Effect of Ultrasonic Peening on Microhardness and Residual Stress in Materials and Welded Elements

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ABSTRACT

The development of the Ultrasonic Peening (UP) technology was a logical continuation of the work done before directed on the investigation and further development of known techniques for surface plastic deformation such as shot peening, hammer peening, needle peening etc. The UP technique is based on the combined effect of the high frequency impacts of the special strikers and ultrasonic oscillation in treated material. The UP was applied successfully for the increasing of the fatigue life of parts and welded elements, eliminating of distortions caused by welding and other technological processes, residual stress-relieving, increasing of the hardness of materials. The results of fatigue testing showed that UP is the most efficient technique for increasing the fatigue life of welded elements as compared to such existing improvement treatments as grinding, TIG-dressing, shot peening, hammer peening, etc. An overview of the UP techology is given with the initial results of investigation of microhardness and residual stresses in UP treated materials and welded elements discussed as well in this paper.

1. Introduction.

Ultrasonic Peening of parts and welded elements is a comparatively recent and promising technology that has emerged from extensive development by engineers mostly from Ukrainian and Russian research institutes. The Ultrasonic Peening (UP) produces a number of beneficial effects in metals and alloys. Foremost among these is increasing the resistance of materials to surface-related failures, such as fatigue and stress corrosion cracking. One of the promising ways of industrial application of UP is the post-weld treatment of welded elements and structures. The results of fatigue testing showed that UP is the most efficient and economical technique for increasing the fatigue life of welded elements as compared to such existing improvement treatments as grinding, TIG-dressing, shot peening, hammer peening etc.

The development of the UP technology was a logical continuation of the work done before directed on the investigation and further development of known before techniques for surface plastic deformation such as shot peening, rolling, hammer peening etc [1]. During the different stages of its development the UP process was also known as “ultrasonic treatment”, “ultrasonic impact technique/technology, “ultrasonic impact peening” or “ultrasonic impact treatment”.

The modern equipment for UP is based on known technical solutions of working heads for hammer peening known from 40’s. At that time and later a number of different multi-strikers working heads were developed for impact treatments of parts and welded elements by using mostly pneumatic driven equipment. In order to more effectively perform the treatment of parts and welded elements by using pneumatic and other types of equipment, the special strikers made of high-strength materials are used. The effective impact treatment is provided when the strikers are not connected to the tip of actuator but are located between the actuator and treated material.

For the first time, the possibility of using ultrasonic technology for improving the service properties of welded structures was described in 1959 by A.V. Mordvintseva [3]. She analyzed the using of ultrasonic treatment for relieving of welding residual stresses.

Initially in the equipment for ultrasonic treatment the deforming elements-strikers were attached to the tip of the ultrasonic transducer [3,4]. In this case the ultrasonic contact with the metal surface is provided by a whole instrument with the force of 100 - 500 N. Such ultrasonic systems can be used, for example, for finishing treatment of metal surfaces. More effective surface deformation by using of the energy of ultrasound is achieved when the strikers are not connected with ultrasonic transducer but are located near the transformer's tip. This technique was proposed in former Soviet Union and USA at the end of 60's [5-9] and, later, different types of ultrasonic equipment were developed based on this idea. In the case of so-called "intermediate" element-striker the force of 30 - 50 N is required for treatment of materials.

At the end of 60's and beginning of 70's the intensive investigation of the influence of high power ultrasonics on the properties of materials and welded elements was initiated at the Institute of Metal Physics (Kiev, Ukraine) [10-12]. The intermediate element-striker was employed for surface strengthening and plastic deformation of materials. This striker oscillated in the gap between the end of the ultrasonic transducer and treated specimen. The changes in the mechanical properties of the materials and texture under the action of the ultrasonic treatment were analyzed [13]. The results of these studies initiated the development of the UP technology. Practically, at the same time the efficiency of the application of intermediate element during ultrasonic treatment for plastic deformation of materials was analyzed in the number of research centers in former USSR and USA [5-18].

At the very beginning of 70's the collaboration between the Paton Welding Institute (PWI) and the Institute of Metal Physique (IMP) in the application of high power ultrasonics and high frequency impacts for improvement treatment of welded elements and structures and relieving of welding residual stresses was started. The first results of this collaboration in the field of ultrasonic impact treatment of welded elements and structures were published in 1974 [14] and later [15, 17-21].

In 1982 the PWI intensifies its efforts in the development of the application of ultrasonic impact technology for increasing the fatigue life of welded elements and structures. For the first time the PWI proposed to use UP for treatment of only the zone of transition from weld to base metal. The oscillating sphere was used for plastic deformation of weld toe creating the radius equals to the radius of sphere. This kind of UP treatment provided significant increase of the fatigue life of welded elements – from 15 to 20 times depending on the level of cyclic loading. The standard ultrasonic equipment USG-10 (power supply 10 kW) and vibrating sphere with the diameter 16 mm were used at that time for UP [22]. The formation of so-called "groove" in the weld toe zone for optimum fatigue life improvement of welded elements by UP was proposed by PWI [23,24]. Later, a number of industrial applications and other aspects of UP technology were developed at PWI. For example, the effectiveness of the UP application for the increase of the fatigue life of welded elements subjected to cyclic compression was analyzed by testing of large-scale welded elements of construction equipment as well as welded elements of bridges [23,25].

Starting form 1987 the results on the development of the UP technology were presented by PWI in some East European countries [26, 27] and later for western scientific and engineering communities [28-33].

In 1993 the results of the development of the UP technology and fatigue assessment of welded specimens after application of the UP were presented for the first time at the International Institute of Welding by the scientists form PWI [34]. Later, more results on the development of the UP technology and fatigue testing of welded specimens, specification for weld toe improvement by UP and also the results of the verification of the efficiency of the UP technology conducted in the frame of IIW test program were presented with participation of the PWI [35-37].

Presently, the field of high power ultrasonics enjoys a renewed interest, and intensive research and development activity in industrial application of high power ultrasonics and particularly ultrasonic impact technique are conducted in Ukraine, Russia, Canada, USA and China [38-44]. During such activity the principles of optimum UP application and corresponding software were developed. The technology and equipment for UP were adapted for different industrial applications. The Computerized Complex for UP of materials, parts and welded elements was developed recently based on using of the high efficient optimized piezoelectric transducers. The complex consists of the compact ultrasonic transducer, generator and laptop with expert system for UP optimum application: maximum possible increase in fatigue life of welded elements with minimum cost, labor and power consumption [45,46].

2. Enhancement of Engineering Properties of Materials and Welded Elements by Ultrasonic Peening

Intense levels of high frequency acoustic energy, or high power ultrasonics, have found practical use in many industrial processes. In most industrial applications, high power ultrasonics involves power levels of hundreds to thousands of watts, and ultrasonic systems operating in the frequency ranges from 15 kHz to 100 kHz. Typical amplitudes range from about 10 to 40 microns. Such ultrasonic system, for instance, operating at 20 kHz creates a cyclic acceleration of around 50,000 g (acceleration of gravity).

One of the promising directions in using of the high power ultrasonics for industrial applications is the Ultrasonic Peening (UP) of materials, parts and welded elements. The UP technique is based on the combined effect of the high frequency impacts of the special strikers and ultrasonic oscillation in treated material.

In the fatigue improvement the beneficial effect is achieved mainly by introducing of the compressive residual stresses into surface layers of metals and alloys, decrease in stress concentration of weld toe zones and the enhancement of the mechanical properties of the surface layer of the material. A schematic view of the cross section of material/part improved by UP is shown on Figure 1 and description of the UP benefits is presented in Table 1.

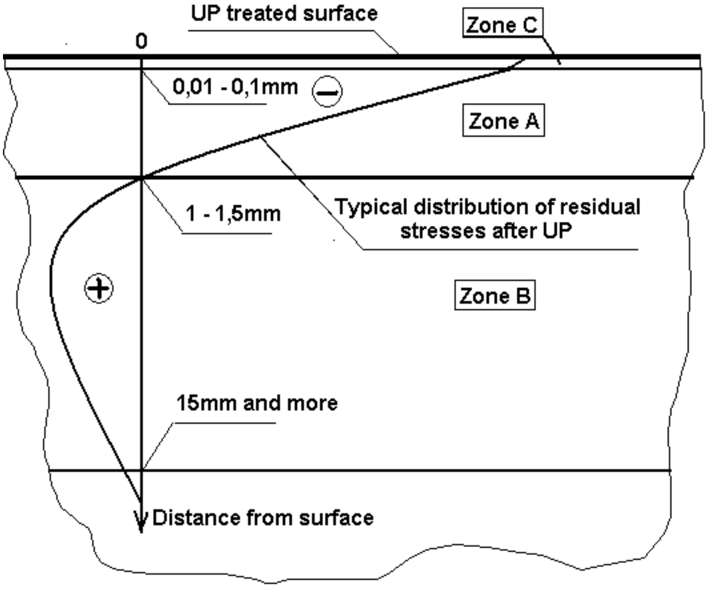

Figure 1. Schematic view of the cross section of material/part Improved by Ultrasonic Peening

Table 1. Zones of Material/Part Improved by Ultrasonic Peening

Zone	Description of zone	Penetration (distance from surface), mm	Improved characteristics
A	Zone of plastic deformation and compressive residual stresses	1 –1,5 mm	Fatigue, corrosion, wear, distortion
B	Zone of relaxation of welding residual stresses	15 mm and more	Distortion, crack propagation
C	Zone of nanocrystallization (produced at certain conditions)	0,01 – 0,1 mm	Corrosion, wear, fatigue at elevated temperature

Figure 2 and Figure 3 show the concept of the fatigue life improvement of welded elements by UP. In case of welded elements for significant increase of the fatigue life it is enough to treat only the weld toe zone – the zone of transition from base metal to the weld and to produce of the so-called groove [23, 24].

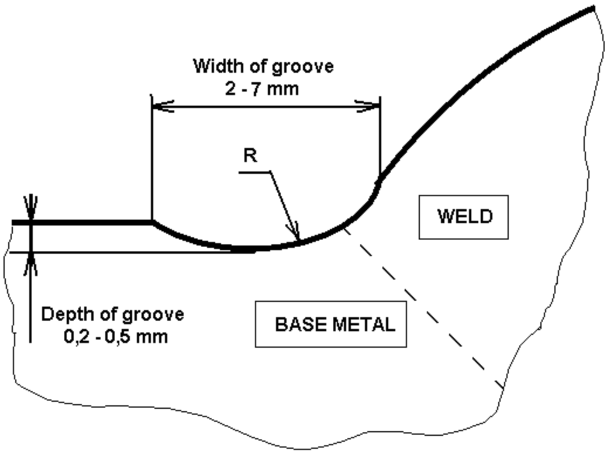

Figure 2. Profile of weld toe improved by Ultrasonic Peening

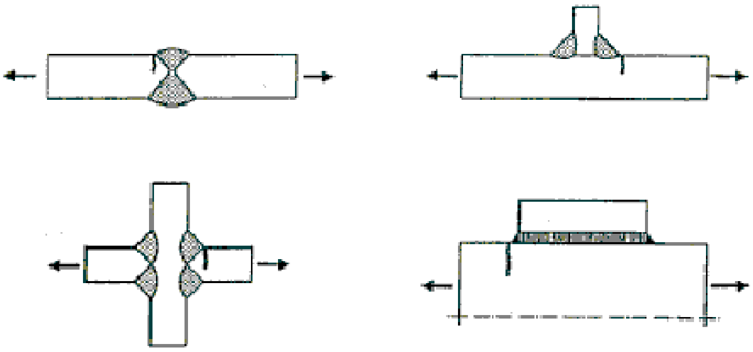

Figure 3. Examples of welded elements suitable for Improvement
(in accordance with IIW Doc. XIII-1815-00)

3. Equipment for Ultrasonic Peening

There are two general types of ultrasonic transducers which can be used for UP: magnetostrictive and piezoelectric. Both accomplish the same task of converting alternating electrical energy to vibratory mechanical energy but do it in a different way (Figue 4). In magnetostrictive transducer the alternating electrical energy from the ultrasonic generator is first converted into an alternating magnetic field through the use of a wire coil. The alternating magnetic field is then used to induce mechanical vibrations at the ultrasonic frequency in resonant strips of magnetostrictive material.

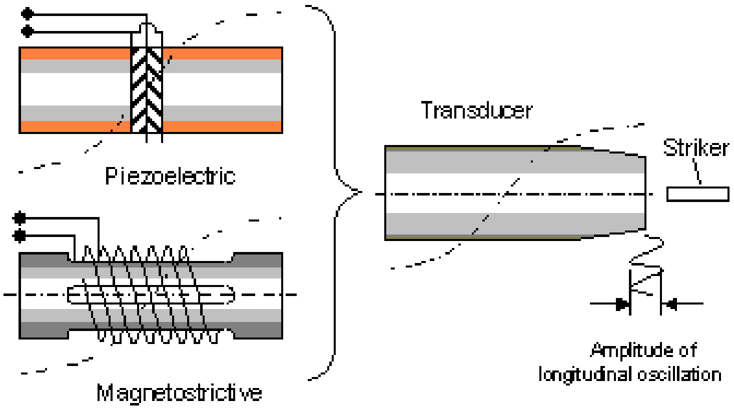

Figure 4. Schematic view of transducer for Ultrasonic Peening.

Magnetostrictive transducers are generally less efficient than the piezoelectric ones. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical. Some efficiency is lost in each conversion. Magnetic hysteresis effects also detract from the efficiency of the magnetostrictive transducer. In addition, the magnetostrictive transducer for UP needs forced water-cooling. The equipment in this case is relatively heavy and expensive.

Piezoelectric transducers convert the alternating electrical energy directly to mechanical energy through the piezoelectric effect. Today's piezoelectric transducers incorporate stronger, more efficient and highly stable ceramic piezoelectric materials, which can operate under the temperature and stress condition. Piezoelectric transducers are reliable today and can reduce the energy costs for operation by as much as 60%.

Due to the high energy efficiency of peiezoelectric treansdusers the effect in fatigue life improvement is practically the same by using of the magnetostrictive transducer with power consumption of 1000 Watts and optimized peiezoceramic treansdusers with power consumption of only 250 Watts (Figure 5).

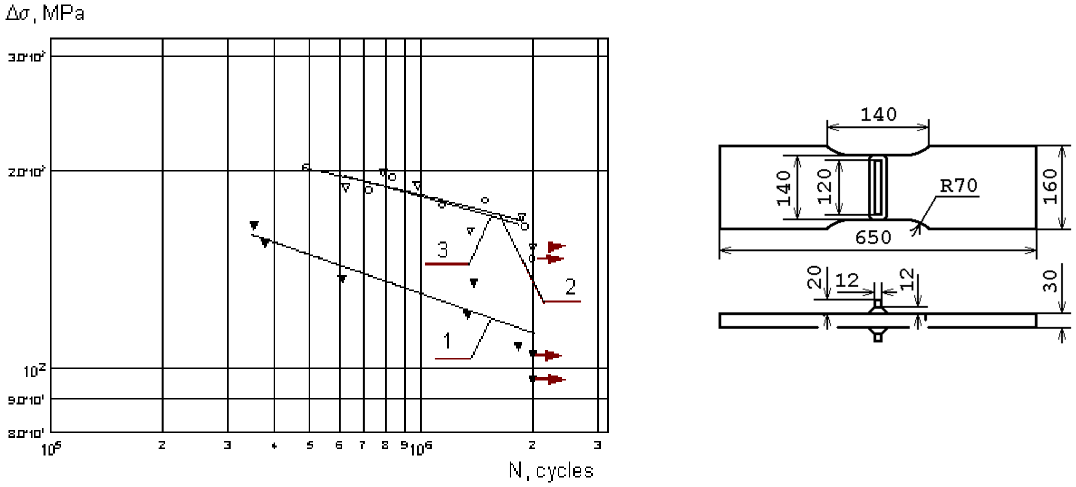

Figure 5. Fatigue curves of non-load carrying fillet welded joint:
1 - in as-welded condition;
2 and 3 - after application of the UP by using magnetostrictive transducer (P = 1 kW) and optimized piezoelectric transducer (P = 0,25 kW)

A Computerized Complex for UP of materials, parts and welded elements was developed recently based on using of the high efficient and reliable piezoelectric transducers. The Complex consists of the compact ultrasonic transducer, generator and laptop with Expert System for UP optimum application (Fig. 6).

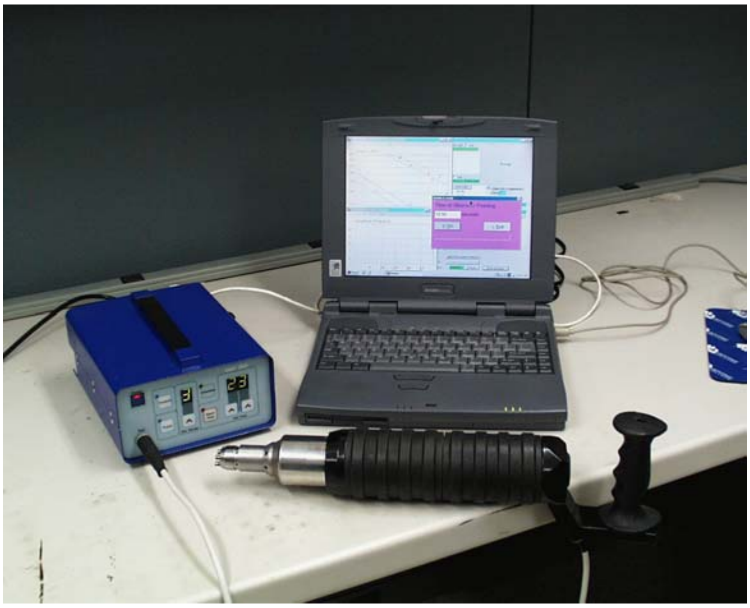

Figure 6. Computerized Complex for Ultrasonic Peening of parts and welded elements

4. Effect of Ultrasonic Peening on Microhardness of Materials

The effect of the UP treatment on the microhardness of metal: a widely used engineering material, the AISI 304 stainless steel was considered. A distribution of microhardness as a function of the depth – distance from the treated surface of material was analysed.

4.1 Samples

The material used was an AISI 304 stainless steel with the following chemical compositions: 0.08 C, 18.20 Cr, 8.60 Ni, 1.10 Mn, 0.60 Si, 0.020 P, 0.010 S and balanced Fe. Two cross-sectioned samples from the AISI 304 were prepared. In the first sample a plane square area of 25mm x 25mm was subjected to a UP treatment. The second sample was used to produce by UP so-called "groove" which is used fatigue life improvement of weld toe zone. After the UP treatment the samples were cross sectioned, moulded in a resin, and then polished to be as smooth as possible for the microhardness tests.

4.2 Measurement of Microhardnes

A Digital Microhardness Tester MMT3 (Buelher) was used with the Vickers indenter to determine the Hardness Vickers of the UP treated samples. The procedure followed the standard ASTM E384-89 (Standard Test Method for Microhardness of Materials). The value of the test load was 100 gf and it lasts 15 sec. The distance between each indentation was minimum 3 times the length of the main diagonal of the identation, as indicated in the standard.

4.3 Results

4.3.1 The groove sample

The profile of microhardness in the sample with the "groove" produced by UP is presented on Figure 7.

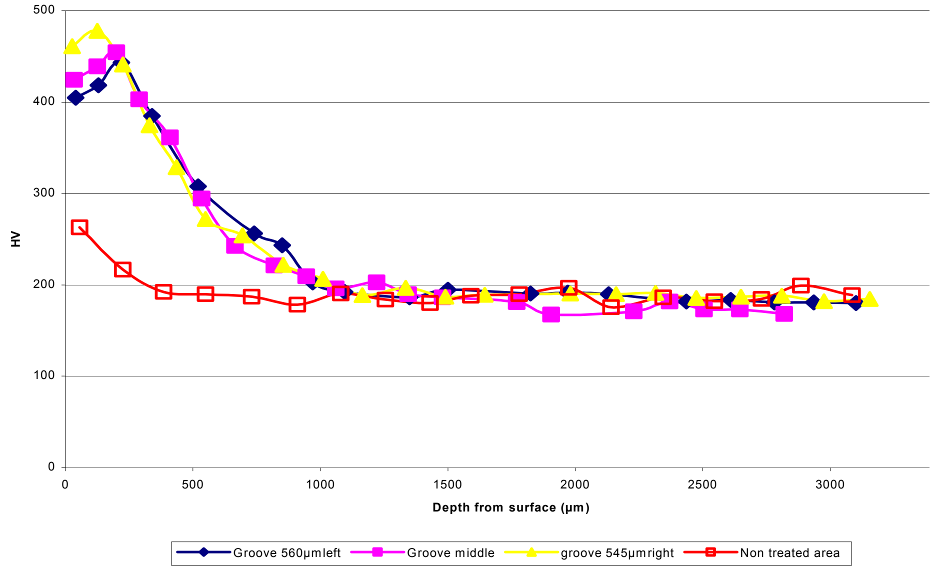

Figure 7. Profile of microhardness distribution in the different locations of the sample with the "groove". produced by Ultrasonic Peening

It could be seen, that the microhardness in the bottom of the groove is significantly higher than in a non-treated area near the top surface layer (the largest difference is about 200 at the depth of 150µm). There is an insignificant increase of microhardness with the increase of the depth for the first 200 µm and then, the microhardness decreases to be stabilized at nearly 1000-1500µm in depth.

4.3.2 The plane sample

The profile of microhardness in the plane sample after UP is presented on Figure 8. Data presented on figure 7 and Figure 8 show that the depth of plastic deformation zone after UP treatment is 1 - 1,5 mm.

5. Residual Stress Measurement

Residual stresses are one of main factors detemining the efficiency of Ultrasonic Peening in fatigue life improvement. The results of residual stress measurement by different experimental techniques in the UP treated specimens are presented on Figure 9-12.

5.1. Ultrasonic Method

Ultrasonic method [47] was used for residual stress measurement in the model of welded element – plate with the welded bead on one side (Figure 9). Averaged through thickness of plate residual stresses were measured by using bulk ultrasonic waves before and after UP of the welded bead. The distribution of residual stresses along the width of specimen in this case imitates the in-depth destribution of residual stresses after UP of real welded joint.

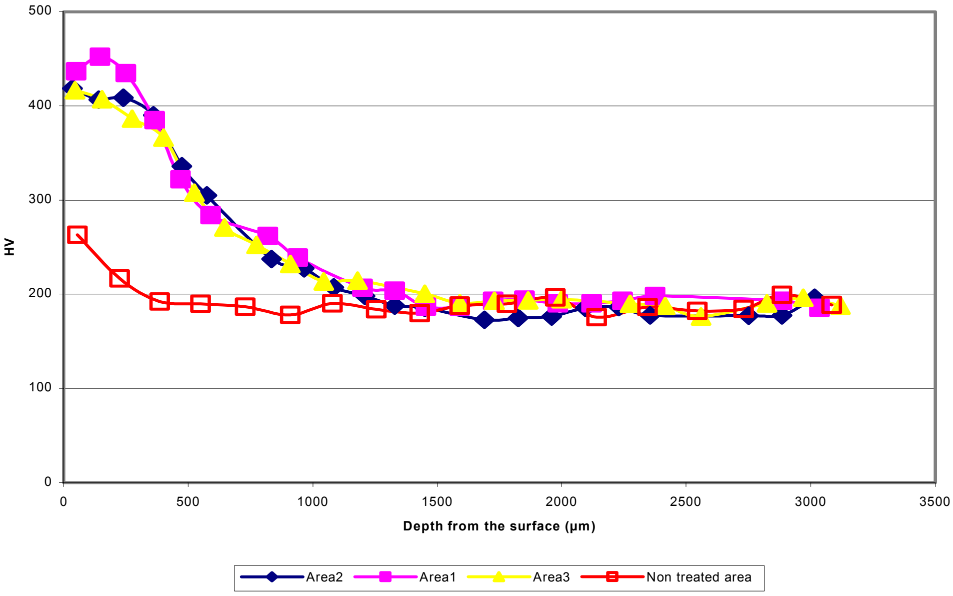

Figure 8. Profile of microhardness distribution in the different locations of the plane sample after Ultrasonic Peening.

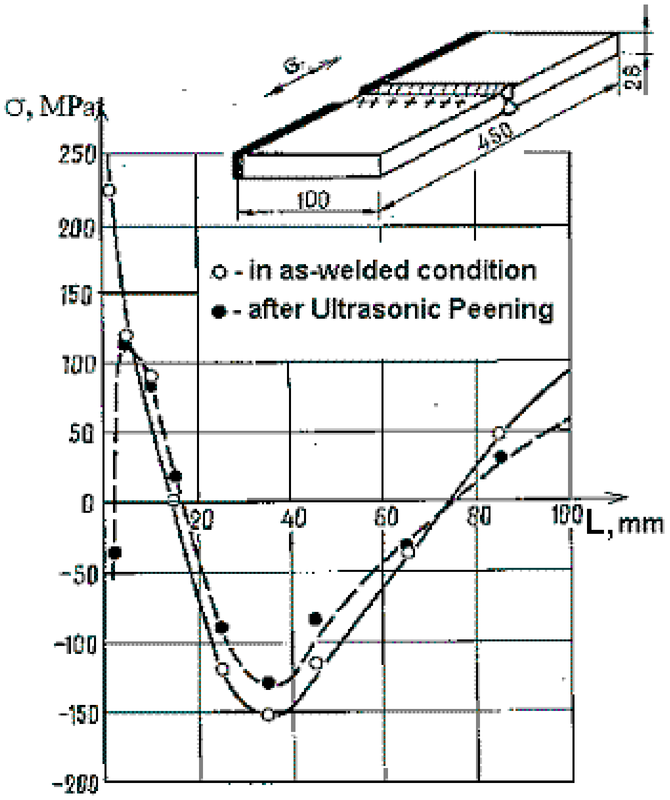

Figure 9. Distribution of residual stresses (averaged through thikness) in the model of welded element before (○) and after (●) Ultrasonic Peening

5.2. X-Ray Method

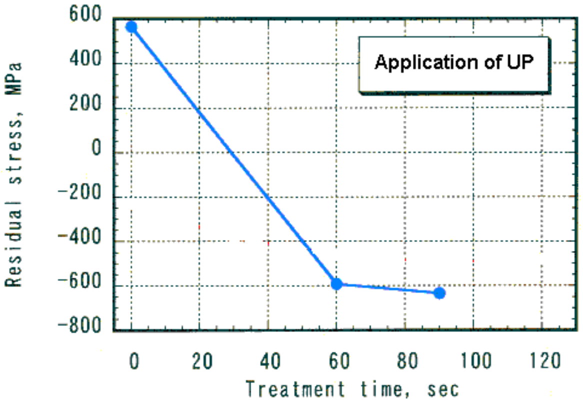

Figure 10. Relieving of induced by EDM harmful tensile residual stresses and introducing of beneficial compressive residual stresses in surface layers of material by Ultrasonic Peening

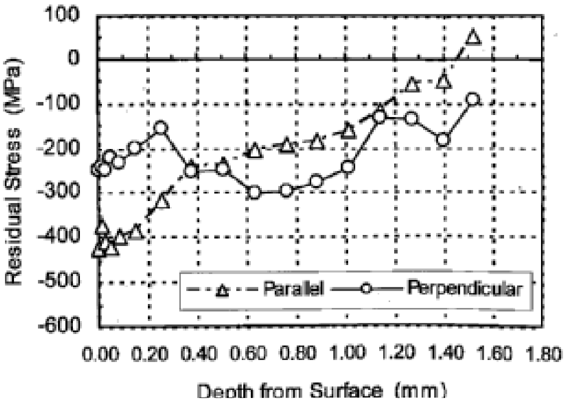

Figure 11. Distribution of residual stresses depending on the distance from the treated surface of material after ultrasonic impact treatment [42].

5.2. Neutron Diffraction Method

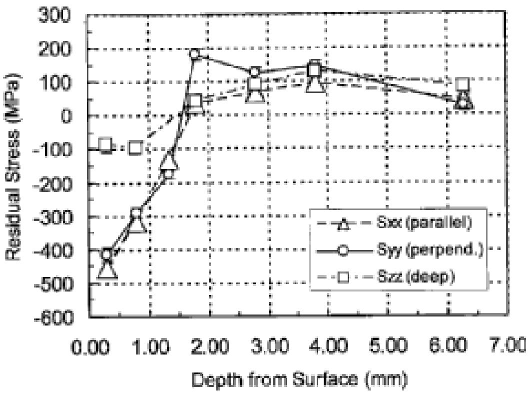

Figure 12. Distribution of residual stresses depending on the distance from the treated surface of material after ultrasonic impact treatment [42].

The results of residual stress measurement by different techniques show that UP causes relieving of harmful tensile residual stresses and inducing beneficial compressive residual stress with the depth of penetration of about 1,5 mm what is well correlated with the depth of plastic deformation determined by microhardness measurements.

Summary

1. One of the promising directions in using of the high power ultrasonics for industrial applications is the Ultrasonic Peening (UP) of materials, parts and welded elements. The UP technique is based on the combined effect of the high frequency impacts of the special strikers and ultrasonic oscillation in treated material. The unique mechanism of UP and developed compact equipment provide the highest increase in fatigue life of welded elements as compared with the application of existing improvement treatments such as grinding, TIG-dressing, shot peening, hammer peening.

2. An advanced computerized complex for UP of parts and welded elements was developed recently based on using of the piezoelectric transducer. The complex consists of the compact ultrasonic transducer, generator and laptop with Expert System for UP optimum application: maximum possible increase in fatigue life of welded elements with minimum cost, labor and power consumption.

3. The UP provide efficient relieving of harmful tensile residual stresses and inducing of beneficial compressive resdidual stresses as well as increase in microhardness of the surface layers of material. The depth of plastic deformation zone after UP is approximately the same as the depth of induced compressive residual stresses: 1-1,5 mm.

4. The developed computerized complex for UP could be used in different applications for increasing of the fatigue life of parts and welded elements, eliminating of distortions caused by welding and other technological processes, residual stress relieving, increasing of the hardness of the surface of materials and surface nanocrystallization.

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