Fatigue Improvement of Welded Joints
by Ultrasonic Impact Treatment

Yuri Kudryavtsev

Structural Integrity Technologies Inc.,

80 Esna Park Drive, Units 7-9, Markham, Ontario, L3R 2R7, Canada

ykudryavtsev@sintec.ca

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Abstract. The ultrasonic impact treatment (UIT) is one of the new and promising processes for fatigue life improvement of welded elements and structures. In most industrial applications this process is known as ultrasonic peening (UP). The developed computerized complex for UP was successfully applied for increasing the fatigue life and corrosion resistance 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. The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures. The areas/industries where the UP process was applied successfully include: Shipbuilding, Railway and Highway Bridges, Construction Equipment, Mining, Automotive, Aerospace.

Introduction

The ultrasonic impact treatment (UIT) is one of the new and promising processes for fatigue life improvement of welded elements and structures [1-7]. In most industrial applications this process is also known as ultrasonic peening (UP) [8-11]. The beneficial effect of UIT/UP is achieved mainly by relieving of harmful tensile residual stresses and introducing of compressive residual stresses into surface layers of materials, decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of surface layers of the material. The fatigue testing of welded specimens showed that the UP is the most efficient improvement treatment when compared with such traditional techniques as grinding, TIG-dressing, heat treatment, hammer peening, shot peening and application of LTT electrodes [1, 12, and 13].

Fig.1.The process of UIT/UP treatment of welded sample for fatigue testing.

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 - 11 kg) includes an ultrasonic transducer, a generator and a laptop (optional item) with software for optimum application of UP - maximum possible increase in fatigue life of parts and welded elements with minimum cost, labor and power consumption. In general, the basic UltraPeen system shown in Fig. 1 could be used for treatment of weld toe or welds and larger surface areas if necessary.

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

Principles, Technology, Equipment for UP

Freely Movable Strikers. The UIT/UP equipment is based on known technical solutions from the 40's of last century of using working heads with freely movable strikers for hammer peening. A more effective impact treatment is provided when the strikers are not connected to the tip of the actuator but could move freely between the actuator and the treated material. At that time and later on, a number of different tools based on using freely movable strikers were developed for impact treatment of materials and welded elements by using pneumatic and ultrasonic equipment. Fig. 2 shows a standard set of easy replaceable working heads with freely movable strikers for different applications of UP.

Fig.2. A set of interchangeable working heads for UIT/UP [7].

Ultrasonic Impact and Effects of Ultrasound. The UP technique is based on the combined effect of high frequency impacts of the special strikers and ultrasonic oscillations in treated material. It is shown that the operational frequency of the transducer and the frequency of the intermediate element-striker are not the same. During the ultrasonic treatment, the striker oscillates in the small gap between the end of the ultrasonic transducer and the treated specimen, impacting the treated area. This kind of high frequency movements/impacts in combination with high frequency oscillations induced in the treated material is typically called the ultrasonic impact.

There are a number of effects of ultrasound on metals that are typically considered: acoustic softening, acoustic hardening, acoustic heating, etc. In the first of these (acoustic softening that is also known as acoustic-plasticity effect), the acoustic irradiation reduces the stress necessary for plastic deformation.

In general, the effect of ultrasound on the mechanical behavior could be compared with the effect of heating on a material. The difference is that acoustic softening takes place immediately when a metal is subjected to ultrasonic irradiation. Also, relatively low-amplitude ultrasonic waves leave no residual effects on the physical properties of metals after acoustic irradiation is stopped.

Technology and Equipment for Ultrasonic Peening. The ultrasonic transducer oscillates at a high frequency, with 20-30 kHz being typical. The ultrasonic transducer may be based on either piezoelectric or magnetostrictive technology. Whichever technology is used, the output end of the transducer will oscillate, typically with amplitude of 20 – 40 μm. During the oscillations, the transducer tip will impact the striker(s) at different stages in the oscillation cycle. The striker(s) will, in turn, impact the treated surface. The impact results in plastic deformation of the surface layers of the material. These impacts, repeated hundreds to thousands of times per second, in combination with high frequency oscillations induced in the treated material result in a number of beneficial effects of UP.

The UP is an effective way for relieving of harmful tensile residual stresses and introducing of beneficial compressive residual stresses in surface layers of parts and welded elements. The mechanism of residual stress redistribution is connected mainly with two factors. At a high-frequency impact loading, oscillations with a complex frequency mode spectrum propagate in a treated element. The nature of this spectrum depends on the frequency of ultrasonic transducer, mass, quantity and form of strikers and also on the geometry of the treated element. These oscillations lead to lowering of residual welding stresses. The second and the more important factor, at least for fatigue improvement, is surface plastic deformation that leads to introduction of the beneficial compressive residual stresses.

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 in weld toe zones and the enhancement of the mechanical properties of the surface layer of the material. The schematic view of the cross section of material/part improved by UP is shown in Figure 3 with the attained distribution of the stresses after the UP. The description of the UP benefits is presented in Table 1.

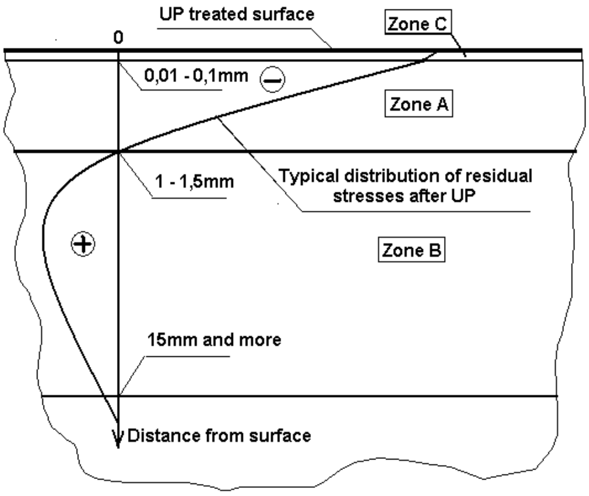

Fig.3. Schematic view of the cross section of material/part improved by UIT/UP [9].

Table 1. Zones of Material/Part Improved by Ultrasonic Peening [9] (see Figure 3 for illustration of the zones)

Zone	**Description of zone**	**Distance from surface**	**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

Fig. 4 illustrates the concept of the fatigue life improvement of welded elements by UP. In case of welded elements, it is enough to treat only the weld toe zone – the zone of transition from base metal to the weld, for a significant increase of fatigue life. A so-called groove, shown in Figures 4 and 5, characterized by certain geometrical parameters is produced by UP [2, 4].

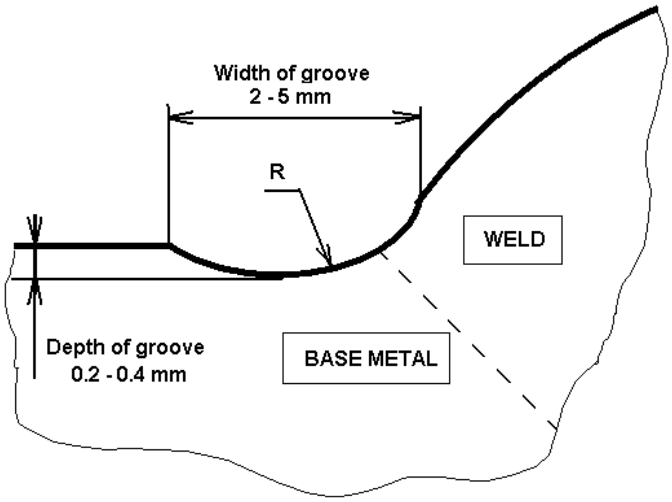

Fig.4. Profile of weld toe improved by Ultrasonic Peening [9].

Application of UP for Fatigue Improvement

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures. Examples of all three applications will be described below.

Manufacturing and Rehabilitation. Three series of large-scale welded samples, designed as shown in Figure 6, were subjected to fatigue testing to evaluate the effectiveness of UP application to the existing welded structures: 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 the expected fatigue life of samples in as-welded condition [9].

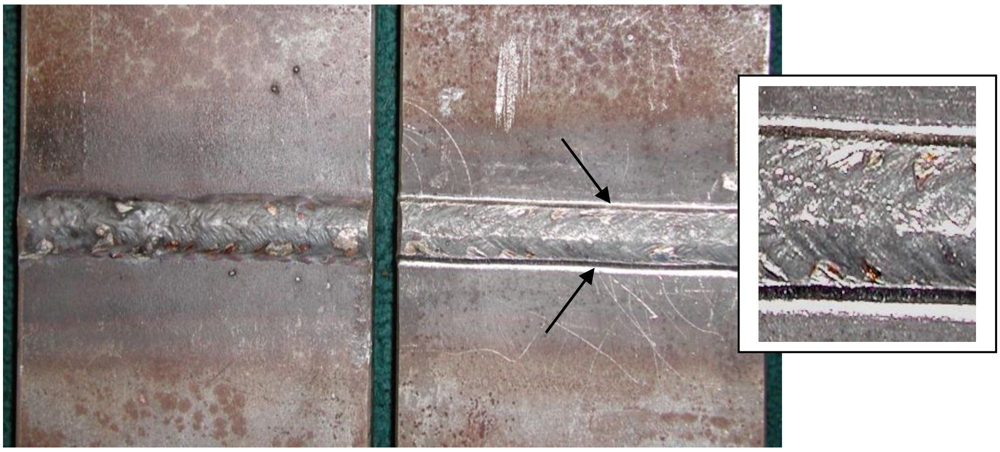

Fig.5. The view of the butt welds in as-welded condition (left side sample) and after application of UP (right side sample) [7]. Notice the formation of a uniform, shiny grove along the weld toe marked with arrows and shown in greater details in the insert.

The results of fatigue testing of the large-scale welded samples imitating the transverse non-load-carrying attachments (Fig. 6) with UP applied to specimens in as-welded condition and also after 50% of expected fatigue life are presented in Fig. 7.

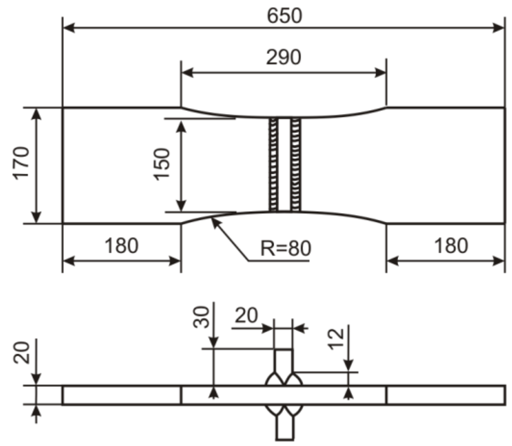

Fig.6. The general view of welded sample for fatigue testing.

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 residual stresses and/or "healing" of fatigue damaged material by UP in comparison with the fatigue curve #2.

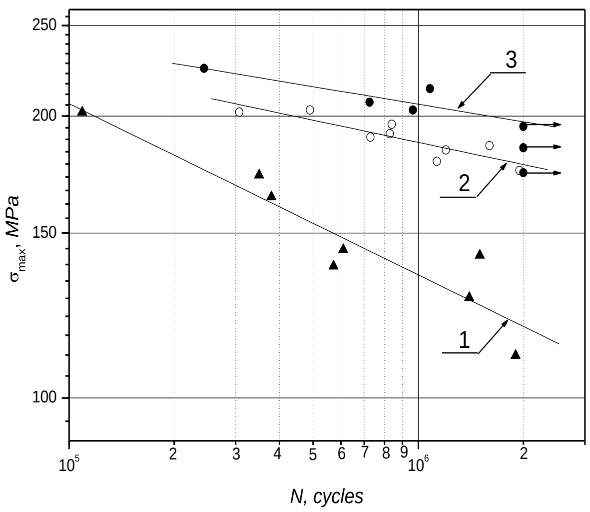

Fig.7. Fatigue curves of welded elements (transverse non-load-carrying attachment:
1 – in as welded condition, 2 – UP was applied before fatigue testing,
3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition.

Weld Repair. In this paper the rehabilitation is considered as a prevention of possible initiation of fatigue cracks in existing welded elements and structures that are in service. The UP could also be effectively used during the weld repair of fatigue cracks [7, 10].

Fig. 8 shows the drawing of a large-scale welded specimen containing non-load carrying longitudinal attachments designed for fatigue testing [7]. Such specimens were tested in as-welded condition and after weld repair with and without application of UP.

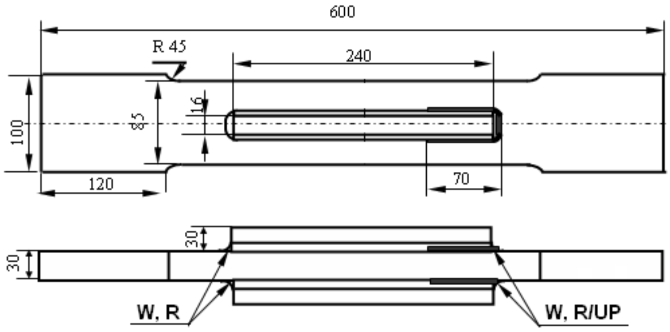

Fig.8. Drawings of welded specimens for fatigue testing at different conditions:
W – as-welded condition; R - repair by gouging and welding; R/UP – repair by gouging, welding and UP.

The testing conditions were zero-to-tension stress cycles (R=0) with different level of maximum stresses. The fatigue testing was stopped and the number of cycles was recorded when the length of fatigue crack on surface reached 20 mm. Then, the fatigue crack was repaired by gouging and welding and the fatigue test was continued. After repair, a number of samples were subjected to UP. The weld toe of the “new” weld was UP treated. The results of fatigue testing of welded specimens in as-welded condition and after weld repair of fatigue cracks are presented in Fig. 9.

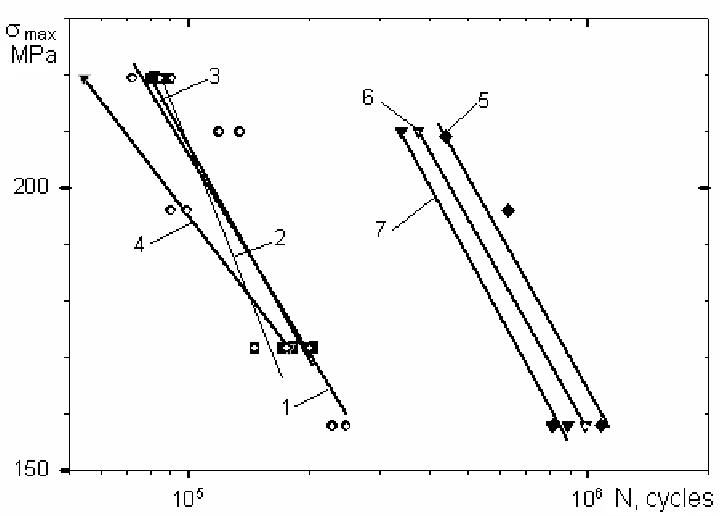

Fig.9. Results of fatigue testing of welded elements:
1 - as-welded condition; 2, 3 and 4 – after first, second and third weld repair;
5, 6 and 7 - after first, second and third weld repair with application of UP.

The fatigue testing of large scale specimens showed that the repair of fatigue cracks by welding is restoring the fatigue strength of welded elements to the initial as-welded condition. Second and third repair of fatigue cracks also practically restored the fatigue life of repaired welded elements to initial as-welded condition.

The application of UP after weld repair increased the fatigue life of welded elements by 3-4 times. Practically the same significant fatigue improvement of repaired welded elements by UP is observed also after second and third repair of fatigue cracks in welded elements.

Summary

1. Ultrasonic Impact Treatment (UIT/UP) is a relative new and promising technique for fatigue life improvement of welded elements and structures in materials of different strength including HSS with the yield strength of 700-1000 MPa. The results of fatigue testing show a strong tendency of increasing of fatigue strength of welded elements after application of UP with the increase in mechanical properties of the material used. It allows using to a greater degree the advantages of the HSS in welded elements, subjected to fatigue loading.

2. The fatigue testing of welded specimens also 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 or application of LTT electrodes.

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

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