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ABSTRACT

Weld repairs are commonly used to improve, update, and rework parts and structural elements. The results of experimental investigation of fatigue life of structural elements containing fatigue cracks repaired by welding are considered in this document. Two types of repairs were considered. In the first case, the welding was applied for repair of fatigue cracks in base metal (not welded). The fatigue cracks in large-scale specimens of base metal were repaired by welding and subjected to further fatigue testing.

In the second part of experimental studies, the efficiency of weld repair of welded elements containing fatigue cracks originated at the weld toe was considered including the second and third repair of welded specimens with subsequent fatigue testing of large-scale specimens.

In both studies of weld repair of fatigue cracks in base metal and in welded elements the efficiency of the application of the Ultrasonic Peening (UP) for fatigue improvement of repaired by welding structural elements was investigated as well. Examples of industrial applications of weld repair of fatigue damaged elements including application of UP for fatigue improvement are also considered.

KEYWORDS: welding, fatigue cracks, repair, fatigue strength, ultrasonic peening

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Abstract

Weld repair is commonly used to improve, update, and rework parts and structural elements. The results of experimental investigation of the fatigue life of structural elements containing fatigue cracks repaired by welding are considered in this document. Two types of repairs were considered. In the first case, the welding was applied for repair of fatigue cracks in base metal (not welded). The fatigue cracks in large-scale specimens of base metal were repaired by welding and subjected to further fatigue testing.

In the second part of experimental studies, the efficiency of weld repair of welded elements containing fatigue cracks originated at the weld toe was considered including the second and third repair of welded specimens with subsequent fatigue testing of large-scale specimens. In both studies of weld repair of fatigue cracks in base metal and in welded elements the efficiency of the application of the Ultrasonic Peening (UP) for fatigue improvement of repaired by welding structural elements was investigated. Examples of industrial applications of weld repair of fatigue damaged elements including application of UP for fatigue improvement are also considered.

Introduction

Welded elements in as-welded condition are much inferior to base metal in fatigue resistance. The fatigue limit for butt joints in low-carbon steel is approximately 50%, while for overlap joints it ranges from 15 to 25% of the fatigue limit for base metal. As for welded joints in steels of high strength, the relative decrease in fatigue strength is even greater [1-3]. Due to the low fatigue resistance of welded elements the proportion of the fatigue fractures of welded structures continues to grow and reached 30-70% of the total number of fractures, depending of the type of structures.

A large number of fatigue damage cases in welded elements and structures were reported [4]. Fatigue cracks are found in welded bridges in various welded details, particularly in the location where plural members are complicatedly weld-assembled. Some of those cracks initiate from weld toe, and the others are from weld inside, like weld root and embedded defect. These cracks may lead to the failure of the cracked elements or even to the collapse of structures. Therefore, it is important to detect the fatigue crack and to apply appropriate countermeasures like repair, retrofit and improvement.

The causes of fatigue damage of welded elements may be classified as follows [4]:

1. Welding defects were included at the time of fabrication.
2. An inappropriate structural detail of low fatigue strength had been adopted.
3. Stresses and deformations unforeseen in design occurred in real service of welded elements
4. The structure behaved in a manner not expected such as due to vibration etc.

The following measures are typically applied for repair and fatigue life improvement of welded elements and structures [4]:

A. removal of crack

B. re-weld

C. surface treatments such as TIG dressing and Peening

D. re-weld + post weld surface treatments

E. installation of high strength bolts

F. shape improving

G. stop hole drilling

H. modification of connection detail

The repair of fatigue cracks by gouging and welding is a method commonly used in the number of industries. It is recommended to excavate the crack to sound metal by grinding, flame or arc gouging or chipping out the damaged metal to form a clean welding groove. Either a V groove or U groove wherein complete penetration of the weld metal is secured may be used. Also it is recommended after excavation of crack and prior to welding to examine the surface of the groove by magnetic particle, dye penetrant, or other acceptable test method.

Fatigue strength of repair weld

R. Dexter et.al. conducted fatigue tests with full-scale-welded beams containing a variety of butt welds in the flanges. The tests establish the original fatigue strength of these details and the remaining fatigue strength after the cracked specimens were repaired in various ways. Fatigue tests were carried under 4 point bending loading with a zero mean load and constant amplitude cyclic load which created a nominal stress range of 120 MPa. The results of fatigue testing of original butt welds and repaired butt welds are presented in [4]. It was concluded that the fatigue life of a butt weld is completely restored by the gouging and re-welding repair. Based on the results of fatigue testing of welded elements after multiple cycles of a repair of butt welds at a single location of a beam, R. Dexter et.al. concluded that multiple cycles of repair, up to four times of repairs, did not have any detrimental effect on the restored fatigue strength.

Typically, when the welding is used for repair one of the post-weld stress-relieving techniques is applied such as heat treatment, shot peening or hammer peening. In this report the results of experimental studies of the efficiency of weld repair of fatigue cracks in base (not welded) material and welded elements containing fatigue cracks originated at the weld toe were considered including the second and third repair of welded specimens with subsequent fatigue testing of large-scale specimens. In both cases the efficiency of the application of the Ultrasonic Peening for fatigue improvement of repaired by welding structural elements was also analyzed.

Technology and Equipment for Ultrasonic Peening of Welded Elements

One of the new and promising processes for effective redistribution of welding residual stress is Ultrasonic Peening (UP) [5-8]. During the different stages of its development the UP process was also known as ultrasonic impact treatment (UIT) [9-11] and ultrasonic impact peening (UIP) [12-13]. The beneficial effect of UP is achieved mainly by relieving of tensile residual stresses and introducing of 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 fatigue testing of welded specimens 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.

Figure 1. Basic Ultrasonic Peening system for fatigue life improvement of welded elements and structures

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 - 8 kg) includes an ultrasonic transducer, a generator and a laptop (optional item) with software for UP optimum application - maximum possible increase in fatigue life of welded elements with minimum cost, labor and power consumption. The basic UP system shown in Figure 1 could be used for treatment of weld toe, welds and larger surface areas. Figure 2 shows the set of working heads for different applications of UP. The working head could be easily replaced, if necessary.

Figure 2. Set of the changeable working heads for different application of Ultrasonic Peening

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures [6,7]. The results of fatigue testing of large-scale welded samples imitating the transverse non-load-carrying attachments where the UP was applied to specimens in as-welded condition and also after

50% of expected fatigue life are presented on Figure 3. 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.

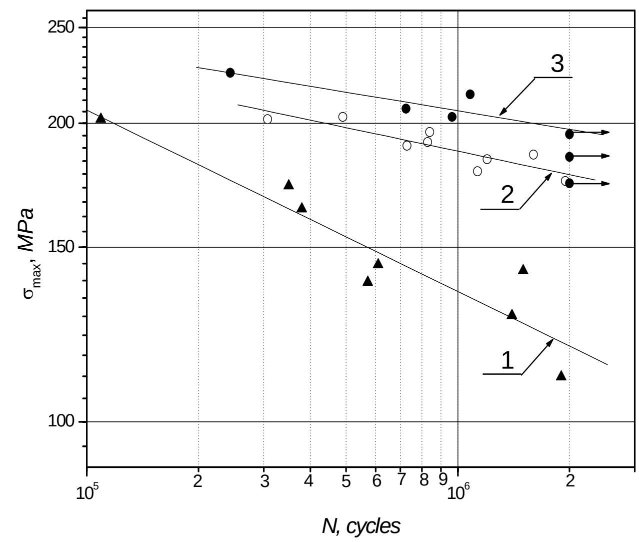

Figure 3. Fatigue curves of welded elements (transverse non-load-carrying attachment): 1 – in as welded condition, 2 – UP was applied before fatigue testing, 3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition.

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

Application of UP for Weld Repair of Fatigue Cracks in Base (Not Welded) Material

The results of experimental investigation of the efficiency of traditional and new techniques for fatigue life improvement of structural elements with fatigue cracks are considered in this chapter. Large-scale specimens (650x250x14mm) containing fatigue cracks for further fatigue testing are presented on Figure 4. The efficiency of the application of following fatigue crack restraining and repair techniques were considered:

- 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.

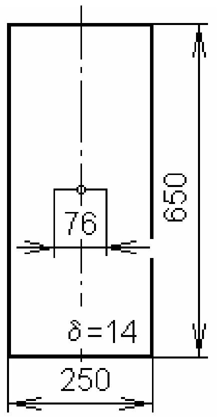

Figure 4. Drawing of specimen with fatigue crack for further fatigue testing

Chemical composition and mechanical properties of considered material are presented in Tables 1 and 2.

Table 1. Chemical composition considered material

Steel	%					
	C	Si	Mn	Cr	Ni	Cu
Low Alloyed	0,096	0,57	0,71	0,25	0,27	0,3

Table 2. Mechanical properties of considered material

Steel	Sy (MPa)	Su (MPa)	δ_5 (%)	KCV^{-40} (J/cm^2)
Low Alloyed	367	553	28	64

The cyclic testing conditions were zero-to-tension stress cycle (R=0) with the maximum stresses of 155 MPa. The Figure 5 shows the view of the central zone of one of the samples after fatigue testing where the tips of the crack were drilled and high strength bolts were installed to increase the service life of fatigue damaged considered specimen.

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 after application of above-mentioned improvement techniques are summarized in Figure 6.

Figure 5. The zone of fatigue fracture of sample with drilled holes and high strength bolts

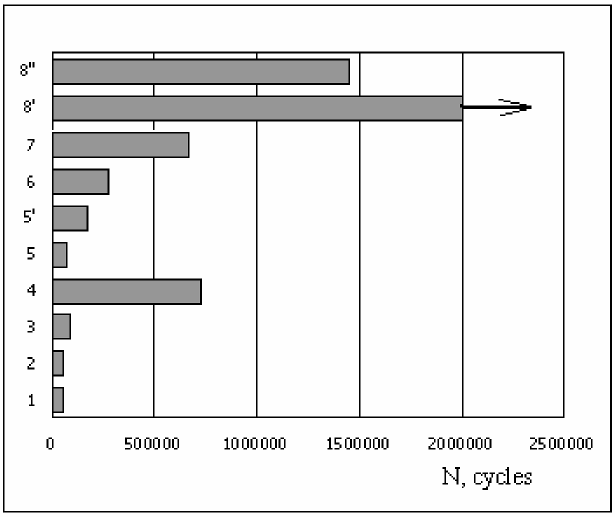

Figure 6. Comparison of the efficiency of different techniques
of restraining and repair of fatigue cracks:
1 - initial condition, 2 and 3 - drilling of the crack tips with and without cold working, 4 - drilling of the crack tips with installation of high strength bolts, 5 – overloading (yield strength), 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.

Application of Ultrasonic Peening for Weld Repair of Fatigue Cracks in Welded Elements

In the second part of experimental studies, the efficiency of weld repair of welded elements containing fatigue cracks originated at the weld toe was considered including the second and third repair of welded specimens with subsequent fatigue testing of large-scale specimens. In this study the efficiency of the application of the UP for fatigue improvement of repaired by welding structural elements was also investigated.

Figure 7 shows the drawings of large-scale welded specimens (600x100x30mm) containing non-load carrying longitudinal attachments for fatigue testing [14]. The manual arc welding with full penetration was used for samples preparation.

The cyclic testing conditions were zero-to-tension stress cycle (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 by UP. The weld toe of "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 on Figure 8. The general view of welded samples after repair and fatigue testing is shown on Figure 9.

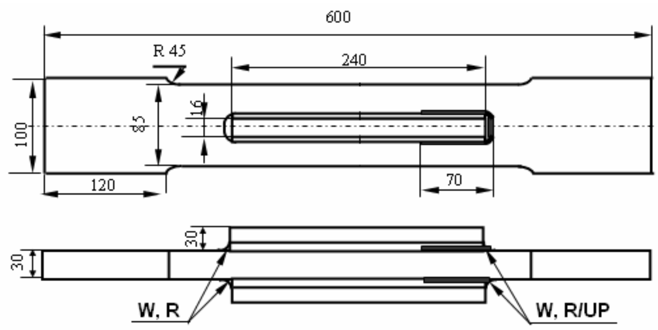

Figure 7. Drawings of welded specimens for fatigue testing at different conditions:
W – as-welded condition;
R - repair by gouging and welding;
R/UP – repair by gouging, welding and UP

The fatigue testing of large scale specimens showed that the repair of fatigue cracks by welding restore the fatigue strength of welded element 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.

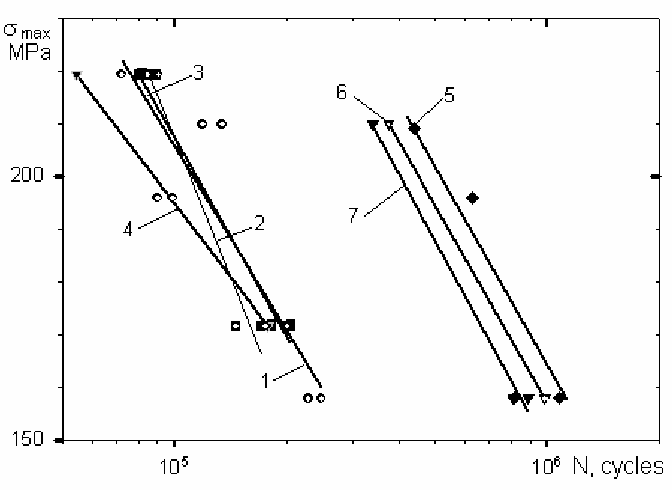

Figure 8. Results of fatigue testing of welded elements:
1 - as-welded condition,
2, 3 and 4 – after first, second and third weld repair,
5, 6 and 7 - after first, second and third weld repair
with application of UP

The comparison of the efficiency of weld repair of fatigue cracks with and without application of UP are summarized on Figure 10. This diagram illustrate the fatigue behavior of the same welded elements in case where UP is not applied (I), UP
applied after weld repair (II) and UP is applied before/during the first phase of service life. Here, 1 unit of service life corresponds to ~ 240.000 cycles of loading at the stress range 158 MPa and to ~ 75.000 at the stress range 220 MPa. Every circle on the drawing starting from the number 1 on service life axis indicate the fatigue fracture and repair of welded element. The benefit from application of UP for weld repair and rehabilitation of welded elements is obvious.

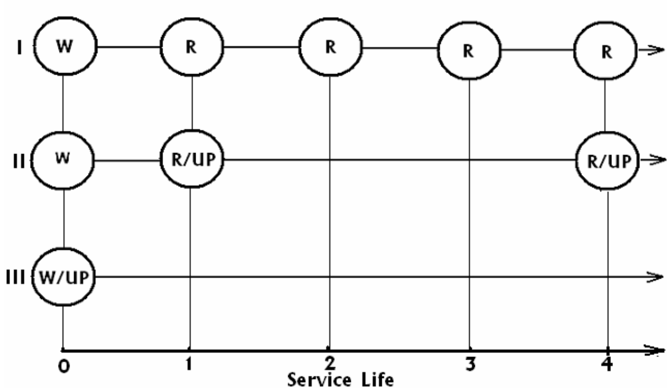

Figure 10. Diagram showing the endurance
of welded element:
I - fatigue crack is repaired by gouging and welding,
II - fatigue crack is repaired by gouging, welding and UP,
III – UP is applied before/during the first phase
of service life,
W – as-welded condition,
R - repair by gouging and welding,
R/UP – repair by gouging, welding and UP,
W/UP- welding and UP

The UP technology and equipment were successfully applied in different industrial projects for weld repair and rehabilitation of parts and welded elements. The areas/industries where the UP was applied successfully include: Railway and Highway Bridges, Construction Equipment, Shipbuilding, Mining, Automotive and Aerospace. A two examples of application of UP for repair and rehabilitation of welded elements subjected to fatigue loading are shown on Figure 11 and 12.

Figure 9. The view of welded samples after repair and
subsequent fatigue testing

Figure 11. Application of UP for rehabilitation and repair of
welded elements of mining equipment

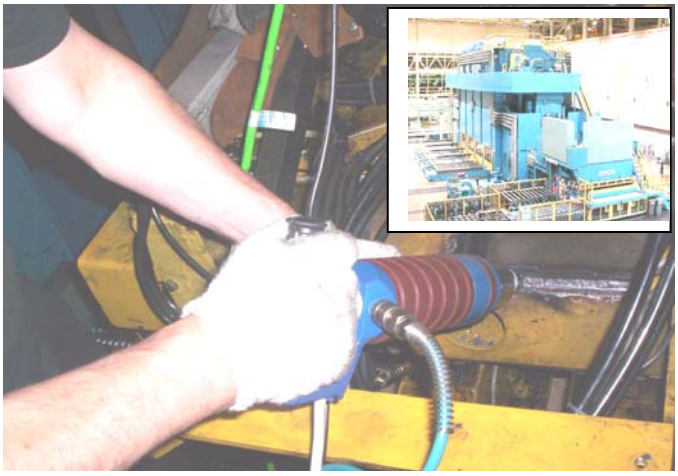

Figure 12. Application of UP for rehabilitation and repair of welded elements of stamping equipment

Summary

1. The results of fatigue testing of large scale specimens demonstrated that the repair of fatigue cracks by gouging and welding with subsequent application of UP provided the higher fatigue life after repair in comparison with the application of other techniques for restraining/prevention of fatigue crack origination and propagation.

2. For welded elements with fatigue cracks originated at the weld toe the repair of cracks by welding restores the fatigue strength of welded element to the initial as-welded condition including second and third repair of fatigue cracks by welding.

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

4. The analysis of the fatigue data shows that the application of the UP before/during the first phase of service life of welded elements and structures will significantly increase the service life, prevent the fatigue damage of welded joints and necessity of the repair of welded elements.

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