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Fatigue Life Improvement of Tubular Welded Joints by Ultrasonic Peening

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ABSTRACT

The development of the Ultrasonic Peening (UP) technology was a logical continuation of the work done before and directed at the investigation and further development of known techniques for surface plastic deformation such as shot peening, hammer peening and needle peening. The UP technique is based on the combined effect of the high frequency impacts of the special strikers and ultrasonic oscillations in treated material. The UP was applied successfully for increasing 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 compared to such existing improvement treatments as grinding, TIG-dressing, shot peening and hammer peening. The basic principles, technology and equipment for UP as well as the efficiency of UP application for fatigue life improvement of tubular welded joints are considered in this document.

KEY WORDS: Fatigue improvement, ultrasonic peening, UP, ultrasonic impact, tubular welded joints, rectangular hollow section, RHS

1. Introduction

One of the promising directions in using of the high power ultrasonic (HPU) for industrial applications is the Ultrasonic Peening (UP) of materials, parts and welded elements [1-4]. The 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, fretting fatigue and stress corrosion cracking. During the different stages of its development the UP process was also known as ultrasonic treatment (UT) [5-7], ultrasonic impact treatment (UIT) [8-10], ultrasonic impact peening (UIP) [11-12].

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 includes an ultrasonic transducer, a generator and a laptop with software for UP optimum application - maximum possible increase in fatigue life of parts and welded elements with minimum cost, labor and power consumption.

The beneficial effect of UP 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 concentration in weld toe zones and enhancement of mechanical properties of the surface layers of the material. The UP treatment 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 and hammer peening.

The UP technology is considered as a leading technology in the application of HPU for fatigue life improvement of parts and welded elements because of the following factors:

1. The UP technology is based on more than 30 years of extensive experience and knowledge of an international group of experts in application of HPU for improvement of quality and service life of parts and welded elements. The first publications of the group on relieving of residual stresses in welded elements by UP are dated back to 1974 [5].
2. The design of the UP equipment is based on "Power on Demand" concept. The power and other parameters of UP equipment correspond to the necessary changes in residual stresses, stress concentration and mechanical properties in the surface layers of materials to attain maximum possible increase in fatigue life of welded elements. The basic UP system covers most of the applications in fatigue improvement with the power consumption of 300-400 watts. More powerful UP systems are also designed and produced on request.
3. The effects of different improvement treatments, including the UP treatment, on the fatigue life of welded elements depend on the mechanical properties of used material, the type of welded joints, parameters of cyclic loading and other factors. For effective application of the UP, depending on the above-mentioned factors, a software package for Optimum Application of UP was developed that is based on original predictive model. In the optimum application, a maximum possible increase in fatigue life of welded elements with minimum time/labor/cost is thought.

The developed technology and computerized complex for UP was successfully applied 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 and Stamping Equipment, Shipbuilding, Mining, Automotive and Aerospace to name a few.

2. Basic Principles, Technology and Equipment for Ultrasonic Peening

2.1. Freely Movable Strikers

The modern equipment for UP is based on known technical solutions of working heads for hammer peening known from the 40's of last century. At that time and later a number of different multi-striker working heads were developed for impact treatments of parts and welded elements by using mostly pneumatic driven equipment. 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 [13-14]. The tools with the freely movable strikers (12 on Figure 1a and 21 on Figure 1b) mounted in holder for impact treatment of materials and welded elements are shown on Figure 1.

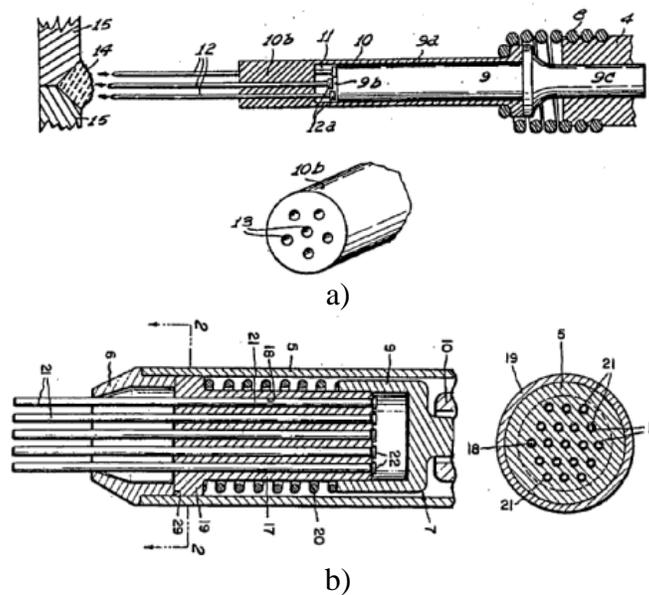


Figure 1. Sectional view through tools with freely movable strikers (12 on Figure 1a and 21 on Figure 1b) for surface impact treatment: a – described in [13], b – described in [14].

Figure 2 show 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 2. Set of the changeable working heads

2.2. Ultrasonic Impact and Effects of Ultrasound on Deformation Characteristics of Metals

The UP technique is based on the combined effect of the high frequency impacts of the special strikers and ultrasonic oscillations in treated material. Some specific features of the ultrasonic impact treatment of metals are described in [15]. It is shown that the operational frequency of the transducer and the frequency of the intermediate element-striker are not the same (Figure 3).

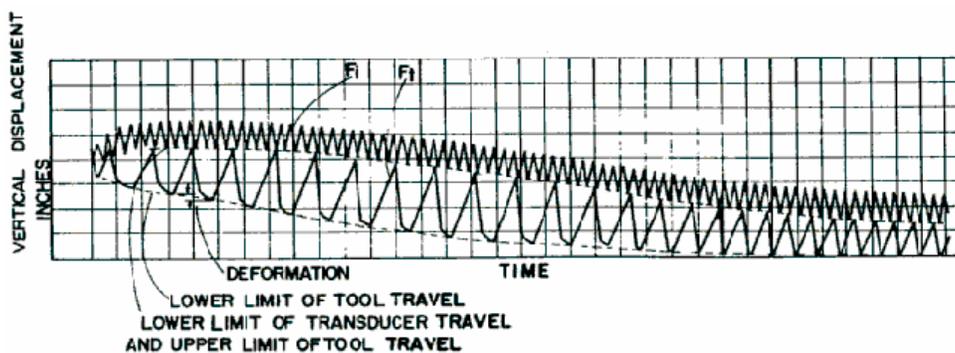


Figure 3. Graphical illustration of the ultrasonic impact technique showing the difference in the frequency of transducer and intermediate element motions [15].

During the ultrasonic treatment the striker oscillates in the small gap between the end of the ultrasonic transducer and treated specimen, impacting the treated area. This kind of high

frequency movements/impacts in the combination with high frequency oscillation 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 and others [16-18]. 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. Figure 4 shows stress-strain curves that were obtained from tensile tests of high-purity aluminum single crystals. The dashed curves indicate the plastic behavior of metal crystals under continuous ultrasonic irradiation at 20 KHz and at various power levels, all tests conducted at a constant temperature of 18 °C. The solid curves represent the plastic behavior of aluminum at different temperatures. As can be seen from Fig.4, the shear stress can be reduced by as much as 100 % down to even "zero stress", when ultrasound of ~50 W/cm² is applied. Acoustic softening has been observed in all other metals that were tested, including cadmium, iron, titanium, tungsten, stainless steel and beryllium [18].

In general, the effect of ultrasound on the mechanical behavior could be compared with the effect of heating of the material (Figure 4). 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 [18].

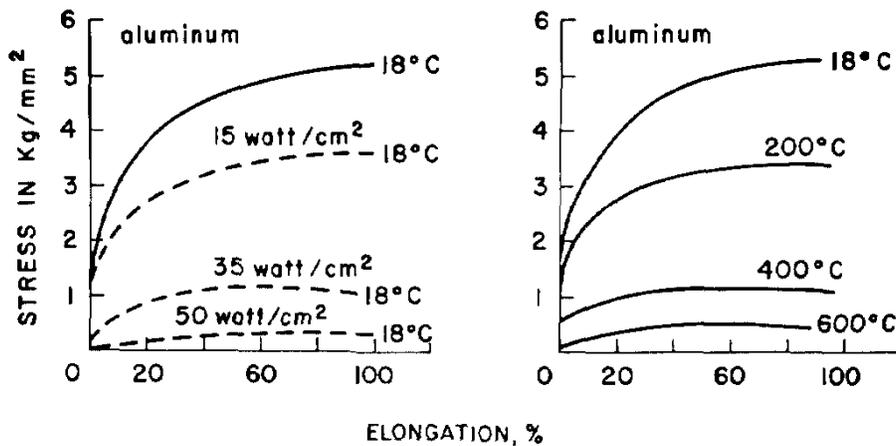


Fig 4. Stress vs. elongation for aluminum single crystals [18]:
dashed curves - during ultrasonic irradiation, solid curves - no ultrasound

2.3. 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 be oscillating, typically with amplitude of 20 – 40 μm. During the oscillations, the transducer tip will impact the striker at different stages in the oscillation cycle.

The striker(s) impacts the treated surface. The impact results in plastic deformation of the surface layers of the material. These high stress impacts, repeated hundreds to thousands of times per second, results 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 stresses 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.

For fatigue life improvement of welded elements it is enough to treat the weld toe zone – the zone of transition from base metal to the weld. During such UP treatment a so-called groove is produced [1,2,8,9]. A typical example when only the weld toe is UP treated for fatigue life improvement and the groove is produced is presented in Figure 5.



Figure 5. The view of the butt welds in as-welded condition (left side sample) and after application of UP (right side sample)

In general, the basic UP system [2,19,20] shown in Figure 6 could be used for treatment of weld toe or welds and larger surface areas if necessarily. The basic UP system (total weight - 6 kg) includes:

1. The hand tool which is based on a piezoelectric transducer. Weight of the tool is 2,5 kg and it is convenient for use. A number of working head types were designed for different industrial application.
2. Ultrasonic generator. Weight of the generator is 3 kg with power consumption of only 400 watts. Output frequency ~ 22 kHz.
3. Laptop (optional item) with software package for Remote Control and Optimum Application of UP.



Figure 6. Using of basic UP system for fatigue life improvement of tubular welded joint.

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures [1,2]. The results of fatigue testing of large-scale welded samples imitating the transverse non-load-carrying attachments are presented on Figure 7.

As can be seen from Figure 7, 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 $N=2 \cdot 10^6$ 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.

3. Ultrasonic Peening and Fatigue Testing of Tubular Welded Joints

The UP was applied for fatigue life improvement of tubular welded joints. The sketch and general view of sample for fatigue testing are shown in Figures 8 and 9. The sample represents a T-joint of rectangular hollow section (RHS) members. One of RHS has a quadratic

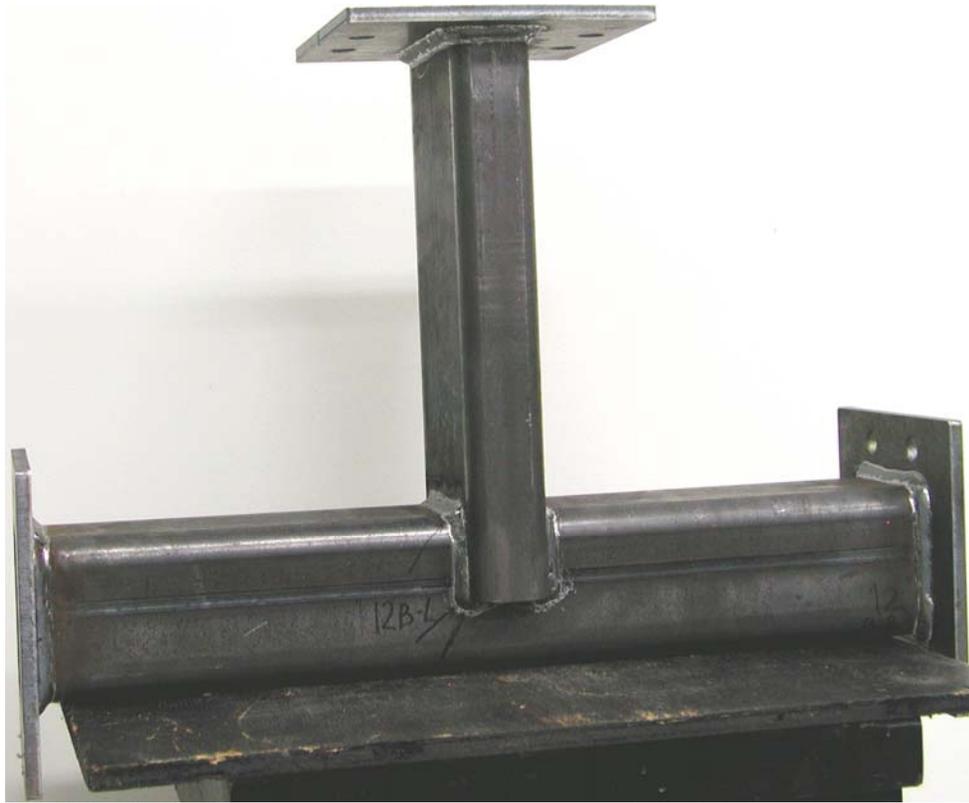


Figure 9. The general view of the welded sample (after application of UP).

section with outer dimensions of 4 x 4 inches (101.6 x 101.6 mm) and the second RHS - rectangular section of 2 x 6 inches (50.8 x 152.4 mm).

Figure 10 represents a detailed view of the ends of welds that are critical from fatigue point of view in as-welded condition and after application of UP. Figure 11 represents a view of welds connecting tubes also in as-welded condition and after application of UP.

The samples were subjected to fully reversed loading as shown in Figure 12. The samples in as-welded condition were tested at 4000, 3000, and 2000 lbs load levels. In all nine samples that were subjected to fatigue loading in as-welded condition the fatigue cracks originated in the zone of weld toe near the end of the 2x6 tube. The zones of fatigue crack are shown by arrows on Figure 11 and figure 13.

Three samples were subjected to UP treatment and fatigue tested after that. In these samples the zone of fatigue crack initiations and propagation as well as weld toes from both sides of welds were UP treated. These samples were tested at 5000, 4000, and 3000 lbs loads. The UP caused significant increase in fatigue strength of considered welded elements. The crack location also changed from the samples in as-welded condition. In the UP treated samples the fatigue initiated in middle of the weld at the 4x4 tube curve (Figure 14).

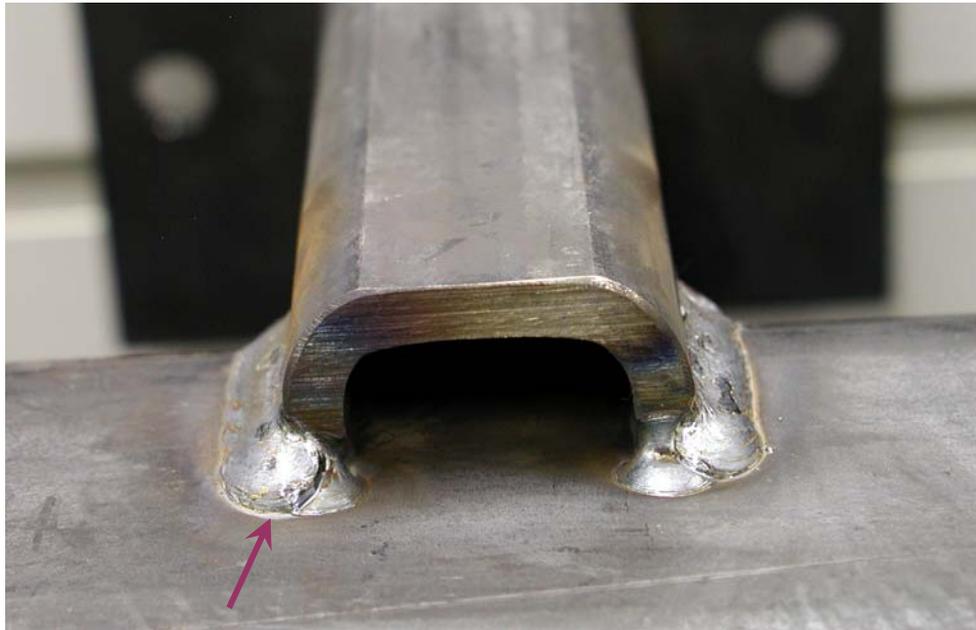


a)

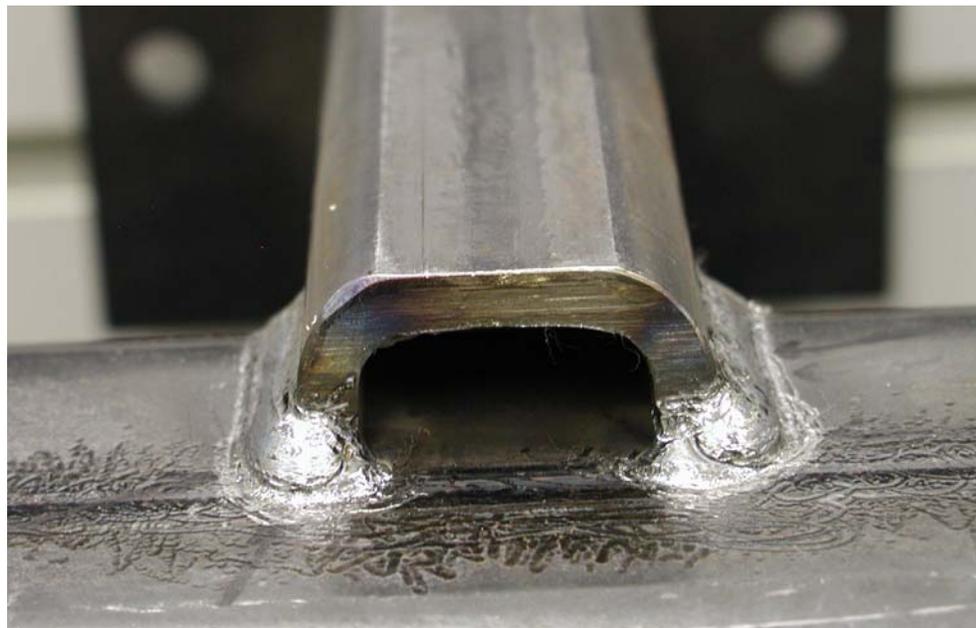


b)

Figure 10. View of welds connecting tubes in as-welded condition (a) and after application of UP (b).



a)



b)

Figure 11. Detailed view of the zone of weld that is critical from fatigue point of view (indicated by arrow) in as-welded condition (a) and after application of UP (b).

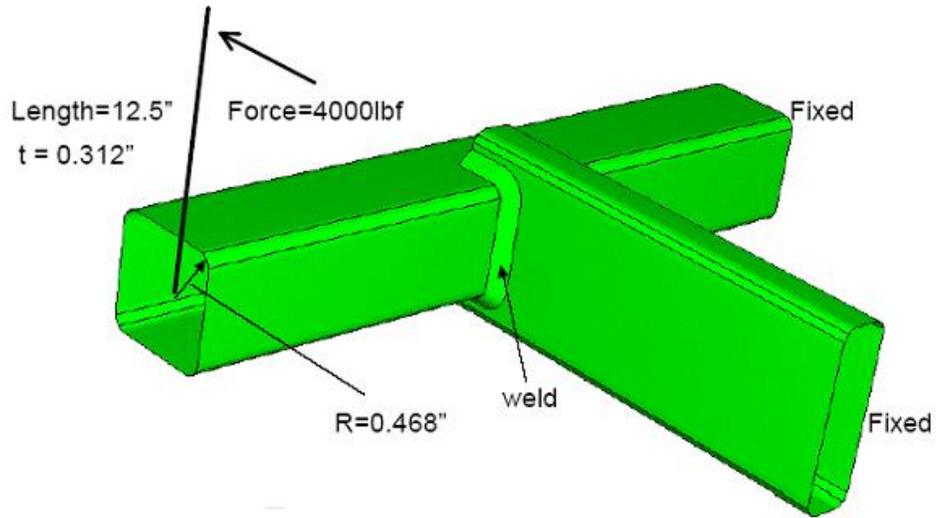


Figure 12. Scheme of loading of considered tubular welded joint.

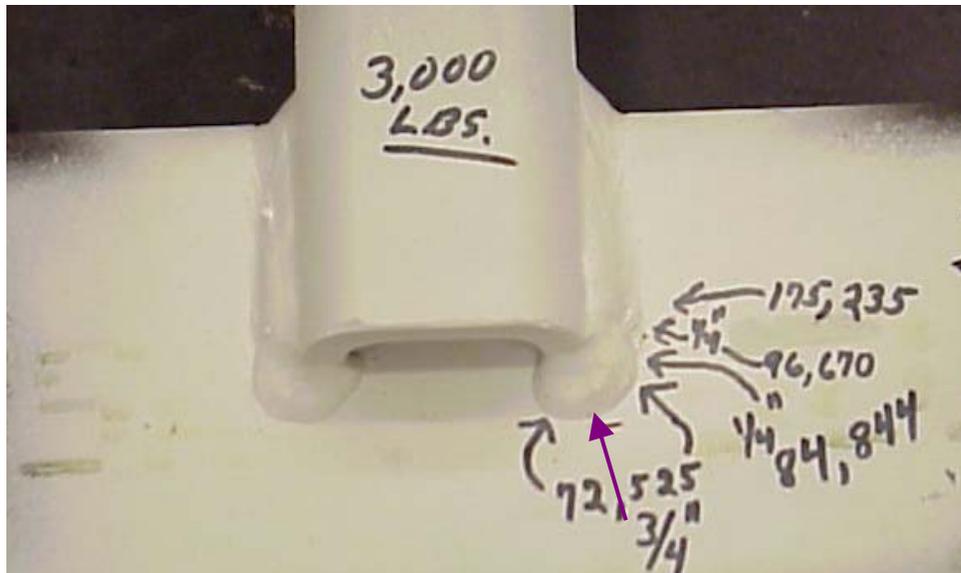


Figure 13. The zone of origination of the fatigue crack (shown by arrow) in the sample that was subjected to fatigue loading in as-welded condition.



Figure 14. The zone of origination of the fatigue crack (shown by arrow) in the sample that was subjected to fatigue loading after Ultrasonic Peening.

The results of fatigue testing of tubular welded joint in as-welded condition and after UP are presented on Table 1. To show the tendency in the efficiency of UP depending on the level of cyclic loading these data are also presented as fatigue curves in terms of level of load and number of cycles on Figure 15.

Table 1. Results of fatigue testing of tubular welded joints in as-welded condition and after Ultrasonic Peening

Sample number	Condition	Level of load, lbs	Fatigue life, cycles
1	As-welded	4000	9,550
2	As-welded	4000	12,085
3	As-welded	4000	10,292
4	As-welded	4000	10,691
5	As-welded	4000	22,000
6	As-welded	4000	28,000
7	As-welded	4000	21,000
8	As-welded	3000	72,525
9	As-welded	2000	500,000
10	After UP	5000	83,000
11	After UP	4000	620,000
12	After UP	3000	1,400,000

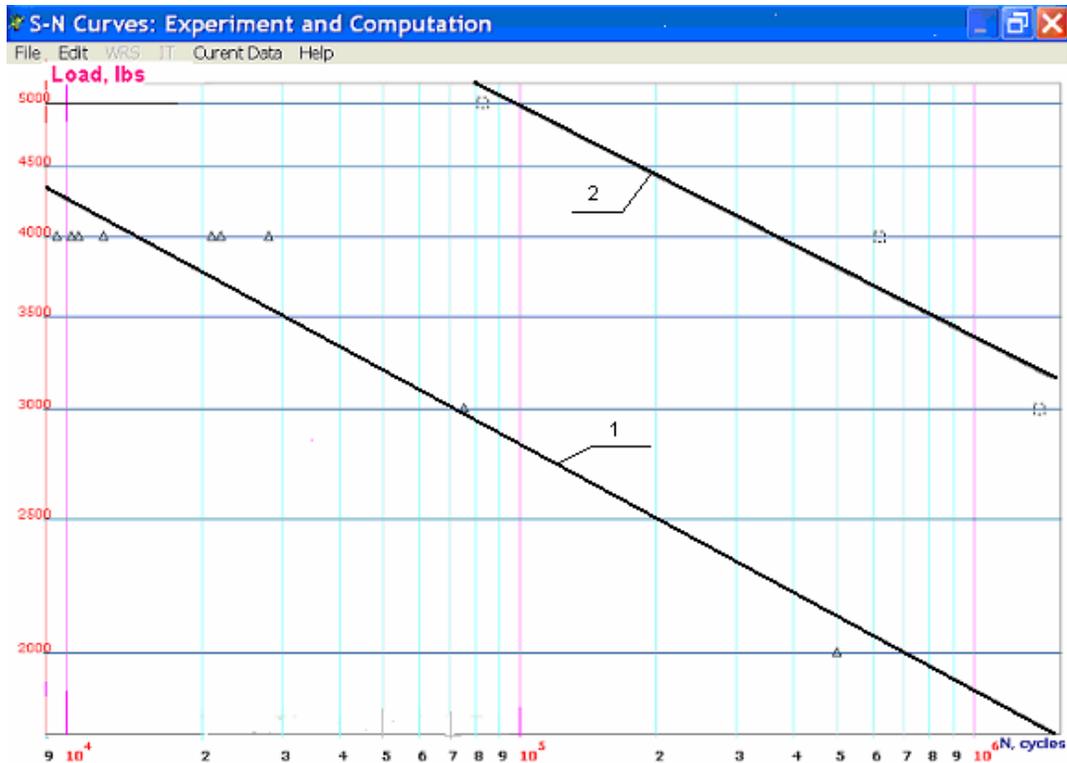


Figure 15. Fatigue curves (tendency) for tubular welded joints showing the beneficial effect of Ultrasonic Peening: 1- as-welded condition, 2- after UP.

The results of fatigue testing show that the UP could be applied efficiently for fatigue life improvement of tubular welded joints. In considered case of welded RHS elements (4x4 to 2x6 inches welded tubes) the UP increased the limit stress range of tubular joints by approximately 70% and the fatigue life - by more than 10 times.

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