# Fatigue of Welded Elements: Residual Stresses and Improvement Treatments

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**Key words:** fatigue, welds, residual stresses, improvement treatments, ultrasonic peening

**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. 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 RS resulted in approximately two-fold increase in the limit stress range.

A concept of residual stress management (RSM) and a number of engineering tools were proposed recently that address major aspects of RS 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 main stages of RSM are considered in this paper. A number of new engineering tools such as ultrasonic computerized complex for RS measurement, software for analysis of the effect of RS on the fatigue life of welded elements as well as a new technology and, based on it, compact system for beneficial redistribution of RS by ultrasonic peening are introduced. Examples of industrial applications of the developed engineering tools for RS analysis and fatigue life improvement of welded elements and structures are discussed.

## 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. In multi-cycle fatigue ($N>10^6$ cycles of loading), the effect of RS can be compared with the effect of stress concentration [2]. 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 (approximately the same as those within the specimens of first type) [2].

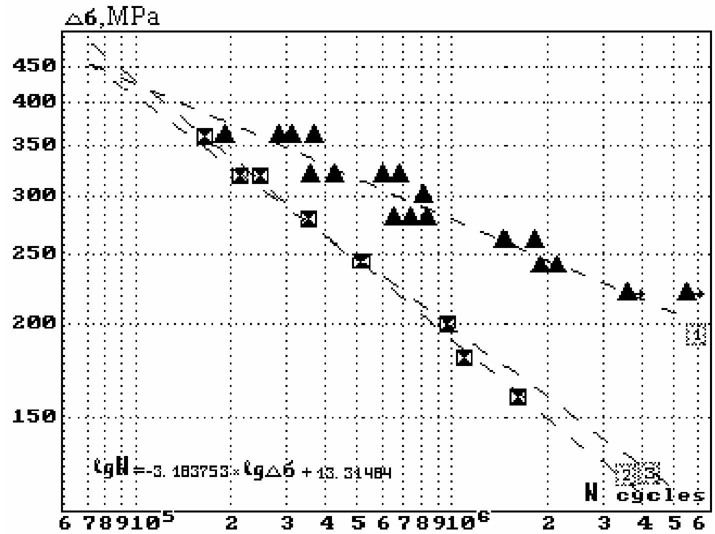


Figure 1. Fatigue curves of butt welded joint in low-carbon steel [2]: 1 - without residual stresses; 2,3 - with high tensile residual stresses (fatigue testing and computation)

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 $N=2\cdot10^6$ 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.

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 (UP) [1,3]. The results of fatigue testing of welded specimens in as-welded condition and after application of UP are presented on 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 [3].

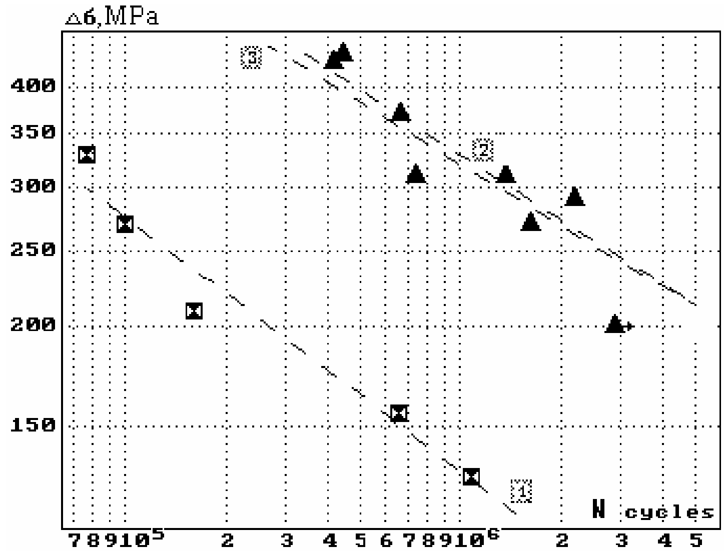


Figure 2. Fatigue curves of non-load caring fillet welded joint in high strength steel [3]:
1 - in as welded condition;
2,3 - after application of ultrasonic peening (fatigue testing and computation)

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. Despite the fact that the RS 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 RS on the fatigue life of parts and structural elements depends greatly not only on the level or RS, but also on the mechanical properties of materials used, the type of welded joints, the parameters of cyclic loading and other factors [1-3]. 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 of welded elements the presented data correspond to the fatigue strength of real welded joints including the effects of welding technology, type of welded element and welding RS [4]. Nevertheless, in many cases there is a need to consider the influence of welding RS 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 RS, analysis of effects of such factors as overloading, spectra loading and application of the improvement treatments.

*Residual Stress Management: Measurement, Fatigue Analysis and Beneficial Redistribution*

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 [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/Assembly
- Application of Stress-Relieving Techniques

The main stages of RSM are briefly considered in this paper with the emphasis on examples of practical application of new engineering tools for RSM that include the ultrasonic complex for RS measurement and a technology and, based on it, compact system for redistribution of RS by ultrasonic peening.

## 2. Measurement of Residual Stresses

Over the last few decades, various quantitative and qualitative methods of RS analysis have been developed [6]. 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 measurement. The most developed non-destructive methods are:
- the X-ray and neutron diffraction methods,
- the ultrasonic techniques,
- the magnetic methods.

Figure 3. The Ultrasonic Computerized Complex for measurement of residual and applied stresses

*Ultrasonic Method and Equipment for Residual Stress Measurement*

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 [6,7]. Some of the advantages of the ultrasonic technique are associated with the facts that the instrumentation is convenient to use, quick to set up, portable, inexpensive and free of radiation hazards. In the proposed in [7] 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 RS. 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.

The Ultrasonic Computerized Complex (UCC) for residual stress analysis [7] includes a measurement unit with supporting software and a laptop (optional item) with an advanced database on RS and an expert system for analysis of the influence of residual stresses on the fatigue life of welded components. The developed device with gages/transducers for ultrasonic RS measurement is presented in Figure 3.

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 (Figure 3) 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 $\sigma_y$ (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: 7 kg.

*Measurement of Residual Stresses in Welded Elements*

The developed ultrasonic equipment could be used for RS measurement for both laboratory and field conditions [7-9]. For instance, the RS were measured in 1000x500x36 mm specimen, representing a butt-welded element of a large transonic wind tunnel. The distribution of biaxial RS was investigated in X (along the weld) and Y directions after welding and in the process of fatigue testing of a specimen [9]. Figure 4 represents the distribution of longitudinal (along the

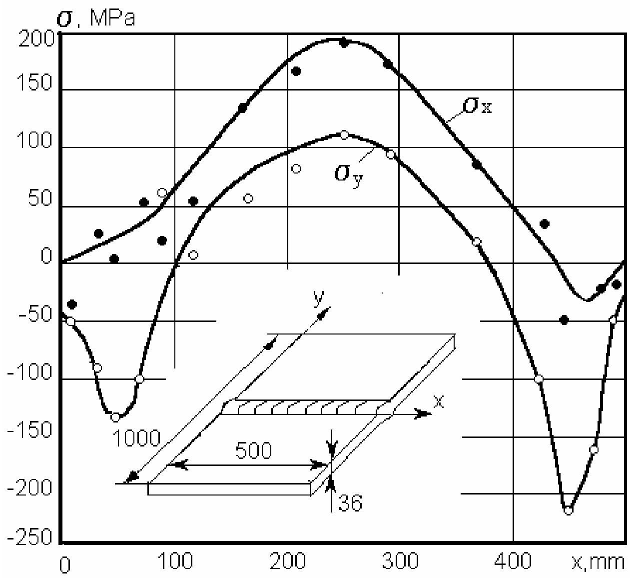


Figure 4. Distribution of longitudinal (along the weld) and transverse components of residual stresses along the butt weld toe [9]

weld) and transverse components of RS along the weld toe before fatigue testing. Both components of RS reached their maximum levels in the central part of a specimen: longitudinal - 195 MPa, transverse - 110 MPa.

**3. Residual Stress in Fatigue Analysis**

The effect of RS on fatigue behavior of welded element could be analyzed based on experimental studies and/or computation (Figures 1 and 2). One of the examples of computation of the effect of RS on fatigue life of welded elements is presented in Figure 5.

These data show how the redistribution of residual stresses will affect the fatigue performance of welded joint. The calculated fatigue curves for the transverse loaded butt weld at R=0 with different levels of the initial RS are shown. The fatigue curve of the welded element will be located between lines 1 and 2 in case of partial relieve of harmful tensile RS (line 3 and line 4). The decrease of the tensile RS from initial high level to 100 MPa causes, in this case, an increase of the limit stress range at $N=2\times10^6$ cycles from 100 MPa to 126 MPa.

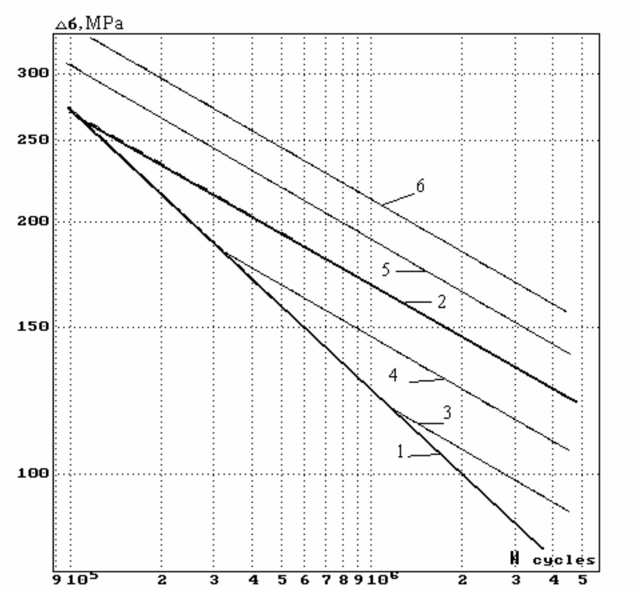


Figure 5. Fatigue curves of transverse loaded butt weld at R=0:
1 - with high tensile residual stresses; 2, 3, 4, 5 and 6 - with residual stresses equal to 0 MPa, 200 MPa, 100 MPa,-100 MPa and -200 MPa

The relieving of the RS 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 0.52σy. As a result, this originally fatigue class FAT 100 welded element could be considered after relieve of RS as the fatigue class FAT 125 element in the multi-cycle region ($N>10^6$ cycles of loading) [4]. After modification of welding RS, 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 (Structural Detail No. 211) or longitudinal butt weld (Structural Details No. 312 and 313) [4]. Introducing of the compressive RS in the weld toe zone can increase the fatigue strength of welded elements even to a larger extend (line 5 and line 6 in Figure 5).

The results of computation presented in Figure 6 show the effect of the redistribution of RS by the UP on 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 RS) were used as initial fatigue data for calculating the effect of the UP. The fatigue strength of certain welded element in steels of different strength in as-welded condition is represented by a universal fatigue curve [2,4].

Four types of steels were considered for fatigue analysis: Steel 1 - ($\sigma_y$ = 270 MPa, $\sigma_u$ = 410 MPa); Steel 2 - ($\sigma_y$ = 370 MPa, $\sigma_u$ = 470 MPa); Steel 3 - ($\sigma_y$ = 615 MPa, $\sigma_u$ = 747 MPa) and Steel 4 - ($\sigma_y$ = 864 MPa, $\sigma_u$ = 897 MPa). Line 1 in Figure 6 is the universal fatigue curve of considered welded joint for all types of steel in as-welded condition, determined experimentally. Lines 3, 5, 7 and 9 are the calculated fatigue curves for the welded joint after application of the UP for Steel 1, Steel 2, Steel 3 and Steel 4, respectively.

As can be seen from Figure 6, the higher the mechanical properties of the material - the higher the fatigue strength of welded joints after application of the UP. The increase in the limit stress range at $N=2\times10^6$ cycles under the influence of 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 UP with the increase in mechanical properties of the material used.

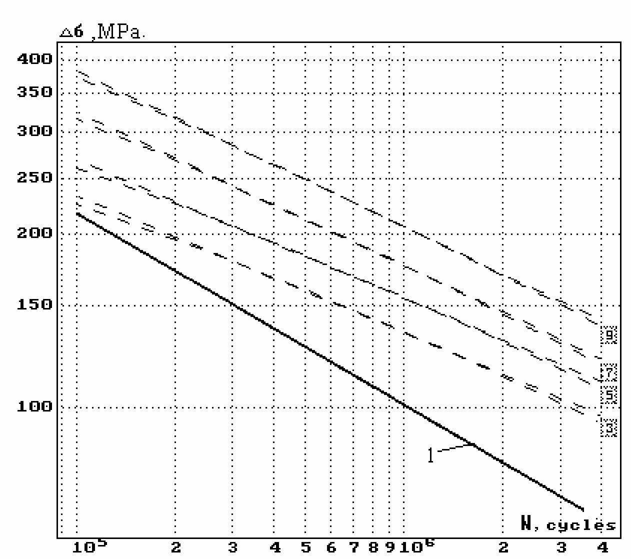


Figure 6. Fatigue curves of non-load-carrying fillet welded joint:
1 - in as-welded condition for all types of steel;
3, 5, 7 and 9 - after application of the UP to Steel 1,Steel 2, Steel 3, and Steel 4

**4. Residual Stress Modification. Ultrasonic Peening**

One of the new and promising processes for effective redistribution of RS is Ultrasonic Peening (UP) [1, 10-12]. During the different stages of its development the UP process was also known as ultrasonic treatment (UT) [13], ultrasonic impact treatment (UIT) [14-16], ultrasonic impact peening (UIP) [17-18]. The beneficial effect of UP is achieved mainly by relieving of harmful tensile RS and introducing of compressive RS into surface layers of metals and alloys, 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 as compared with traditional techniques such as grinding, TIG-dressing, heat treatment, hammer peening, shot peening etc. [2,11,12].

Figure 7. Using of basic UP system for fatigue life improvement of tubular welded joint [12].

The UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material. The developed system for UP treatment (total weight - 7 kg) includes an ultrasonic transducer, a generator and a laptop (optional item) with software for UP optimum application - maximum possible increase in fatigue life of parts and welded elements with minimum cost, labor and power consumption[10-12]. In general, the basic UP system shown in Figure 7 could be used for treatment of weld toe or welds and larger surface areas if necessary.

Figure 8 shows the basic set of working heads for different applications of UP. The working head could be easily replaced, if necessary. Four different working heads are provided with the standard UP package:

- one four-pins working head with the pin's diameter of 3 mm,
- one three-pins working head with the pin's diameter of 4 mm,
- one seven-pins working head with the pin's diameter of 5 mm,
- one single-pin working head with the pin's diameter of 4 mm.

Figure 8**.** Basic set of the changeable working heads

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures [11]. The results of fatigue testing of large-scale welded samples imitating the transverse non-load-carrying attachments where the UP was applied to specimens in as-welded condition and also after 50% of expected fatigue life are presented on Figure 9. The UP caused a significant increase in fatigue strength of the considered welded element for both series of UP treated samples. The increase in limit stress range (at $N=2\cdot10^6$ cycles) of welded samples is 49% (from 119 MPa to 177 MPa) for UP treated samples before fatigue loading and is 66% (from 119 MPa to 197 MPa) for UP treated samples after fatigue loading, with the number of cycles corresponding to 50% of the expected fatigue life of the samples in as-welded condition. The higher increase of fatigue life of UP treated welded elements for fatigue curve #3 could be explained by a more beneficial redistribution of RS and/or "healing" of fatigue damaged material by UP in comparison with the fatigue curve #2.

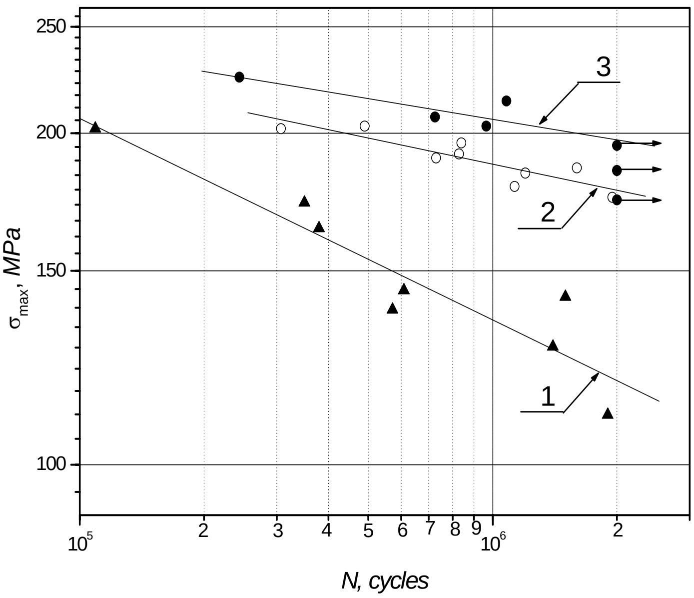


Figure 9. Fatigue curves of welded elements (transverse non-load-carrying attachment):
1 – in as welded condition, 2 – UP was applied before fatigue testing,
3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition.

The developed computerized complex for UP was successfully applied in different applications for increasing of the fatigue life of welded elements, elimination of distortions caused by welding and other technological processes, residual stress relieving, increasing of the hardness of the surface of materials and surface nanocrystallization. The areas/industries where the UP was applied successfully include: Railway and Highway Bridges, Construction Equipment, Shipbuilding, Mining, Automotive and Aerospace.

## 5. Summary

1. Residual stresses play an important role in operating performance of materials, parts and welded elements. Their effect on the engineering properties of materials such as fatigue and fracture, corrosion resistance and dimensional stability can be considerable. The influence of residual stresses on the multi-cycle fatigue life of welded elements can be compared with the effects of stress concentration. The residual stresses, therefore, should be taken into account during design, fatigue assessment, manufacturing and repair of welded elements and structures.

2. Certain progress has been achieved during the past few years in improvement of traditional techniques and development of new methods for residual stress management. 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 software for analysis of the effect of residual stresses on the fatigue life of welded elements and structures were recently developed and verified for different industrial applications.

3. The beneficial redistribution of the residual stresses is one of the efficient ways of fatigue improvement of welded elements. The ultrasonic peening is the most effective and economical technique for increasing of the fatigue strength of 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 parts and welded elements, subjected to fatigue loading.

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