Computerized Complex for Ultrasonic Peening of Parts and Welded Elements

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Biographical Sketch

Dr. Yuri Kudryavtsev obtained his M. Sc. degree in mechanical engineering from the National Technical University (KPI), Kiev, Ukraine in 1977 and his Ph.D. from the Paton Welding Institute of the Ukrainian Academy of Sciences in 1984, studying the welding residual stresses, improvement treatments and their effect on fatigue life of welded elements. Dr. Kudryavtsev has 25 years of experience and he is a recognized authority in the field of:

- fatigue and fracture analysis of welded elements and structures,
- residual stress analysis,
- development and practical application of the improvement treatments of welded elements,
- design and manufacturing of parts and welded elements with enhanced fatigue performance.

His current research efforts are concentrated on the development and practical application of:

- technology, equipment and software for ultrasonic peening of parts and welded elements,
- ultrasonic computerized complex for residual and applied stress measurement,
- predictive model and software for analysis of the effect of residual stresses and improvement treatments on the fatigue life of welded elements and structures.

During 18 years Dr. Y. Kudryavtsev was a Senior Scientist in the field of welded structures at the Paton Welding Institute (Kiev, Ukraine) and beginning from 1996 he is a Head of Stress Engineering Division at the Integrity Testing Laboratory Inc. (Markham, Canada).

Dr. Kudryavtsev has authored over 80 publications and he holds six patents.

Abstract

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

Application of UP treatment may increase/restore the designed stress range of welded elements up to the fatigue strength of the base material. The increase of fatigue life by UP is achieved

mainly by relieving of harmful tensile residual stresses and introducing of 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.

1. Introduction

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 UP process is also known as “ultrasonic treatment”, “ultrasonic impact peening” or “ultrasonic impact treatment”. In order to transmit the ultrasonic vibration energy into the treated material the special strikers made of high-strength materials are used. The effective surface deformation by the UP is provided when the strikers are not connected with ultrasonic transducer but are located near the transformer’s tip.

The modern equipment for UP is based on known technical solutions of working heads for hammer peening known from 40’s. At that time a number of different multi-strikers working heads were developed for improvement treatments of parts and welded elements.

In parallel to the development of different impact techniques for surface treatment of materials and welds such as hammer peening and shot peening, after WWII the intensive R&D directed on using of high power ultrasound for the treatment of the materials, parts and welded elements were conducted mainly in USSR and USA. Only in former USSR there were more than ten independent research and scientific centers that worked in the above-mentioned. As a result of the efforts of these centers the different tools were developed based on using ultrasound technique for surface plastic deformation of materials and welded elements.

Until now, there is an intensive research and development activity in industrial application of high power ultrasonics worldwide. Significant number of publications and patents on application of ultrasound for improvement treatments of materials, parts, welded elements and structures are known. The Computerized Complex for Ultrasonic Peening of Parts and Welded Elements developed in the frame of the cooperation between Paton Welding Institute (Ukraine), Institute of Metal Physique/Ultramet (Ukraine) and Integrity Testing Laboratory Inc. (Canada) and some relevant publications are described in this paper.

2. Development of the Technology and Compact Equipment for UP

Beginning from 60’s the Paton Welding Institute (Kiev, Ukraine) is actively involved in the improvement of the traditional techniques and the development of the new advanced improvement treatments of welded elements and structures. The results of this work including analysis and further development of the improvement treatments of welded elements based of surface plastic deformation are presented in more than 200 publications and 20 patents.

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 with one or multi-strikers working heads etc [1]. In case of hammer peening the pneumatic and electro-mechanical actuators were used for increasing of the fatigue life of welded elements.

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 Physique (Kiev, Ukraine) [2-4]. The so-called "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 [5]. 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.

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 treatment of welded elements and structures were published in 1974 [6] and later [7-10, P1-P3 etc.].

Beginning from 1982 the PWI intensifies its efforts in the development of the application of ultrasonic technology for increasing the fatigue life of welded elements and structures. For the first time it is proposed to treat only the weld toe zone with the width of 4 mm and create so-called "groove" for significant increase of the fatigue life of welded elements – up to 20 times. The standard ultrasonic equipment USG-10 (power supply 10 kW) and vibrating ball with the diameter 16 mm were used for improvement treatment.

Beginning from 1983 the PWI started collaboration with the Northern Machine-Building Enterprise - SMP (Severodvinsk, Russia) in the development of ultrasonic treatment for increasing of the fatigue life of welded elements of high strength steel. The recommendations for the improvement treatment of welded elements made of high strength steel by UP were developed in the frame of this collaboration [11-13]. The increase of the fatigue life by UP was achieved by the following factors: relieving of harmful tensile residual stresses and introducing of beneficial compressive residual stresses, decreasing of stress concentration and changes of the mechanical properties of the surface layer of material [13-16]. The different aspects of the UP technology were developed and patented by PWI jointly with the SMP and GNPP "Kvant" (Severodvinsk, Russia) [P4-P7].

During the period of 1987-2001 a number of industrial applications and other aspects of UP technology were investigated at PWI. A number of welded elements after UP were tested and recommendation for the design and improvement of the fatigue strength of welded elements of cryogenic wind tunnel was developed [17]. 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 in as welded condition and after application of UP [18]. The effectiveness of the UP was analyzed and the recommendations for its practical application were developed for tubular welded connections and for welded elements of bridges [19-21].

At the PWI the comparison of the efficiency of UP of welded elements made from aluminum alloys by using magnetostrictive and peizoceramic ultrasonic transducers was performed. The influence of different parameters of UP on the fatigue life of welded elements were analyzed. Better results for fatigue life improvement were received when the piezo-ceramic transducer with power consumption 0,3 kW was used for UP [22]. The role of the decreasing of stress concentration during the UP treatment on the fatigue strength of welded elements was also evaluated [23]. Based on the analysis of the changes of residual stresses, stress concentration and mechanical properties of the surface layer under the action of UP the predictive model was developed for evaluation of the effectiveness of UP without the fatigue testing of large-scale welded specimens [1,24,25]. One of the advantages of the developed predictive model is the possibility to optimize the parameters of UP for the increasing of the fatigue life of welded elements.

During the period of 1970-2000 the IMP was actively involved in development of the technology and equipment for UP and investigation of surface strengthening of different materials by high frequency impact loading [26-33, P1-P3]. Significant attention was paid to the physical aspects of the influence of the impact loading on the texture of metals and alloys. The diffusion in the surface layers of the materials [33-36] and the behavior of different types of texture defects under the action of ultrasonic impact loading were investigated [37-43].

The company Ultramet represents beginning from 1996 the interests of the group of researchers from the IMP working in the field of development and practical application of the UP technology. The new advanced compact equipment including original generator, ultrasonic transducer and working heads for UP treatment of welds of different configuration were developed and patented by Ultramet [P8, P9].

Starting form 1987 the results on the development of the UP technology were presented by PWI in some East European countries [44-46] and later for western scientific and engineering communities.

In 1990-1991 the efficiency of UP application for increasing the fatigue life of welded elements was verified by the Welding Institute of France. The welded specimens made form high strength steel were tested in as-welded condition and after application of UP. The UP of welded elements was performed at the PWI. The results of fatigue testing at the Welding Institute of France confirmed the high efficiency of UP application [47]. Later, the welded specimens made form low alloy steel and aluminum alloy were tested to determine the increase in fatigue life by UP

[48].

In 1993 a group of scientists from the PWI visited USA and for the first time presented the UP technology in the North America. The UP technology and results of the fatigue testing of large-scale welded specimens were presented at AWS Annual Convention, Offshore Conference, American Bureau of Shipping in Houston and New York and at the Lehigh University [49-51]. Also, in 1993 the UP technology was presented by PWI at Ship Structure Symposium in USA and at the industry briefing at the Welding Institute (UK) where the recent technological advances from Ukraine were exposed to the western industry [52,53].

In 1993 scientists presented the results of the development of the UP technology and fatigue assessment of welded specimens after application of the UP for the first time at the International Institute of Welding from PWI [55]. Later more results on the development of 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 [56-60].

Beginning from 1997 the Integrity Testing Laboratory Inc. - ITL (Canada) participates in joint R&D activity with PWI and Ultramet on development of the technology and equipment for UP. In the frame of this cooperation the principles of optimum UP application and corresponding software were developed. The technology and equipment for UP were adapted for different industrial applications. As a result of this work the Computerized Complex for UP of parts and welded elements was developed recently based on using of the 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 [61-65, P10-P12].

3. Increasing of Fatigue Life of Welded Elements by Ultrasonic Peening

The increase in fatigue strength of welded elements after application of UP is achieved mainly due to the removal of harmful tensile residual stresses and formation of favorable compressive residual stresses in weld toe zones, decrease in stress concentration and the enhancement of the mechanical properties of the surface layer of the material. Multiple results of fatigue testing of large-scale welded specimens showed that application of UP allows to increase the fatigue life of welded joints by 5 to 10 times and limit stress range by 50 to 200%, depending on mechanical properties of the material used, type of joint and parameters of cyclic loading. Some examples of experimental studies of the increasing of fatigue strength of welded joints under the effect of UP are presented below.

In first case the efficiency of improvement treatment was estimated for butt joint in low-carbon steel. The results of fatigue testing of specimens in as-welded condition shown on Figure 1 (line 1). To induce in these specimens the high tensile residual stresses typical for actual structures the longitudinal beads were deposited on both sides of specimens. As a result, the initial tensile residual stresses in welded specimens reached the yield strength of base material.

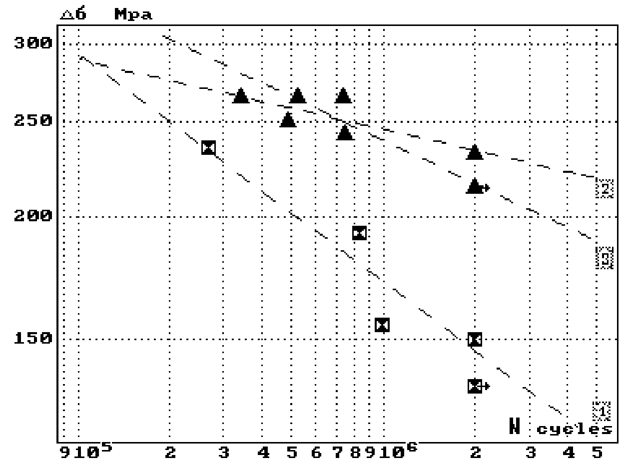

Figure 1. Fatigue curves of butt welded joint in low-carbon steel: 1-in as welded condition; 2,3 - after application of UP, determined by fatigue testing and computation respectively

The weld toe zones of butt welds were subjected to ultrasonic treatment. The application of UP of welded joints leads to introducing in the treated zones the compressive residual stresses close to the yield strength of base material. The results of fatigue testing showed that in case of butt joint in low-carbon steel the ultrasonic treatment caused the 50% increase in the limit stress range at $N=2*10^6$ cycles as compared to the similar joint in as-welded condition.

In second case the change of fatigue strength of non-load caring fillet welded joint in high strength steel under the effect of UP was analyzed. The results of fatigue testing of welded specimens in as-welded condition and after UP are presented on Figure 2. In case of high strength steel, the application of ultrasonic treatment resulted in approximately two times increase in limit stress range.

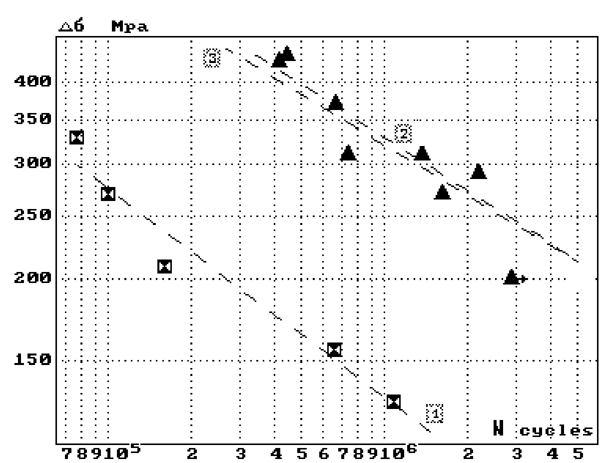

Figure 2. Fatigue curves of non-load caring fillet welded joint in high strength steel:
1 - in as welded condition; 2,3 - after application of UP, determined by fatigue testing and by computation respectively

4. 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. 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.

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%.

A Computerized Complex for UP (CCUP) of parts and welded elements was developed recently based on using of the piezoelectric transducers. The CCUP consists of the compact ultrasonic transducer, generator and laptop with Expert System for UP optimum application (Fig. 3).

Figure 3. Computerized Complex for Ultrasonic Peening of parts and welded elements

5. Expert System for Optimum UP Application

The effect of the UP on the fatigue life of parts and welded elements depends greatly on the technological parameters of UP, level of induced compressive residual stresses, mechanical properties of used material, the type of welded element, parameters of cyclic loading and other factors.

To apply effectively the UP treatment an Expert System (ES) for UP optimum application (a maximum possible increase in fatigue life of structural elements with minimum cost, labor- and power-consumption) was developed based on an original predictive model. The main functions of the developed software are:

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

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

- quality monitoring of UP process;

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

The UP effect is evaluated using as the initial data for computation a) the generalized S-N curves presented in the international and national standards and codes on fatigue design and b) the original experimental results of fatigue testing in as-welded condition.

An example of the optimization of UP parameters for increasing the fatigue life of welded element is presented below. Figure 4 shows the results of fatigue testing of a non-load-carrying fillet welded element made form low carbon steel. The fatigue curve of welded element in as-welded condition with high tensile residual stresses (line 1 on Fig.4) was used as initial fatigue data for analysis of the UP effect. Figure 4 represents also the fatigue curves of non-load-carrying fillet welded joint after application of UP (line 2 and 3). Application of the UP caused the increase of the limit stress range of welded element from 112,9 MPa to 164,4 MPa in case of technology #1. By using optimized UP technology #2 the limit stress range of considered welded element was increased to 226,1 Mpa (Fig. 4).

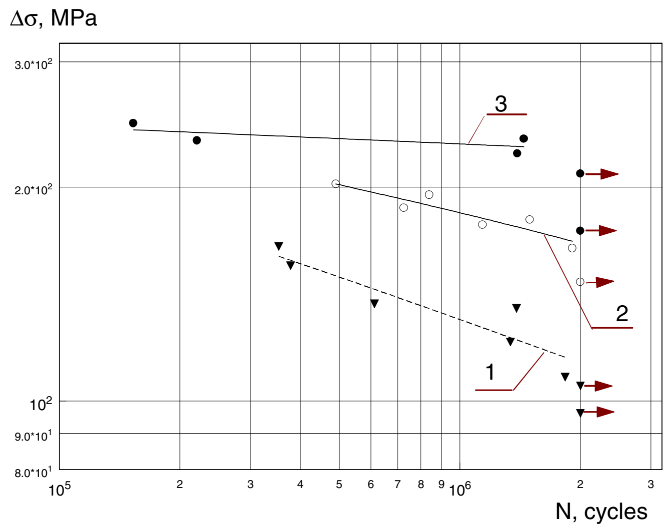

Figure 4. Fatigue curves of non-load carrying fillet welded joint:
1 - in as-welded condition;
2 and 3 - after application of the UP by using technology #1 and technology #2(optimized)

6. Summary

1. 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.

2. 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.

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