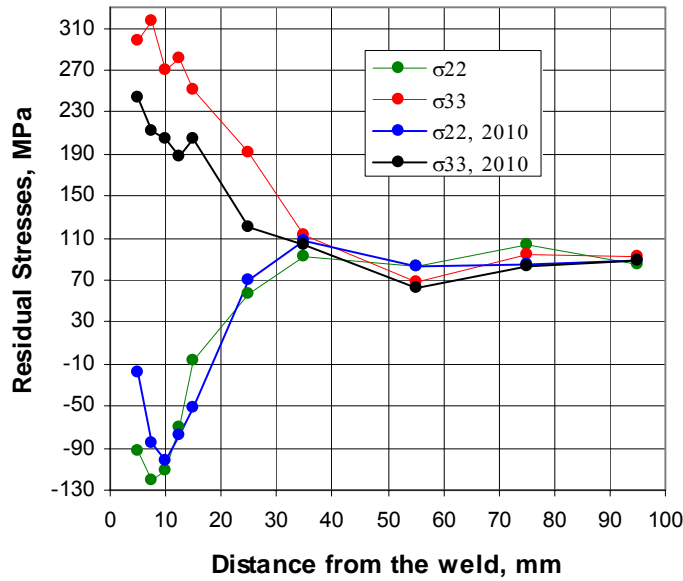


Figure 13. The distributions of residual stress in large-scale welded panel near the weld that is critical from the fatigue point of view in as-welded condition and after 2010 cycles of loading [11]

The process and some of the results of ultrasonic measurement of residual stresses in welded elements of a bridge are shown in Figures 14 and 15. The residual stresses were measured by ultrasonic method in the main wall of the bridge span near the end of one of welded vertical attachments. In the vicinity of the weld the measured levels of harmful tensile residual stresses reached 240 MPa. Such high tensile residual stresses are the result of thermo-plastic deformations during the welding process and are one of the main factors leading to the origination and propagation of the fatigue cracks in welded elements.



Figure 14. Process of measurement of residual stresses in a welded bridge

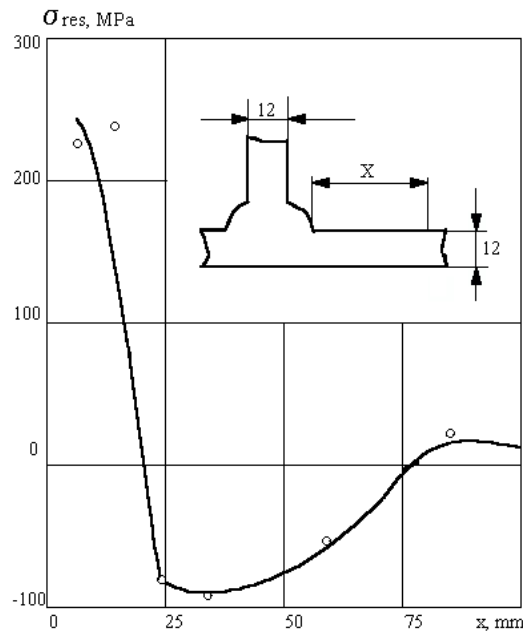


Figure 15. Distribution of longitudinal (oriented along the weld) residual stresses near the fillet weld in bridge span: x – distance from the weld toe

Based on the ultrasonic method the stresses were measured in the bridge both in conditions of no traffic on the bridge as well as in condition when a few heavy loaded trucks were put in certain locations to determine the total stress.

6 SUMMARY

1. Residual stresses play an important role in operating performance of materials, parts and structural elements. Their effect on the engineering properties of materials such as fatigue and fracture, corrosion resistance and dimensional stability can be considerable. The residual stresses, therefore, should be taken into account during design, fatigue assessment and manufacturing of parts and welded elements.

2. Certain progress has been achieved during the past few years in improvement of traditional techniques and development of new methods for residual stress measurement. 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.

REFERENCES

- [1]. Handbook on Residual Stress. *Volume 1. Edited by Jian Lu. Society for Experimental Mechanics. 2005. 417 p.*
- [2]. V. Trufyakov, P. Mikheev and Y. Kudryavtsev. Fatigue Strength of Welded Structures. Residual Stresses and Improvement Treatments. *Harwood Academic Publishers GmbH. London. 1995. 100 p.*
- [3]. Y. Kudryavtsev and J. Kleiman. Fatigue Improvement of Welded Elements and Structures by Ultrasonic Impact Treatment (UIT/UP). *International Institute of Welding. IIW Document XIII-2276-09. 2009.*
- [4]. Y. Kudryavtsev. Residual Stress. *Springer Handbook on Experimental Solid Mechanics. Springer – SEM. 2008. P. 371-387.*
- [5]. Y. Kudryavtsev and J. Kleiman. Residual Stress Management: Measurement, Fatigue Analysis and Beneficial Redistribution. *X International Congress and Exposition on Experimental and Applied Mechanics. Costa Mesa, California USA, June 7-10, 2004. pp. 1-8.*
- [6]. Handbook of Measurement of Residual Stresses. *Society for Experimental Mechanics. Edited by J. Lu. 1996. 238 p.*
- [7]. Y. Kudryavtsev. Application of the ultrasonic method for residual stress measurement. *Development of fracture toughness requirement for weld joints in steel structures for arctic service. VTT-MET. B-89. Espoo. Finland. 1985. p.62-76.*
- [8]. Y. Kudryavtsev, J. Kleiman and O. Gushcha. Residual Stress Measurement in Welded Elements by Ultrasonic Method. *IX International Congress on Experimental Mechanics. Orlando. Florida. USA, June 5-8, 2000. p. 954-957.*
- [9]. Y. Kudryavtsev, J. Kleiman and O. Gushcha. Ultrasonic Measurement of Residual Stresses in Welded Railway Bridge. *Structural Materials Technology: An NDT Conference. Atlantic City. NJ. February 28-March 3, 2000. p. 213-218.*
- [10]. Y. Kudryavtsev, J. Kleiman, O. Gushcha, V. Smilenko and V. Brodovy. Ultrasonic Technique and Device for Residual Stress Measurement. *X International Congress and Exposition on Experimental and Applied Mechanics. Costa Mesa, California USA, June 7-10, 2004. pp. 1-7.*
- [11]. H. Polezhayeva, J. Kang, J. Lee, Y. Yang and Y. Kudryavtsev. A Study on Residual Stress Distribution and Relaxation in Welded Components. *Proceedings of the 20th International Offshore (Ocean) and Polar Engineering Conference ISOPE-2010, June 20–26, 2010, Beijing, China.*