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Jacob Kleiman, Yuri Kudryavtsev
Structural Integrity Technologies (Sintec) Inc., 80 Esna Park Drive, Units 7-9, Markham, Ontario, L3R 2R7, Canada

RESIDUAL STRESS MANAGEMENT IN WELDED ELEMENTS AND STRUCTURES

Клейман Я.И., Кудрявцев Ю.Ф.
Технологии Структурной Прочности (СИНТЕК) – 80 Эсна Парк Драйв, Маркхам, Онтарио

МЕНЕДЖМЕНТ ОСТАТОЧНЫХ НАПРЯЖЕНИЙ В СВАРНЫХ ЭЛЕМЕНТАХ И КОНСТРУКЦИЯХ

Residual stresses introduced before, during or after welding may change considerably the engineering properties of materials and structural components by affecting their fatigue life, distortion, dimensional stability, corrosion resistance, etc. They play an exceptionally significant role in fatigue of welded elements.
The concept of residual stress management is helping the welding community to fully understand the effect of residual stresses by addressing major aspects of residual stresses in welds and welded structures. According to the concept three major stages, i.e. RS determination, RS analysis and RS redistribution are considered and evaluated, either experimentally or theoretically to achieve the optimum performance of welded structures.
The welding community benefits directly from the RSM concept at all stages of the welding process. This report will provide an overview on the advancements made in addressing the development of instrumentation for providing solutions in the major stages of the RSM concept. New examples of industrial applications of the developed engineering tools for residual stress analysis and fatigue `life improvement of welded elements and structures are given.
Keywords: residual stresses; ultrasonic method; non-destructive measurment; underwater ultrasonic peening; UltraMARS-7

Introduction

If we shall look up for a definition of residual stresses, the most common definition associates them with stresses that remain, after the original cause(s) of the stresses (external forces, heat gradient, mechanical processing) have been removed, along a cross section of the part, even without the external cause. Residual stresses that occur, for instance as a result of heat treatment of welded parts may cause localized expansion, which is taken up during welding by either the molten metal or the placement of parts being welded. When the finished weldment cools, some areas cool and contract more than others, leaving residual stresses

Residual stresses may change considerably the engineering properties of materials and structural components by affecting their fatigue life, distortion, dimensional stability, corrosion resistance, etc. It is very important, therefore, to consider the problem of residual stress as a complex problem including, at least, stages of the determination, the analysis and the beneficial redistribution of residual stresses. The combined consideration of the above-mentioned stages of residual stress analysis gives rise to so called Residual Stress Management (RSM) concept approach that addresses major aspects of residual stresses in welds and welded structures. According to the concept three major stages, i.e. RS determination, RS analysis and RS redistribution are considered and evaluated, either experimentally or theoretically to achieve the optimum performance of welded structures [1-3].

Fatigue life, distortion, dimensional stability, corrosion resistance and brittle fracture may be affected strongly by residual stresses (RS) [4]. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures [5] and, for that reason, the knowledge of residual stresses and their behavior are necessary in the design of parts and structural elements and in the estimation of their reliability under real service conditions. 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. Beneficial compressive RS with a level close to the yield strength of the material can be introduced in the weld toe zones by various post-weld improvement treatments of which the ultrasonic peening (UIT/UP) is one example [5-9].

Over the last few decades, various quantitative and qualitative methods of RS analysis have been developed [10]. 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 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 relationships 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 application of the non-destructive ultrasonic method for residual stress measurements had shown that this technique, in many cases, allows measuring very efficiently the residual stresses both in laboratory conditions and in real structures for a wide range of materials [11-16].

Ultrasonic Measurements 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 acousto-elastic 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 1. As can be seen from Fig. 1, the intensity and character of such changes could be different, depending on material properties.

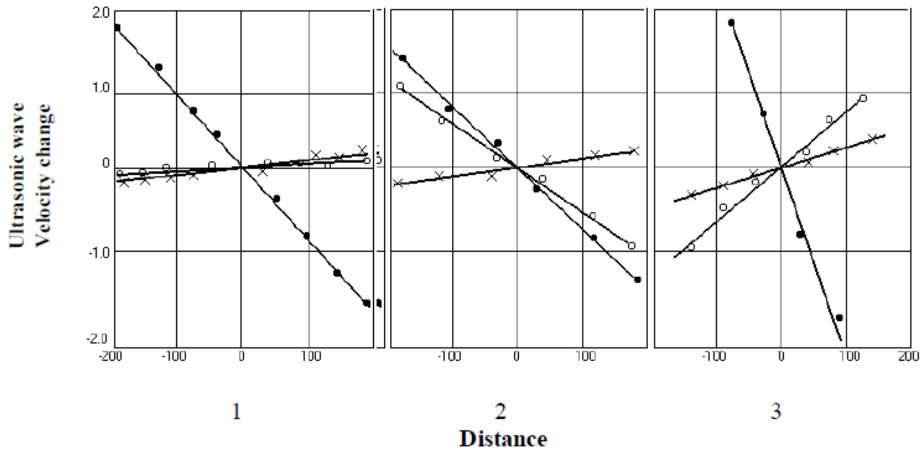

Fig. 1. Change of ultrasonic longitudinal wave velocity (CL) and shear waves velocities of orthogonal polarization (C SX3; C SX2) depending on the mechanical stress σ in steel A (1), steel B (2) and aluminum alloy (3) [10]: ● - C SX3; ○ – C SX2; x - C L

Figure 2 presents the results of measurement of the three ultrasound components during loading in compression of a small sample of a material that is used in shipbuilding. The longitudinal velocity is presented by the ΔF1/F10 data line and the two shear waves of orthogonal polarization are presented by the ΔF2/F20 and ΔF3/F30 data lines. The changes in the velocities are expressed in Fig. 2 as ultrasound wave frequency changes. Different configurations of ultrasonic transducers can be used for residual stress measurements (Fig. 3).

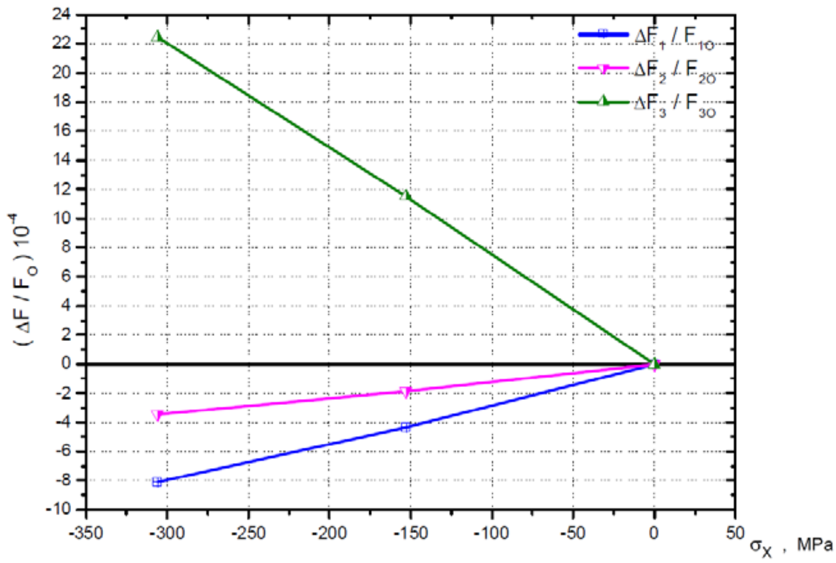

Fig. 2. Changes of ultrasonic wave velocities in the sample of considered material under the action of applied stresses

The technique when the same transducer is used for excitation/sending and receiving of ultrasonic waves is often called pulse-echo method (Fig. 3a). The through-thickness pulse-echo method is effective for analysis of residual stresses in the interior of material. In this case the average of residual stresses through-thickness is measured.

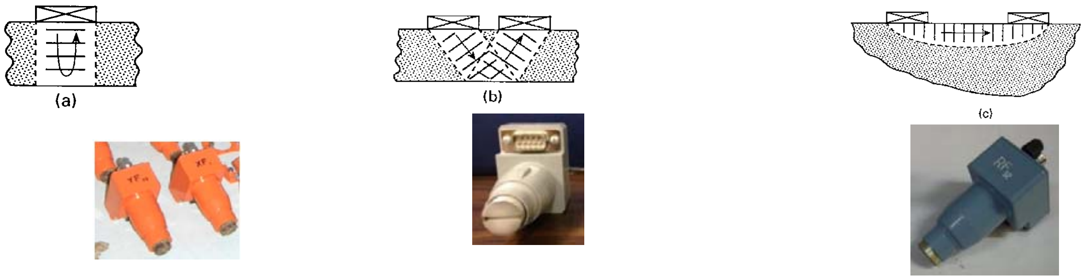

Fig. 3. Schematic presentation and examples of transducers for ultrasonic measurement configurations: (a) through-thickness pulse-echo, (b) through-thickness pitch-catch and (c) surface pitch-catch

The methods when waves are launched by a transmitting transducer, propagate through a region of the material and are detected by a receiving transducer are called through-thickness pitch-catch (Fig. 3b) and surface pitch-catch (Fig.3c) [4]. In the configuration shown in Figure 3c, the residual stress in a surface/subsurface layer is determined. 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. Among other advantages of the ultrasonic technique one can mention the convenience of use, a quick set up, portable, inexpensive and free of radiation hazards.

In the proposed technique [12, 14, 15], the velocities of longitudinal ultrasonic wave and shear waves of orthogonal polarization are measured in the same 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 and the acousto-elastic constants 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.

Ultrasonic Equipment and Software for Residual Stress Measurement

The major parts of the Ultrasonic Computerized Complex (UCC) for residual stress analysis that was developed recently based on an improved ultrasonic methodology [11-15] (Figure 4) include a measurement unit with supporting software (position 1 in Fig.4), a preamplifier (position 2a in Fig.4) with a magnetic (position 2b in Fig.4) or mechanical holder and interchangeable transducers (position 3 in Fig.4). For selection of the appropriate reflected wave and tuning in manual mode an oscilloscope (position 4 in Fig.4) is used. The UCC allows determining uni- and biaxial applied and residual stresses for a wide range of materials and structures. In addition, the developed Expert System (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.

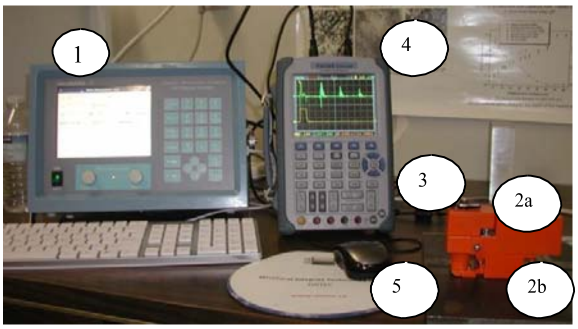

Fig. 4. Ultrasonic Computerized Complex for residual and applied stress measurement
(1) - Measurement unit with supporting software, (2a) – Preamplifier, (2b) – Magnetic holder, (3) – Transducer, (4) – Oscilloscope, (5) – Sample

The developed equipment allows determining the magnitude and sign 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 ultrasonic transducers for bulk or surface and subsurface measurements are held in contact with the object of investigation by a magnetic or electromagnetic holder for ferrous materials (see Figure 4) or by special clamping straps for non-ferrous materials.

Using the developed equipment stresses can be measured in materials with thickness 2 - 200 mm. The stress, strain and force measurements can be done in fasteners (pins) 25 to 1000 mm long. The error of stress determination (from external load) is estimated at 5 - 10 MPa and the error of residual stress determination is estimated at 0.1 □y (yield strength) MPa. The overall dimensions of the measurement unit are 300x200x150 mm and the weight of the unit with sensors is ~ 6 kg.

Recently, the software and hardware of the UltraMARS-7 system were upgraded to allow for presenting the results of the measurements in a form of a graph that is built on the screen as the measurements progress. The data can be saved and stored in the memory and transferred by uploading it to a USB device for further processing. Figure 5 presents an example of the data on the stress components σ22 and σ33 measured in a sample with stresses and displayed on the screen of the UltraMARS-7 system.

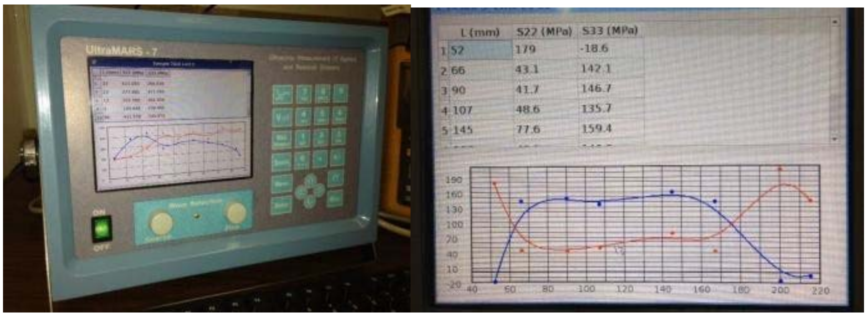

Fig. 5. A view of the UltraMARS-7 system (left) and a screenshot of the residual stresses distribution results (stress components σ22 and σ33) as measured, calculated and displayed on the screen of the UltraMARS-7 instrument

The supporting software allows controlling the measurement process, storing the measured and other data and calculating and plotting the distribution of residual stresses on the screen of the unit. The measurement unit is equipped with a number of USB ports allowing for easy transfer of data. In addition, provisions are made to connect a PC computer to the unit. The developed system also offers, in addition to the stress measurements, determination of the Young modulus and Poisson Ratio, the measurement of the acousto-elastic coefficients and determination of the thickness of parts.

Ultrasonic Impact Treatment Equipment

The ultrasonic impact treatment (UIT) [17-22] that in most industrial applications is also known as ultrasonic peening (UP) [23-27] is gaining worldwide acceptance as one of the new and promising processes for fatigue life improvement of welded elements and structures. The beneficial effect of UP is achieved mainly by relieving of harmful tensile residual stresses and introducing of compressive residual stresses into surface layers of materials, decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of the surface layers of the material. The fatigue testing of welded specimens showed that the UP is the most efficient improvement treatment when compared with such traditional techniques as grinding, TIG-dressing, heat treatment, hammer peening, shot peening and application of low temperature transformation (LTT) electrodes [17,28,29].

The UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material. A number of basic units for different application were developed to include treatments in air and underwater (Fig. 6) [30, 31] .

The most recent design of the UP equipment (Fig. 6a) is based on "Power on Demand" concept. Using this concept, the power and other operating parameters of the UP equipment are adjusted to produce the necessary changes in residual stresses, stress concentration and mechanical properties of the surface layers of materials to attain the maximum possible increase in fatigue life of welded elements and structures

Fig. 6. Basic ultrasonic peening system for fatigue life improvement of welded elements and structures (a) and the underwater peening instrument (b) and various modifications of the basic peening tool (c)

All peening tools have replaceable interchangeable working heads that were developed based on the requirements in particular applications and that vary in geometry, shape and number of pins. Figure 7 shows some of the designs of the interchangeable working heads.

Fig. 7. Examples of the replaceable interchangeable working heads developed for the ultrasonic peening of materials and structures

Examples of Application of the RSM Tools in Industry

To demonstrate the efficiency of the RSM approach, a few examples of projects are given below where both, the measurement of residual stresses and the post-weld treatment were used to evaluate the efficiency.

Evaluation of residual stresses before and after UP treatment in welded joints

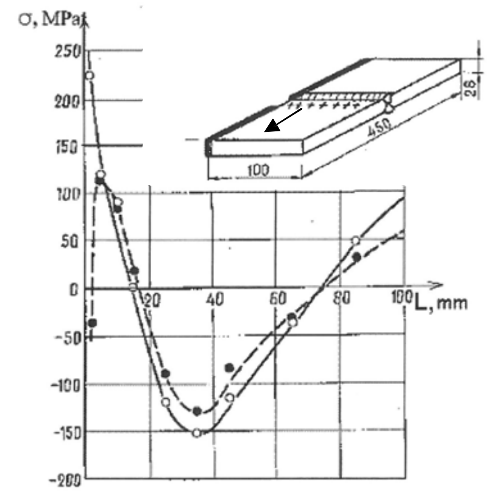

Fig. 8. Distribution of residual stresses (averaged through thickness) in a welded element sample before (○) and after (●) Ultrasonic Peening

A number of butt-welded joint samples were prepared from 28 mm thick regular steel material that measured 450 mm by 100 mm (see insert in Fig. 8) [32].

The weld was treated by UP, with only the weld line exposed to the UP. The distribution of averaged through thickness residual stresses was measured in the samples before and after ultrasonic peening starting from the weld and advancing to the edge of the sample along its length as shown with the arrow in the insert of Fig. 8. As can be seen from Fig. 8, the high tensile stresses that reached 240 MPa near the weld before the UP treatment, converted into compressive – 40 MPa in the vicinity of the weld after the UP.

A similar project was conducted using a different type of weld joint, i.e. a fillet joint. As previously, the residuals tresses were measured in the welded sample along the sample starting from the weld before and after a post- weld treatment by UP. Figure 9 presents the results of these measurements, with the geometry of the joint shown in the insert

Measurement of Residual Stresses in Large Welded Structures

The developed ultrasonic equipment UltraMARS® was used for RS measurement for both laboratory/factory and field conditions. Below an example of measurement of residual stresses in large-scale welded panel (YS=360 MPa, UTS=470 MPa) are provided. The stresses were measured in as-welded condition and during the fatigue loading of the panels [16]. 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 10 shows the set-up for residual stress measurement in the large-scale panel. Figure 11 illustrates the distributions of the residual stress in the 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.

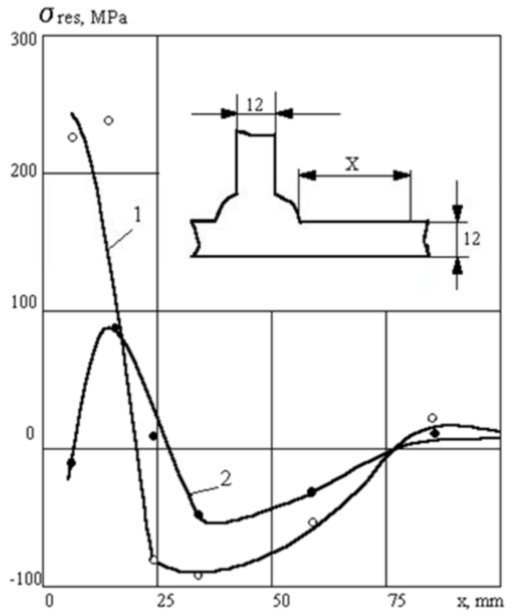

Fig. 9. Distribution of residual stresses (averaged through thickness) in a welded element sample before (1) and after (2) Ultrasonic Peening

Fig. 10. Measurement of residual stresses using UltraMARS system in large-scale welded panel in as-welded condition and during the fatigue loading of the panel

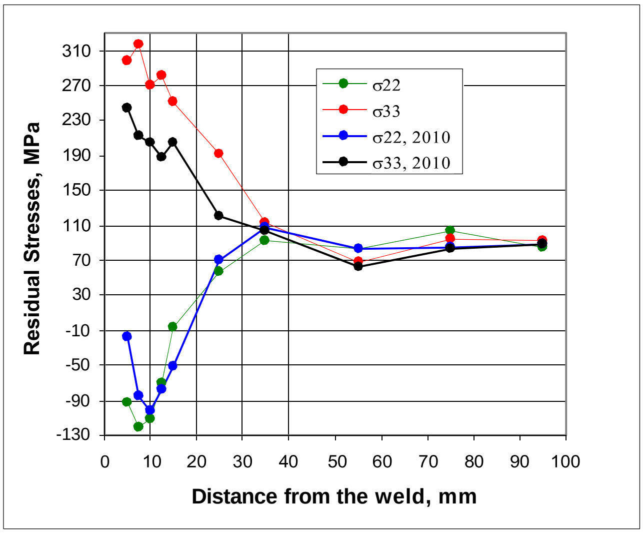

Fig. 11. The distributions of residual stress in large-scale welded panel near the weld that is critical from the fatigue point of view in as-welded condition and after 2010 cycles of loading [16]

Ultrasonic Peening Treatment of Large Welded Structures

Ultrasonic peening was applied successfully in mining industry to repair and rehabilitate welded elements subjected to fatigue loading. All welds in two large grinding mills (Fig. 12) used for iron ore crushing were treated by UP to increase the fatigue performance of the mills and to allow increasing the ore load.

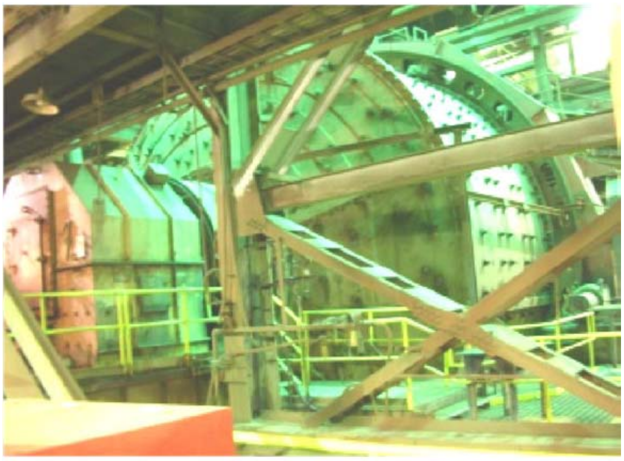

Fig. 12. General view of one of the grinding mills that was treated by UP

About 300 meters of welds critical from fatigue point of view were UP treated on each of the mills as shown in Fig. 13 to provide the improved fatigue performance.

Fig. 13. Application of UP for rehabilitation of welded elements of a large grinding mill shown in Fig. 12

Ultrasonic Underwater Peening (UUP) Treatment of Welded Structures

An ultrasonic system was designed and built for applications under water [31]. The system (Fig. 14) looks similar to the basic UP system shown in Fig. 6a, but actually is very different in design.

Fig. 14. The new ultrasonic system UltraPeen® with easy replaceable working heads for underwater ultrasonic peening

A study was conducted to evaluate the efficiency of new technology and equipment UltraPeen® for underwater ultrasonic peening (UUP) of welded elements. Thirty four large-scale welded samples were produced (see insert in Fig. 16). Half of these samples were welded in open air and another half – underwater (Fig. 15). Then, 50% of the samples from both batches were subjected to UUP and all samples were fatigue tested. The results of the fatigue testing (Fig. 16) showed that the UUP provides significant fatigue improvement of welded elements, similar to what is observed for UP in air. The fatigue life of welded samples increased under the action of UUP 4-5 times depending on the level of applied stresses

Fig. 15. The process of underwater ultrasonic peening using UltraPeen® system. a) Manual treatment by an operator. b) ultrasonic peening treatment under water using an automated mode, without the help form an operator

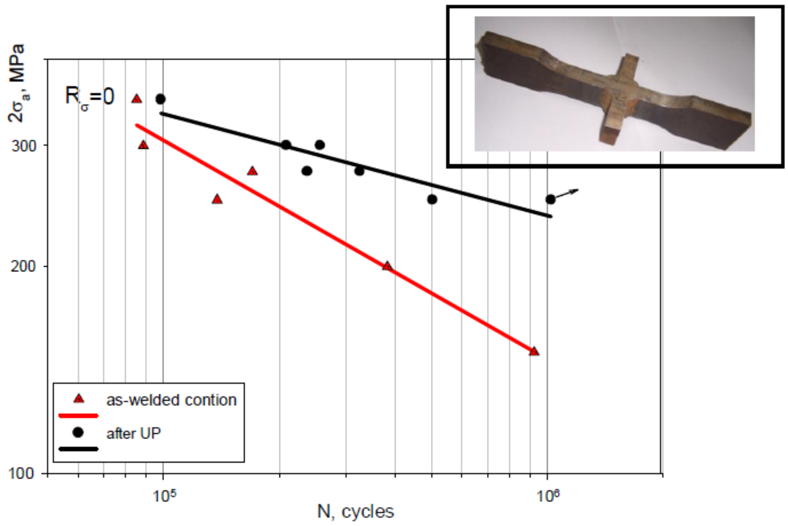

Fig. 16. Results of fatigue testing of the large metal samples in as-welded condition (triangles) and after the UUP treatment (solid circles)

Summary

In summary, it is safe to say that the concept of residual stress management is helping welders and the welding community to fully understand the effect of residual stresses by addressing major aspects of residual stresses in welds and welded structures. When the elements of the RSM are used together the optimum performance of welded structures can be achieved. The effect of residual stresses on material properties like fatigue, fracture, corrosion resistance and dimensional stability can be considerable and they, therefore, should be taken into account during design, fatigue assessment and manufacturing of parts and welded elements.

Substantial technological progress was made in the non-destructive measurement of applied and residual stresses by ultrasonic method. The UltraMARS-7 system incorporates new software and new functional capabilities, allowing evaluate the bulk, average through thickness stresses as well as the subsurface and surface stress changes. In addition it allows also evaluating the thickness of the materials and their Young modulus and Poisson ratio. The residual and applied stresses can be measured, calculated and their distribution displayed on the screen of the UltraMARS-7 instrument as continuous curves, with the option of transferring the date onto an USB device for further processing.

The developed advanced ultrasonic method and based on it portable instrument were used successfully in laboratory and field conditions for non-destructive measurement of applied and residual stresses in real parts and structural elements. The ultrasonic peening technology was also matured with new models of the instrumentation for underwater treatments being developed and successfully demonstrated. The UP equipments 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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