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Rehabilitation and Repair of Welded Elements and Structures by Ultrasonic Peening

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ABSTRACT

The Ultrasonic Peening (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. The results of experimental investigation of the efficiency of UP for rehabilitation and repair of welded elements and structures with the goal of preventing the origination and propagation of fatigue cracks are considered in this document. UP treatment was applied to large-scale welded specimens in as-welded condition, after 50% of expected fatigue life and after repair of fatigue cracks. Also, different techniques for restraining and repair of fatigue cracks were analyzed and compared: overloading; drilling of the crack tips; drilling of the crack tips with installation of high strength bolts; local explosive treatment; local heat treatment; welding with and without UP of weld toe zones. As an example, the practical application of UP for rehabilitation and repair of welded elements of highway and railway bridges are also considered in this document.

KEY WORDS: Ultrasonic peening, welded elements, fatigue, rehabilitation, repair, highway and railway bridges

1. Introduction

The Ultrasonic Peening (UP) is one of the efficient ways for fatigue life improvement of welded elements and structures [1,2]. During the different stages of its development the UP process was also known as ultrasonic treatment (UT) [3-5], ultrasonic impact technique/technology/treatment (UIT) [6-8], ultrasonic impact peening (UIP) [9-10].

The UP technology is considered as a leading technology in the application of High Power Ultrasound 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 extensive experience and knowledge of an international group of experts in application of High Power Ultrasound for improvement of quality and service life of parts and welded elements. One of the first publications on this problem by one of the group leading scientists, Prof. G. Prokopenko is dated back to 1974 [3] (see also historical review on UP in [1]).

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 of 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 300-500 watt. More powerful UP systems could be designed and produced on request. Basic UP systems for manual and robotic applications are shown on Figure 1.

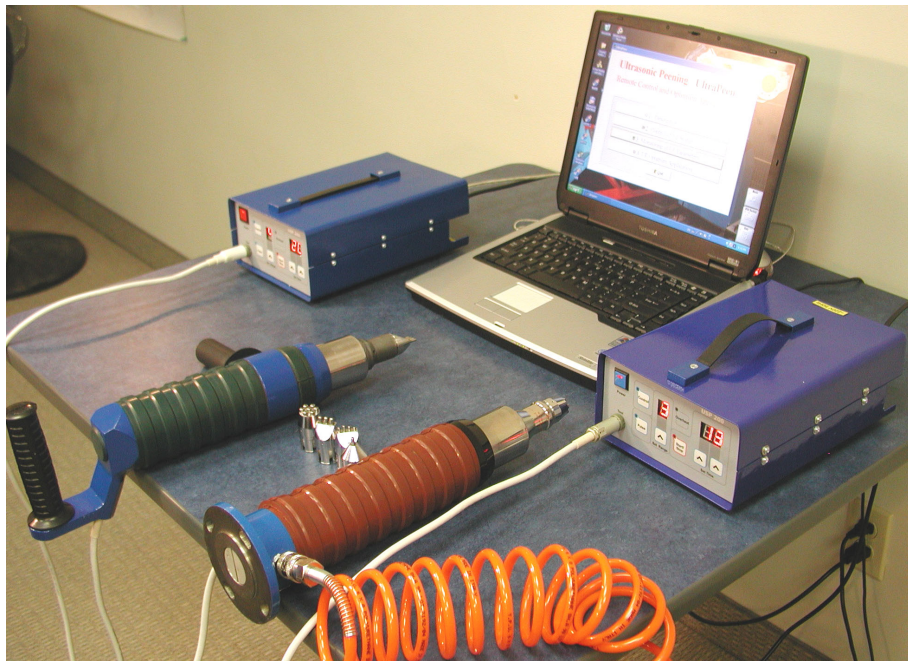


Figure 1. Basic UP systems for manual (left) and robotic (right) applications

3. The effects of improvement treatments, particularly 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 the effective application of the UP,

depending on the above-mentioned factors, a software package for Optimum Application of Ultrasonic Peening was developed that is based on an original predictive model. In the optimum application, a maximum possible increase in fatigue life of welded elements with minimum time-, labor- and power-consumption is thought [1].

The UP technology was applied successfully for fatigue life improvement of different parts and welded elements in a number of different areas/industries including: Railway and Highway Bridges, Shipbuilding, Construction Equipment, Mining, Automotive and Aerospace.

The results of experimental investigation of the efficiency of UP for rehabilitation and repair of welded elements and structures with the goal to prevent the origination and propagation of fatigue cracks are considered in this document. The UP treatment was applied to large-scale welded specimens in as-welded condition, after 50% of expected fatigue life and after repair of fatigue cracks. Also, the efficiency of using of the UP in repair of fatigue cracks was analyzed in comparison with other techniques. The following techniques for restraining of fatigue cracks were considered; overloading; drilling of the crack tips; drilling of the crack tips with installation of high strength bolts; local explosive treatment; local heat treatment; welding without and with UP treatment of weld toe zones. As an example, the practical applications of UP for rehabilitation and repair of welded elements of highway and railway bridges are also considered in this document.

2. Application of UP for Rehabilitation of Welded Elements and Structures

One of the examples of the effective application of UP is the fatigue life improvement of welded elements of highway and railway bridges. Analysis of publications and observations of welded bridges had shown [6] that the typical zones of fatigue crack origination are the ends of vertical welded stiffeners (crack types T1 and T2 in Figure 2). The effectiveness of

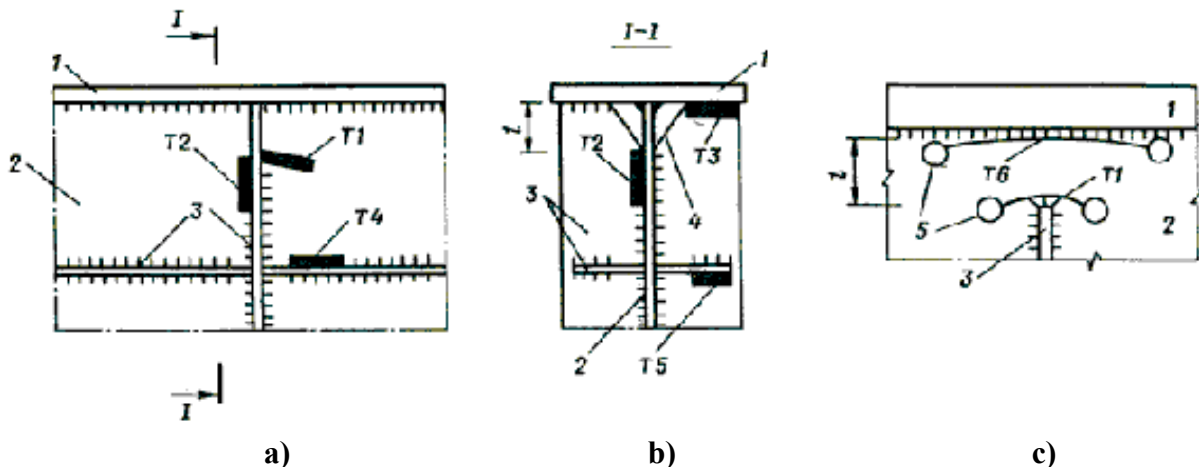


Figure 2. Schematic presentation of the location of fatigue cracks in welded elements of railway (a,b) and highway (c) bridges: T1-T6 – zones of fatigue crack initiation; 1, 2, and 3 – upper flange, web and stiffeners of the bridge span; 4 – openings in the stiffener; 5 – holes produced to prevent the propagation of fatigue cracks; l – zone of local bending of the web [6].

application of UP for prevention of fatigue crack origination and propagation in such locations was studied based on results of fatigue testing of large-scale welded samples (Figure 3). The results of fatigue testing showed that the UP could prevent the initiation of fatigue cracks in the considered types of welded elements at considered conditions of cyclic loading. It was shown that UP treatment of about 100 mm of a weld in the end zones of the welded stiffeners leads to a significant increase of the fatigue life of the considered welded element and could eliminate the fatigue crack origination. During such UP treatment only the weld toe is treated and the so-called groove is produced (Figure 3) [6,7].

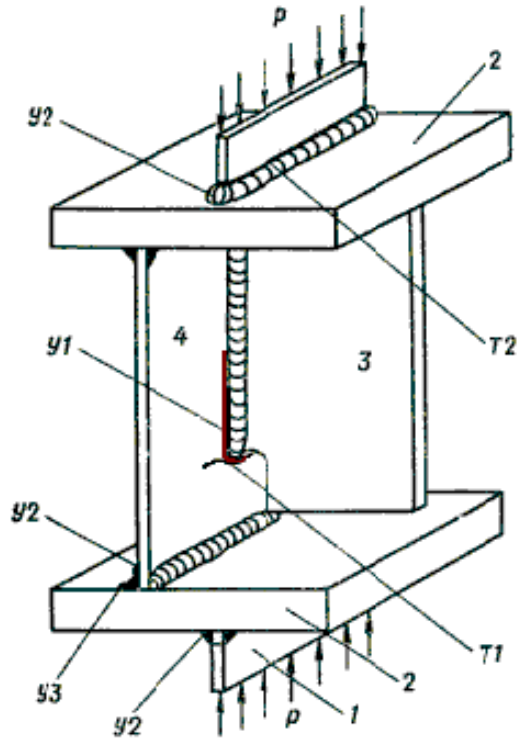


Figure 3. Drawing of welded sample imitating the attachment of the vertical stiffener to the web for fatigue testing in as-welded condition and after UP [6]:
T1 – zone of fatigue cracks initiation, Y1 – zone of UP treatment,
3 – welded stiffener, 4 –web.

While the fatigue testing of welded elements showed that the UP could be effectively applied for the prevention of fatigue crack initiation in welded bridges, it was not known how effective will be the UP if applied to a bridge, exposed to the conditions of cyclic loading, after a certain number of years in service. Practically, all previous results of fatigue testing that had shown the high efficiency of improvement treatment were obtained for conditions when UP was applied before fatigue loading of the samples. The following chapter describes the results of fatigue testing of welded elements directed at evaluation of the efficiency of UP treatment in cases when UP is applied after 50% of expected fatigue life of welded element in as-welded condition.

2.1. Effectiveness of UP applied after 50% of expected fatigue life of welded elements

Three series of welded samples 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.

The general view of welded sample for fatigue testing is shown of Figure 4.

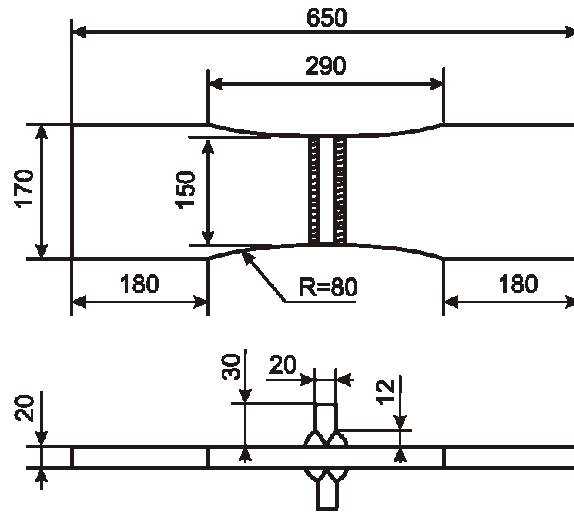


Figure 4. The general view of welded sample for fatigue testing

The data on mechanical properties and chemical composition of base material are presented in Table 1 and Table 2.

Table 1. The mechanical properties of base material

σ_y, MPa	σ_u, MPa	$\delta, \%$	$\psi, \%$
260	465	37,6	63

Table 2. The data on chemical composition of base material

%							
<i>C</i>	<i>Si</i>	<i>Mn</i>	<i>S</i>	<i>P</i>	<i>Cr</i>	<i>Ni</i>	<i>Cu</i>
0,210	0,205	0,52	0,019	0,007	0,04	0,04	<0,01

All welded samples were tested at stress ratio $R=0$. The results of the fatigue testing are presented on Figure 5.

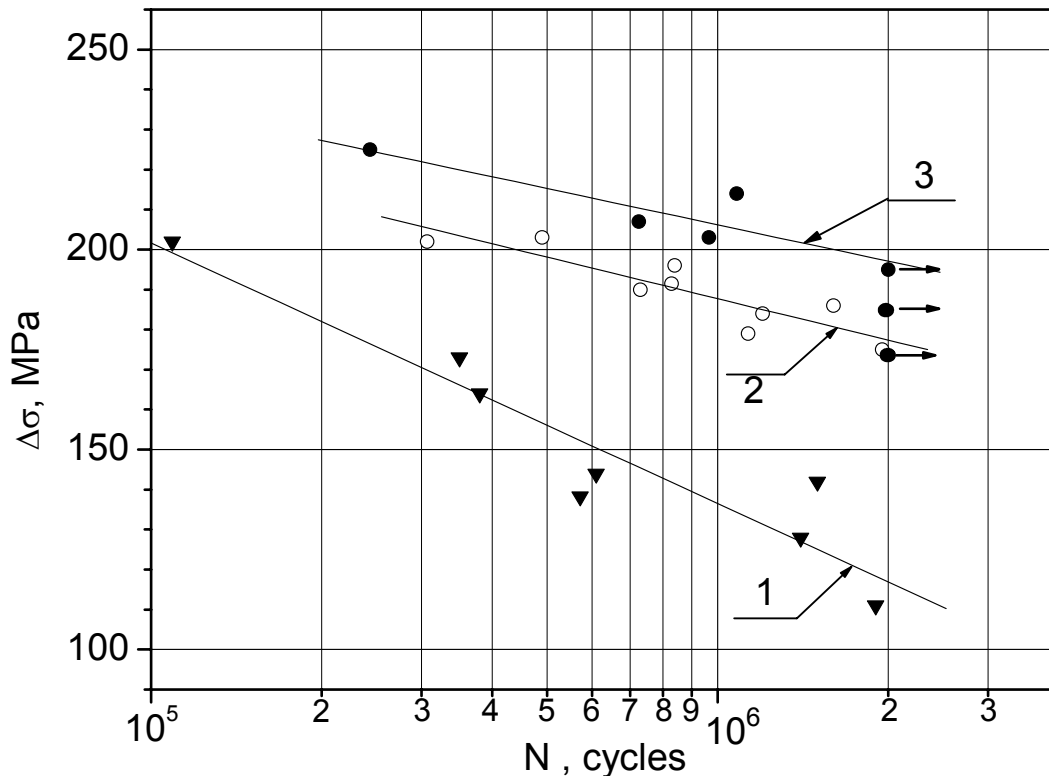


Figure 5. Fatigue curves of welded samples (transverse non-load-carrying attachment):

- 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.

As can be seen from Figure 5, 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 53% (from 118 MPa to 180 MPa) for UP treated samples before fatigue loading and – 67% (from 118 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. Also, on average, the UP caused 4-6 times increase in fatigue life of welded samples depending on the level of applied loading. 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. Additional work is now in progress to explain this and similar results.

In cases where there are no experimental data on fatigue life improvement by UP for a certain material, the type of welded elements and the conditions of cyclic loading, the benefit factor that is described in IIW recommendations on fatigue life improvement of welded elements for different peening techniques [11,12] could be applied to determine the expected increase of fatigue strength of welded elements by UP. This benefit factor is 1.3 for steels with the yield strength less than 355 MPa, and 1.6 - for steels with the yield strength of more than 355 MPa. The benefit factor for aluminum alloys is 1.6. This factor could be applied to increase the limit stress range (at $2 \cdot 10^6$ cycles) of treated welded element. The benefit factor of, for instance 1.3, corresponds to a 2.2 times increase in fatigue life of the welded element [11,12].

3. Application of UP for Repair of Fatigue Cracks in Welded Elements and Structures

In the previous chapter it was shown that UP treatment is an effective way for rehabilitation of welded structures. In this document the rehabilitation is considered as a prevention of possible fatigue cracks initiation in existing welded structures that are in service. The UP could also be used during the repair of fatigue cracks.

The results of experimental investigation of the efficiency of traditional and advanced techniques for fatigue life improvement of structural elements with fatigue cracks are considered in this chapter. Large-scale specimens containing fatigue cracks were subjected to further fatigue testing. A number of techniques of restraining and repair of the fatigue cracks were analyzed and compared: overloading, drilling of the crack tips, drilling of the crack tips with installation of high strength bolts, local explosive treatment, local heat treatment, welding with and without UP of weld toe zones.

A number of large scale specimens (Figure 6) with fatigue cracks were subjected to further fatigue loading with the goal to determine their fatigue performance at the following conditions:

- initial condition,
- drilling of the crack tips with and without cold working;
- drilling of the crack tips with installation of high strength bolts;
- overloading
- local explosive treatment;
- local heat treatment;
- repair by welding with and without UP of weld toe zones.

The cyclic testing conditions were zero-to-tension stress cycle ($R=0$) with the maximum stresses of 155 MPa. The fatigue testing of large scale specimens showed that the repair of fatigue crack by welding with the subsequent UP treatment provided longest fatigue life in comparison with other ways to prolong the service life of structural elements with fatigue cracks. The results of fatigue testing of specimens with cracks subjected to the above-mentioned improvement techniques are summarized in Figure 7.

A predictive model and software for fatigue assessment of welded elements with cracks in as-welded condition and after application of the improvement techniques based on introduction of beneficial compressive residual stresses in the zone of crack tip were also developed and

experimentally verified [13]. In some specimens the residual stresses were measured by non-destructive ultrasonic method [14,15] with the obtained information used for further computation of the effect of compressive residual stresses on the fatigue crack propagation.

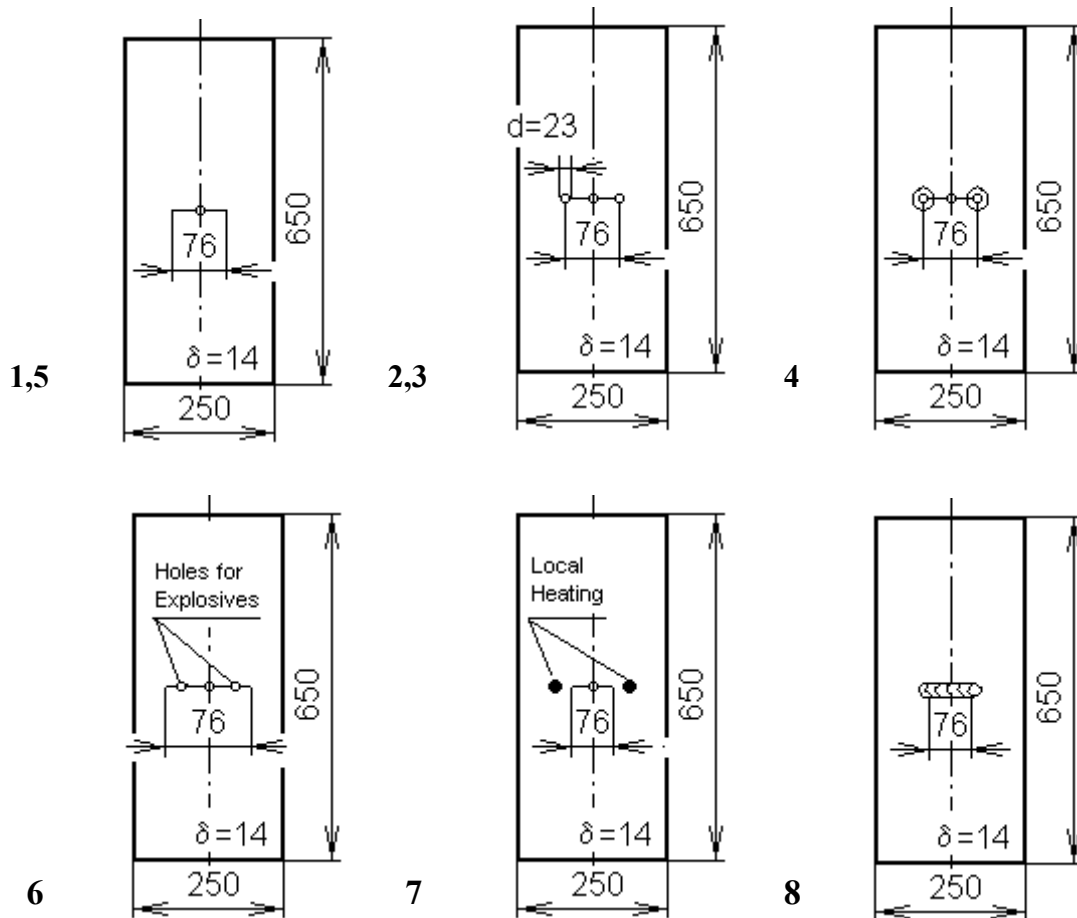


Figure 6. Drawings of specimens with fatigue cracks for further fatigue testing at the following conditions: 1 - initial condition, 2 and 3 - drilling of the crack tips with and without cold working, 4 - drilling of the crack tips with installation of high strength bolts, 5 - overloading, 6 - local explosive treatment, 7 - local heat treatment, 8 - welding with and without UP of weld toe zones.

4. Examples of Practical Application of UP for Rehabilitation and Repair of Welded Structures

4.1. Rehabilitation (prevention of fatigue cracks initiation)

Based on the fatigue data and the solution described above, the UP was applied for rehabilitation of welded elements of a bridge over Ohio river in USA (Figure 8 and Figure 9). The bridge was constructed about 30 years ago. The welded elements of the bridge did not have fatigue cracks.

The reason for application of the UP for fatigue life improvement of this bridge was the fatigue cracking in welded elements of another bridge of approximately the same age and design. The stages of preparation for UP and UP treatment of one of the welded vertical stiffeners are shown on Figure 8 and Figure 9. The total length of UP treated welds was about 500 meters and more than two thousands welded elements that are critical from fatigue point of view were UP treated.

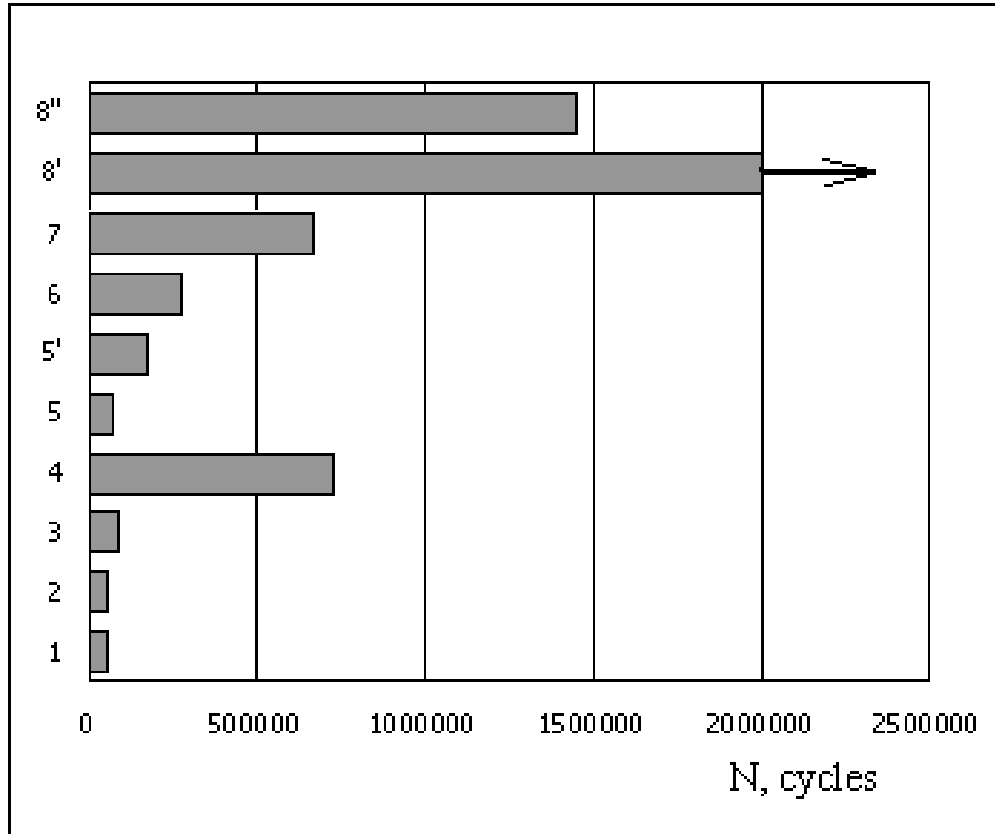


Figure 7. Comparison of the efficiency of different techniques of restraining and repair of fatigue cracks:

- 1 - initial condition, 2 and 3 - drilling of the crack tips with and without cold working,
- 4 - drilling of the crack tips with installation of high strength bolts,
- 5 – overloading (yield strength), 5' – overloading (0.7 yield strength),
- 6 - local explosive treatment, 7 - local heat treatment,
- 8' – repair by welding with UP treatment of the weld toe zones,
- 8'' – repair by welding without UP.

4.2. Repair of Fatigue Crack

During the regular inspection of the bridge over Dnepr River in Ukraine, a fatigue crack was found in one of the welds of the bridge span. The fatigue crack was located in the weld connecting the upper flange and the web. The length of the crack was about 1 meter. The location of fatigue crack in welded element of bridge span shown on Figure 10.



Figure 8. Ultrasonic Peening of welded Bridge: Preparation for UP treatment
(Two UP Systems/Lifts)



Figure 9. Ultrasonic Peening of welded bridge: UP of the end of one of welded
vertical stiffeners

The fatigue crack was repaired by standard welding procedure. To prevent possible origination of fatigue cracks at the same location the repaired zone was UP treated. The process of UP treatment of repaired zone in welded element of bridge span are shown on Figure 10 and Figure 11.



Figure 10. Photo showing the location of fatigue crack in welded element of bridge span and application of UP during the repair of crack



Figure 11. Enlarged view of the zone of repair (welding +UP treatment) of fatigue crack in welded element of bridge span.

5. Summary

1. Ultrasonic Peening is a relatively new and promising technique for fatigue life improvement that could be efficiently used for rehabilitation and repair of welded elements and structures.
2. The application of Ultrasonic Peening for treatment of welded elements of existing structures provides, practically, the same increase in fatigue life of welded elements that could be achieved by treatment after/during construction.
3. The results of fatigue testing of large-scale specimens showed that the welding and subsequent application of ultrasonic peening provides the highest endurance of specimens with fatigue cracks as compared with other considered techniques for fatigue life improvement.
4. The modern equipment for Ultrasonic Peening could be efficiently applied for rehabilitation and repair of welded elements of highway and railway bridges

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