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RESIDUAL STRESS MANAGEMENT IN WELDING: MEASUREMENT, FATIGUE ANALYSIS AND IMPROVEMENT TREATMENTS

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Residual stress (RS) management is a concept according to which three major stages, i.e. RS determination, RS fatigue analysis and RS beneficial redistribution are considered and evaluated, either experimentally or theoretically to achieve the optimum performance of welded structures. All three stages as well as a number of new engineering tools such as ultrasonic computerized complex for residual stress measurement, UltraMARS, software for analysis of the effect of residual stresses on the fatigue life of welded elements, ReSIsT, and new technology and, based on it, compact system for beneficial redistribution of residual stresses by ultrasonic impact treatment, UltraPeen, will be discussed. Examples of industrial applications of the developed engineering tools for residual stress analysis and fatigue life improvement of welded elements and structures will be given. 10 Ref., 8 Figures.

Key words: ultrasonic measurement, residual stress, software, prediction of fatigue life, redistribution of stresses, ultrasonic impact treatment, industrial application

1. Introduction. Residual stress management

Residual stress management is a concept 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.

Residual stress can significantly affect engineering properties of materials and structural components, notably, fatigue life, distortion, dimensional stability, corrosion resistance etc. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures. For that reason, the residual stress analysis is a compulsory stage in the design of structural elements and in the estimation of their reliability under real service conditions. Systematic studies had shown that welding residual stresses may lead to a drastic reduction in fatigue strength of welded elements. In multi-cycle fatigue ($N > 10^6$ cycles) the effect of residual stresses can be compared with the effect of stress concentration. Even more significant are the effects of residual stresses on the fatigue life of welded elements in the case of relieving harmful tensile residual stresses and introducing beneficial compressive residual stresses in the weld toe zones. The results of fatigue testing of welded specimens in as-welded condition and after application of ultrasonic peening showed that in case of non-load caring fillet welded joint in high strength steel, the redistribution of residual stresses resulted in approximately two-fold increase in the limit stress range [1, 2]. The residual stresses, 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 techniques for residual stress management, a considerable effort is still required to develop efficient and cost-effective methods of residual stress measurement and analysis as well as technologies for the beneficial redistribution of residual stresses.

It is very important to consider the problem of residual stress as a complex problem including, at least, stages of the determination, the fatigue 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. The RSM concept includes the following main stages:

Stage 1: Residual Stress Determination. The stresses can be evaluated directly through measurements either using destructive method or non-destructive method and through computation.

Stage 2: Analysis of the Residual Stress Effects. The effect of residual stresses can be evaluated either through experimental studies or via computational methods.

Stage 3: Residual Stress Modification, if required. The modification of the residual stresses could be performed through changes in the technology of manufacturing/assembly and/or through application of stress-relieving techniques.

A number of new advanced engineering tools for all three stages of RSM were developed recently at Structural Integrity Technologies (SINTEC) Inc. located in Markham, Canada in cooperation with Ukrainian scientists. Short descriptions of the new engineering tools for residual stress management and examples of their practical application are presented below.

2. Residual stress measurement

2.1. Current Situation with Residual Stress Measurements

Over the last few decades, various quantitative and qualitative methods of residual stress measurement have been developed. In general, a distinction is usually made between destructive and non-destructive techniques [2].

The first series of methods is based on destruction of the state of equilibrium of the residual stress after sectioning of the specimen, machining, layer removal or hole drilling. The redistribution of the internal forces leads to local strains that are measured to evaluate the residual stress field. The residual stress is deduced from the measured strain using the elastic theory (analytical approach or finite element calculations). Among the most commonly used methods one can mention a few like:

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

The second series of non-destructive methods of residual stress measurement is based on the relationship between the physical and the crystallographic parameters and the residual stress. The most developed methods are:

- *The X-ray and neutron diffraction methods*. These methods are based on the use of the lattice spacing as the strain gauge. It allows studying and separating the three kinds of residual stresses. Currently, the X-ray method is the most widely used non-destructive technique for residual stress measurements.
- *The ultrasonic techniques*. These techniques are based on variations in the velocity of ultrasonic wave propagation in the materials under the action of mechanical stresses.
- *The magnetic methods*. These methods rely on the interaction between magnetization and elastic strain in ferromagnetic materials. Different magnetic properties can be studied: permeability, magnetostriction, hysteresis, and Barkhausen noise.

While there are various destructive and nondestructive methods to detect and quantify the residual stresses described in technical literature, new industrial problems, new geometrical and material complexities related to them, combined with a general need for fast and economical residual stress measurements create strong demand in new effective techniques and devices that is increasing dramatically. The most desired technology must be reliable and user-friendly, i.e. it should not require guessing and intuition from the engineer/technician and it must be computerized for quick analysis. One such new system for residual stress measurement that is based on using of the ultrasound is described below.

2.2. Ultrasonic Computerized Complex for Residual Stress Measurement

The Ultrasonic Computerized Complex (UCC) was developed for residual stress measurement in laboratory and in field conditions [3-5]. The UCC “UltraMARS” (Ultrasonic Measurement of Applied and Residual Stresses) includes a measurement unit with supporting software and an optional laptop with an advanced database and an Expert System (ES) for analysis of the influence of residual stresses on the fatigue life of welded elements (Figure 1). 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 structural elements, depending on the mechanical properties of the used materials, the type of welded elements and the parameters of cyclic loading.

The supporting software allows controlling the measurement process, storing the ultrasonic measurement data and calculating and plotting the residual stresses distribution. The software allows the use of the designed method and equipment with standard PC’s.

The main technical characteristics of the measurement unit:

-The stress can be measured in materials with thicknesses 2–150 mm;

-The error of stress determination (from external load) is 5–10 MPa;

-The error of residual stress determination is ~ 0.1

Figure 1. Ultrasonic Computerized Complex for residual and applied stress measurement: a — UltraMARS® model shown with a laptop and an oscilloscope; b — Next generation UltraMARS® -7 model shown with all transducers, transducer holders and attachments

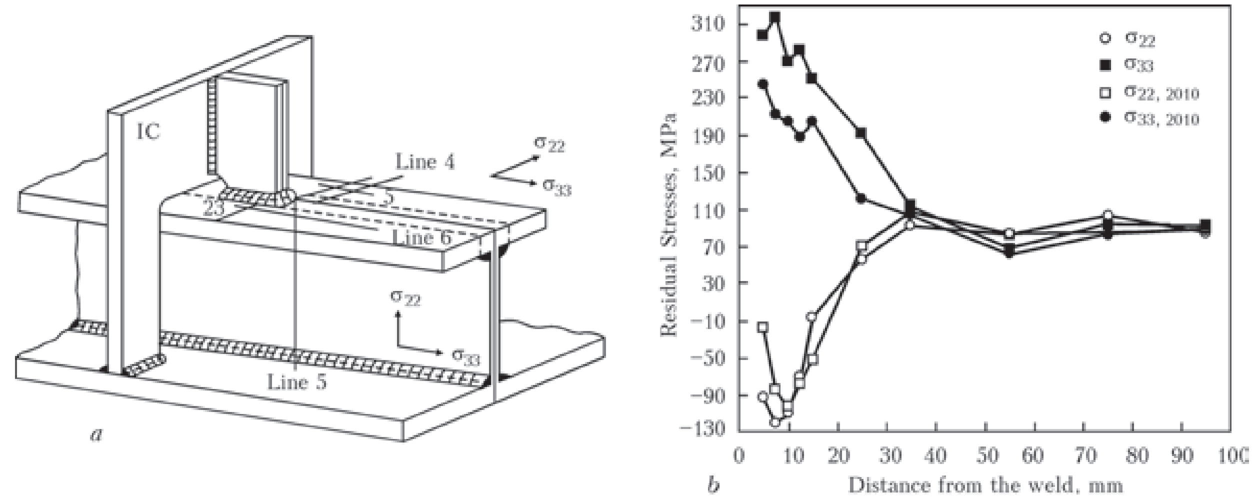

Figure 2. Measurement of residual stresses in a fragment of a real ship structure: a — schematic view of a fragment of the welded panel with details on residual stress measurement zones. The measurements were conducted along lines 4, 5 and 6, b — the distribution of residual stress along the welded stiffener (along line 6) in the welded panel before and after 2010 cycles of loading

σ_y (MPa);

-The stress, strain and force measurement can be performed in fasteners (pins) 25–1000 mm long;

-The system can be powered from an independent power supply (accumulator battery 12 V);

-The overall dimensions of the measurement instrument 300×200×150 mm;

-The weight of the unit with transducers is 6 kg.

One of the main advantages of the developed system UltraMARS® 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. An examples of practical application of the developed ultrasonic technique and equipment for residual stress measurement in welded elements is presented below.

Figure 2b shows the distribution of residual stress in large scale welded panel shown schematically in Fig. 2a along the welded stiffener in as-welded condition and after cyclic loading [6]. It can be seen from Fig. 2 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.

Figure 3 shows two other typical examples of field application of the Ultrasonic Computerized Complex – UltraMARS® on a section of a highway bridge and on a section of a submarine hull.

3. Residual stress in fatigue analysis

despite the fact that the residual stresses have a significant effect on the strength and reliability of parts and welded elements, their influence is not sufficiently reflected in corresponding codes and regulations. This is, mainly, because the influence of residual stresses on the fatigue life of structural elements depends greatly not only on the level of residual stresses, but also on the mechanical properties of used materials, the type of welded joints, the parameters of cyclic loading and on other factors [1,2]. Presently elaborate, time-and labor-consuming fatigue tests of large-scale specimens are required for this type of analysis.

Generally, in modern standards and codes on fatigue design [7] the presented data correspond to the fatigue strength of real welded joints including the effects of welding technology, the type of welded element and the welding residual stresses. Nevertheless, in many cases there is a need to consider the influence of welding residual stresses on the fatigue life of structural components in greater details. These cases include use of the results of fatigue testing of relatively small welded specimens without high tensile residual stresses, analysis of effects of such factors as overloading, spectra loading, application of the improvement treatments, etc.

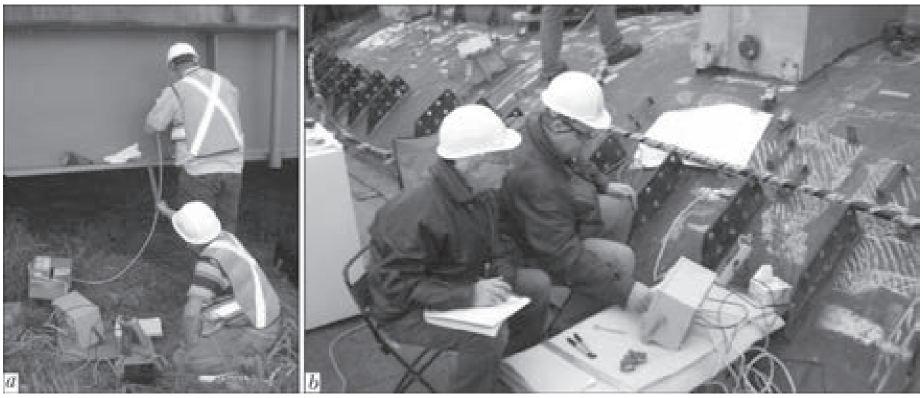

Figure 3. Application of the UltraMARS system for measurement of residual stresses in the zones of welded elements of a highway bridge (a) and a submarine pressure hull (b)

An Expert System for

Fatigue Assessment and Optimization of Welded Elements “ReSIsT” was developed to resolve the above-mentioned problem [2]. The ES “ReSIsT” (Residual Stresses and Improvement Treatments) is based on the original predictive model for analysis of the influence of the residual stresses and their redistribution under the effect of cyclic loading and improvement treatments on the fatigue life of welded elements.

The optimization of welded elements is based on their fatigue assessment in the dialog mode. The following important parameters of welded structures are analyzed with the goal to enhance the fatigue performance:

- Material selection,
- Preferred design of welded elements,
- Weld processes and materials,
- Residual stresses,
- Application of improvement treatments,
- Influence of possible repair technologies,
- Realistic service conditions.

The ES includes a package of programs allowing to perform storing, classifying and statistical processing of the fatigue testing results and subsequent comparative analysis of the fatigue life of welded elements in the initial condition (after welding) and after application of improvement treatments. The developed ES includes the possibility to assess through calculations the effect of welding residual stresses and the application of improvement treatments on the fatigue life of welded elements without having to perform the time and labor consuming fatigue tests. The application of heat-treatment, vibration treatment, overloading, ultrasonic peening and other improvement treatments are considered. During fatigue assessment, the mechanical properties of the materials, the type of welded elements and stress concentrations, as well as the cyclic loading parameters are taken into account. A detailed analysis of the influence of residual stresses and their redistribution under the effect of cyclic loading in the zones of stress concentration is performed during such assessment.

The significant increase in the fatigue strength of parts and welded elements can be achieved by beneficial redistribution of residual stresses. To demonstrate this point, the calculated fatigue curves for a transverse loaded butt weld with different levels of initial residual stresses are shown in Figure 4. The fatigue curve of the welded element will be located between lines 1 and 2 in the case of partial removal of tensile residual stresses (i.e. lines 3 and 4). The decrease of the residual stresses from initial high level (line1) to 100 MPa (line 4) causes, in this case, an increase of the limit stress range at N = 2·10^6 cycles from 100 to 126 MPa.

The relieving of the residual stresses in welded element to the level of 100 MPa could be achieved, for example, by heat treatment or overloading of this welded element at a level of external stresses equal to $0.52\sigma_y$. As a result, this fatigue Class 100 welded element becomes the fatigue Class 125 element [7]. After modification of welding residual stresses, the considered welded element will have an enhanced fatigue performance and, in principle, can be used instead of transverse loaded butt weld ground flush to plate (No. 211) or longitudinal weld (No. 312 and 313) [7]. Introducing of compressive residual stresses into the weld toe zone can increase the fatigue strength of welded elements even to a larger extend (lines 5 and 6 in Figure 4).

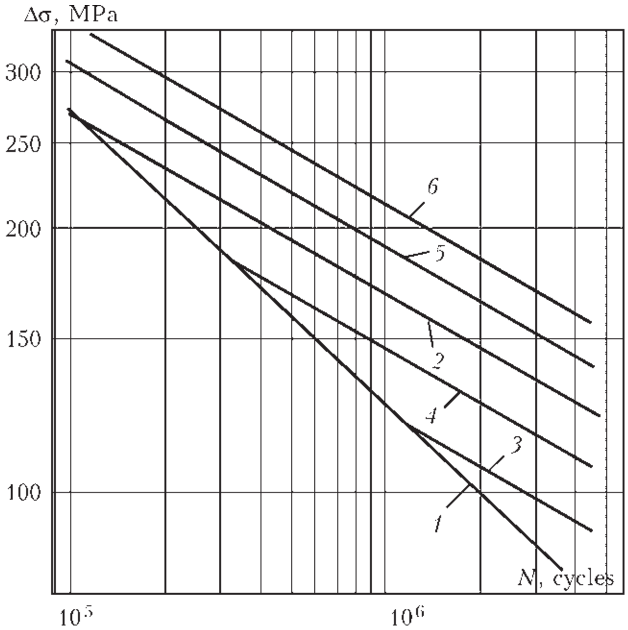

Figure 4. Fatigue curves of transverse loaded butt weld at R=0: Line 1– with high tensile residual stresses; Lines 2...6 – with residual stresses equals to 0 MPa, 200 MPa, 100 MPa, –100 MPa and –200 MPa, respectively

4. Residual stress modification

In many cases, the beneficial redistribution of residual stresses can improve drastically the engineering properties of parts and welded elements. The detrimental tensile residual stresses could be removed and beneficial compressive residual stresses could be introduced into the subsurface layers of treated materials by application of heat treatment, overloading, hammer peening, shot peening, laser shock peening, etc. One of the new processes for effective redistribution of residual stresses is Ultrasonic Impact Treatment (UIT) or Ultrasonic Peening (UP) [8-10].

The UIT/UP produces a number of beneficial effects in metals and alloys. Foremost among these is increasing the resistance of materials and welded elements to surface-related failures, such as fatigue, fretting fatigue and stress corrosion cracking. The beneficial effect is achieved mainly by relieving of harmful tensile residual stresses and introducing compressive residual stresses into surface layers of metals and alloys, decreasing of stress concentrations in weld toe zones and the enhancement of the mechanical properties of the surface layers of the material. The fatigue testing of welded specimens showed that the UIT/UP is the most efficient improvement treatment as compared with traditional techniques such as grinding, TIG-dressing, heat treatment, hammer peening, shot peening etc. [1, 10]. A new advanced system UltraPeen® (Ultrasonic Peening) for UIT/UP of parts and welded elements is shown in Figure 5.

For the effective application of UIT/UP, depending on the above-mentioned factors, a software package for Optimum Application of Ultrasonic Peening was developed that is based on an original predictive model.

In the optimum application, a maximum possible increase in fatigue life of welded elements with minimum labor-and power-consumption is thought. The main functions of the developed software are:

-Determination of the maximum possible increase in fatigue life of welded elements by UIT/UP, depending on the mechanical properties of used material, the type of welded element, the parameters of cyclic loading and other factors;

- Determination of the optimum technological parameters of UIT/UP (maximum possible effect with minimum labor-and power-consumption) for every considered welded element;

- Quality monitoring of UIT/UP process;

- Final fatigue assessment of welded elements or structures after UIT/UP, based on detailed inspection of UIT/UP treated zones and computation.

The developed software allows to assess, through calculations, the influence of residual stress redistribution by UIT/UP on the service life of welded elements without having to perform the time-and labor-consuming fatigue tests and to compare the results of calculations with the effectiveness of other improvement treatments such as heat-treatment, vibration treatment, overloading etc. The results of computation presented in Figure 6 show the effect of application of the UIT/UP for increasing the fatigue life of welded joints in steels of different strength. The data of fatigue testing of non-load-carrying fillet weld specimens in as-welded condition (with high tensile residual stresses) were used as initial fatigue data for calculating the effect of the UIT/UP. These results are in agreement with the existing statement that the fatigue strength of certain welded element in steels of different strength in as-welded condition is represented by a unique fatigue curve [1,7]. Four types of steels were considered for fatigue analysis: Steel 1 – (σ_y = 270 MPa, σ_u = 410 MPa); Steel 2 – (σ_y = 370 MPa, σ_u = 470 MPa); Steel 3 – (σ_y = 615 MPa, σ_u = 747 MPa) and Steel 4 – (σ_y = 864 MPa, σ_u = 897 MPa). Line 1 in Figure 6 is the unique fatigue curve of considered welded joint for all types of steels in as-welded condition that was determined experimentally. Lines 3, 5, 7 and 9 are the calculated fatigue curves for the welded joint after application of the UIT/UP for Steel 1, Steel 2, Steel 3 and Steel 4, respectively.

Figure 5. Advanced compact equipment for UIT/UP of materials, parts and welded elements

As can be seen from Figure 6, the higher the mechanical properties of the material, the higher is the fatigue strength of welded joints after application of the UIT/UP. The increase in the limit stress range at $N = 2\times10^6$ cycles under the influence of UIT/UP for welded joint in Steel 1 is 42%, for Steel 2 – 64%, for Steel 3 – 83% and for Steel 4 – 112%. These results show a strong tendency of increasing the fatigue strength of welded elements after application of UIT/UP with the increase in mechanical properties of the material used. In cases of high strength steels, the application of UIT/UP caused a two-fold increase in the limit stress range and over 10 times increase in the fatigue life of the welded elements.

As an example of application of UIT/UP, the results of fatigue testing of a tubular welded joint in as-welded condition and after UIT/UP are presented in Fig. 7. As can be seen from Fig 7, in the considered case of welded T-joint of rectangular hollow section (RHS) member elements (4”×4” to 2”×6” welded tubes as shown in the insert of Fig. 7) the UIT/UP increased the limit stress range of tubular joints by approximately 70% and the fatigue life – by more than 10 times.

Figure 8 shows examples of industrial application of the UP system in treatment of a large grinding mill in an effort to increase the capacity of the load (Fig. 8a) and for redistribution of residual stresses in a critical from the fatigue point of view region of a landing gear (Fig. 8b).

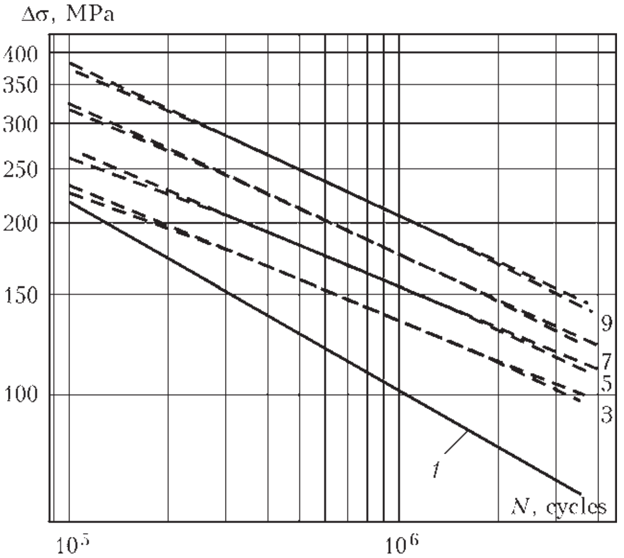

Figure 6. Fatigue curves of non-load-carrying fillet welded joint: 1 – in as-welded condition for all types of steel; 3, 5, 7 and 9 – after application of the UP to Steel 1, Steel 2, Steel 3, and Steel 4

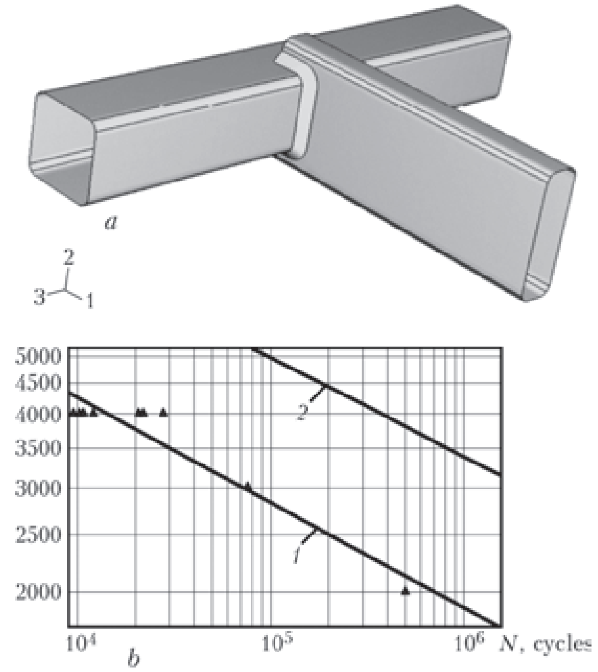

Figure 7. Fatigue curves (tendency) for tubular welded joints (as shown in the insert) showing the beneficial effect of UIT/UP: *1* — as-welded condition, *2* — after UIT/UP

5. CONCLUSIONS

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. A number of new engineering tools for residual stress management such as ultrasonic computerized complex for residual stress measurement, technology and equipment for ultrasonic penning and expert system for fatigue assessment and optimization of welded elements and structures were recently developed and verified for different applications.

3. The beneficial redistribution of the residual stresses is one of the efficient ways of improvement of the engineering properties of parts and structural elements. Application of the ultrasonic impact treatment causes a remarkable improvement of the fatigue strength of parts and welded elements in materials of different strength. The higher the mechanical properties of treated materials – the higher the efficiency of ultrasonic peening application. It allows using to a greater degree the advantages of the high strength material application in welded elements and structures, subjected to fatigue loading.

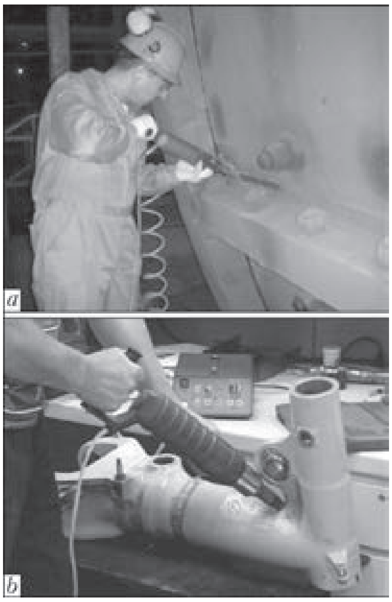

Figure 8. Examples of application of the UltraPeen system for fatigue improvement: a — of grinding mill when over 250 meters of welds were treated, b — of landing gear where critical from the fatigue point of view zone was treated

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