FATIGUE STRENGTH OF A LONGITUDINAL ATTACHMENT IMPROVED BY ULTRASONIC IMPACT TREATMENT

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ABSTRACT

Improvement methods can be divided into two main groups: weld geometry modification and residual stress modification. The former remove weld toe defects and/or reduce the stress concentration while the latter introduce compressive stress fields in the area where fatigue cracks are likely to initiate. Ultrasonic impact treatment belongs to residual stress improvement methods. It makes use of an ultrasonic carrier frequency to accelerate hardened tools that, in turn, impact the weld toe. The fatigue strength of non-load carrying attachments in the as-welded condition has been experimentally compared to the fatigue strength of ultrasonic impact treated welds. Longitudinal attachment specimens made of two thicknesses of steel S355 J0 have been tested for determining the efficiency of ultrasonic impact treatment. Treated welds were found to have about 50% greater fatigue strength, when the slope of the S-N-curve is three. High mean stress fatigue testing based on the Ohta-method did not decrease the degree of weld improvement due to UIT. This indicated that the method could be also applied for large fabricated structures operating under high reactive residual stresses equilibrated within the volume of the structure.

IIW-Thesaurus keywords: *Fatigue strength; Mechanical properties; Fatigue loading; Loading; Ultrasonic processing; Post weld operations; Peening; Work hardening; Combined processes; Fatigue cracks; Cracking; Defects; Corrosion; Compression; Stress distribution; Residual stresses; Welded joints; Weld toes; Weld metal; Weld shape; Test pieces; Thickness; Nonload carrying; GMA welding; Arc welding; Gas shielding arc welding; Process parameters; Statistical methods; Accessories; Carbon manganese steels; Steels; Practical investigations; Classifying; Reference lists.*

1 INTRODUCTION

Prevention of fatigue failure is a dominant objective in the design of many load-carrying structures used in the mechanical engineering and process industries. Construction and agricultural equipment, ships, cranes, and rotating equipment are just a few examples of heavily fatigue loaded complex welded structures. During cyclic loading, the weakest point in fabricated structures tends to be the welded joints themselves. Welds represent regions of global stress concentration, very high local stress concentration, and normally possess high tensile residual stress. For these reasons, fatigue cracks in welded structures are normally observed to initiate and begin cycle-by-cycle growth very early in the service life of a structure [1].

Numerous methods have been investigated to improve the fatigue resistance of welded joints. Weld improvement techniques can be implemented in the initial fabrication stage, but more common is the use of weld improvement techniques during the repair of large structures where fatigue cracks have been observed indicating that the original design strength was not sufficient. To avoid unacceptable limits on the design capacity, it is desirable to enhance the fatigue resistance of common attachment details such as transverse stiffeners, cover plates, gusset plates and other welded details [2]. Enhancement of fatigue resistance of welded joints by plastic deformation of the surface and by improvement of weld toe characteristics is well established. It is known that the conventional improvement techniques such as grinding, shot peening, air hammer peening, gas tungsten arc (TIG) re-melting and welding consumables with improved weld toe characteristics can improve fatigue resistance of welded details [2-4].

Ultrasonic impact treatment (UIT) was originally developed in the former Soviet Union for use in shipbuilding to reduce welding residual stresses and deformations, introduce compressive stresses in fatigue critical locations, increase corrosion fatigue strength of welded joints and specifically enhance the fatigue resistance at subzero temperatures [2, 5-11]. The UIT tool and units for vibration generation and control of treatment parameters are shown in Fig. 1. Other mechanical residual stress modifying techniques, e.g., hammer and needle peening, operate at relatively low frequencies, typically in the range of 50 to 100 Hz. The effectiveness of such

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Fig.1. The 27 kHz ultrasonic impact treatment equipment.

treatments always depends on the pressure on the tool against the treated surface (not less than 20 kgf). The result is that the severe vibrations of the tool are transmitted directly to the hands of the operator, the peening tool moves in an unsteady manner, necessitating considerable effort to keep the tool aligned on the weld toe line during treatment. This leads to some concerns about quality control when such methods are applied. Additionally, the high levels of vibration and noise make these peening methods uncomfortable. In contrast, the UIT method is based on the generation and utilisation of impacts from ultrasonic vibrations at a carrier frequency of approximately 27 kHz. Because of this, the UIT method is a very effective treatment that is independent of the pressure on the tool, which is very small (not greater than 3 kgf without the weight of the tool), and the noise and vibration are much lower. The ease of use of the UIT method may result in considerable benefits in terms of quality of the treatment compared with conventional peening methods [2, 11]. A photograph of the UIT tool in use and the smooth transition obtained in the treated weld toe region is shown in Fig. 2.

In the current study, the fatigue strength of welded connections has been measured experimentally. Strength in

Fig.2. The performance of ultrasonic impact treatment.

the as-welded condition is compared with the strength of UIT treated specimens for two specimen thicknesses. Non-load carrying longitudinal attachment specimens have been used to estimate the efficiency of UIT and examine possible material thickness effects.

2 POST WELD TREATMENT METHODS

Post-weld fatigue improvement methods can be divided into two main groups: weld geometry modification methods and residual stress improvement methods.

The former removes weld toe defects and/or reduces the stress concentration while the latter introduces beneficial compressive stresses in the area where cracks are likely to initiate. The UIT method belongs to residual stress improvement methods and at the same time significantly improves the weld geometry at the toe of the weld. A summary of the various improvement techniques is shown in Fig. 3 [4, 12]. In this figure, ultrasonic peening is classified as a mechanical peening method that has a primary function of improving the residual stress state and introducing compressive stresses in the stress concentration zone. This paper addresses only this aspect of the UIT effect on the welded joint material.

UIT is a method for improving the quality and reliability of welded joints. The method is able to provide a more gradual weld metal to base metal transition as compared to conventional peening techniques. The area being treated is highly plastically deformed which has the

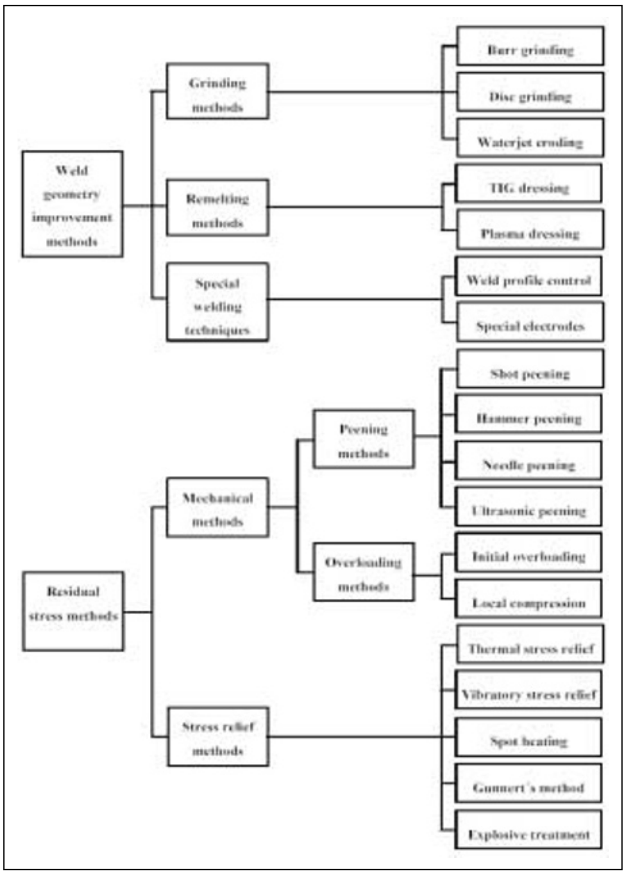

Fig. 3. Classification of post weld treatment methods [12].

effect of both work hardening the material and introducing favourable compressive residual stresses. UIT can be used to improve fatigue strength and, under certain conditions, form a so-called “white-layer” possessing high corrosion fatigue resistance [8].

3 TEST SPECIMENS AND TESTING METHODS

Longitudinal non-load carrying test specimens were fabricated from S355 J0 steel using both 5 mm and 8 mm thick plate. Chemical composition and mechanical properties of S355 J0 are presented in Tables 1 and 2. Specimen geometry is shown in Fig. 4. Approximately half of the test specimens were treated with UIT in the weld toe region at the attachment ends. This is the area most sensitive to fatigue cracking for axially loaded as-welded specimens. This weld geometry is often used in laboratory fatigue studies of welded connections because even relatively small specimens have high tensile residual stresses similar to those observed in larger and more complex structures. Welding parameters and UIT parameters are given in Table 3.

Table 1. Chemical composition of material S355 J0 [%].

C	Mn	Si	P	S	N
0.23	1.70	0.60	0.050	0.050	0.011

Table 2. Mechanical properties of material S355 J0.

Yield strength R_{eh} [MPa]	Ultimate strength R_m [MPa]	Elongation A_5 [%]	Impact ductility *KV* [J, 0 °C]
355	490-630	20	27

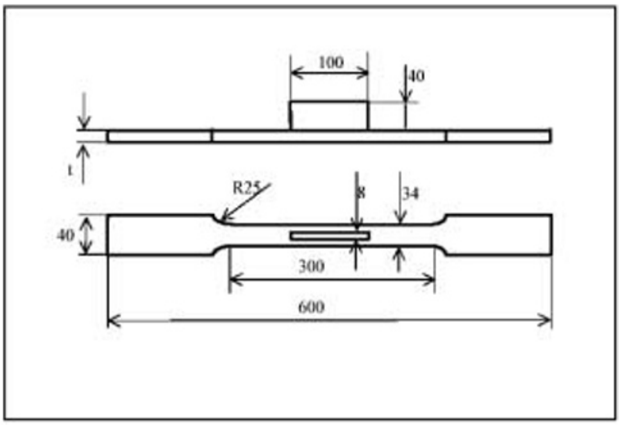

Fig. 4. Geometry of the longitudinal non-load carrying welded specimen (*t*= 5 mm or 8 mm).

Fatigue testing was performed using a 150 kN servo-hydraulic test frame using constant amplitude axial loading. Test frequency was 5 Hz. The ratio between minimum and maximum stress was R = $\sigma_{min} / \sigma_{max}$ = 0.1. Some tests were also carried out using a constant maximum stress ($\sigma_{max} = f_y$) based on the test method developed by Ohta *et al.* [13]. In this paper, this test procedure is referred to as the Ohta method and is intended to simulate the detrimental effect of yield magnitude residual stresses that are present in large fabricated structures but are lacking in most small-scale test coupons.

Table 3. Welding and ultrasonic impact treatment parameters.

Welding parameters	
Welding process	Gas metal arc welding
Current [A]	280
Voltage [V]	29
Shield gas: Argon / CO_2 [%]	90 / 10
Filler material	OK 12.51
Travel speed [cm/min]	34
Ultrasonic impact treatment parameters	
Depth of treated groove [approximate, mm]	0.5
Diameter of UIT indenter end [mm]	3
Carrier frequency of transducer vibrations [nominal, kHz]	27
Ultrasonic vibration amplitude/power [μm/W]	30/1 100*
Ultrasonic impact frequency [kHz]	350-400*
Amplitude of ultrasonic impacts, rebounds [mm]	1.5-1.8*
Press force on the tool without its weight [kgf]	Up to 2.5*
Groove roughness	Not greater than 2.5 μm (sampling length of 2.5 mm)
Treatment speed [cm/min]	42

*Data provided by the Northern Scientific and Technology Company, Severodvinsk, Russia.

4 RESULTS

For all as-welded specimens, fatigue cracks initiated from the weld toe while fatigue cracking in all UIT treated welds initiated at UIT groove. Measured fatigue strength of the welded specimens is presented in Figs. 5 and 6 in the form of S-N curves and numerically in Appendix 1. In these figures the stress values are recorded as the structural stress ranges at the weld toe most susceptible to fatigue failure. The structural stress range is the nominal stress range multiplied by a structural concentration factor, K_s. The mean value of concentration factor was K_s = 1.7 for 5 mm thick specimens and K_s = 1.4 for 8 mm thick specimens. The advantage of using structural stress as compared to nominal stress is that secondary bending stresses are also considered and specimens with different geometries are more easily compared. One strain gauge per test specimen has been used to help evaluate the structural stress. The data points including the test results are presented in Appendix 1.

5 DISCUSSIONS

As can be seen from Fig. 5.1, the UIT treated specimens had consistently greater fatigue strength. In this figure, tests that resulted in run-outs are indicated RO. The as-welded specimens clearly tend to follow a curve with slope near 3 while the UIT specimens follow a curve with a slope closer to 10. An SN slope of 3 is commonly observed for welded structures and normally indicates that cracking has initiated very early in the fatigue process. The greater slope of the UIT treated specimens normally indicates that a significant crack initiation period has been added to the total fatigue life. There is only a slight difference in the fatigue behaviour of 5 mm and 8 mm thick specimens.

Fig. 6.1 shows the UIT treated welds for 5 and 8 mm thick specimens tested using both R = 0.1 loading and the Ohta method ($\sigma_{max} = f_y$). It can be observed that test at R = 0.1 had somewhat longer lives but both sets of data tended to have similar degrees of scatter.

Data has been evaluated according to the statistical methods outlined by the Huther [14]. The term fatigue class (FAT) indicates the characteristic stress range in MPa, which gives a fatigue life of two million cycles at 95% survival probability. Statistical values of test series have been calculated according to equations (1) – (5).

$$\Delta\sigma_i^m \cdot N_i = C_i = FAT^m \cdot 2000000 \quad (1)$$

$$\log C_{50\%} = \frac{\Sigma \log C_i}{n} \quad (2)$$

$$s = \sqrt{\frac{\Sigma (\log C_i - \log C_{50\%})^2}{n-1}} \quad (3)$$

$$\log C_{95\%} = \log C_{50\%} - s \cdot (1{,}64 + \frac{1{,}15}{\sqrt{n}} \quad (4)$$

$$FAT_{95\%} = \sqrt[m]{\frac{C_{95\%}}{2000000}} \quad (5)$$

In these equations:

$\Delta\sigma i$ is the stress range of specimen i,

Ni is the number of cycles to failure for specimen i,

s is the standard deviation of the test series,

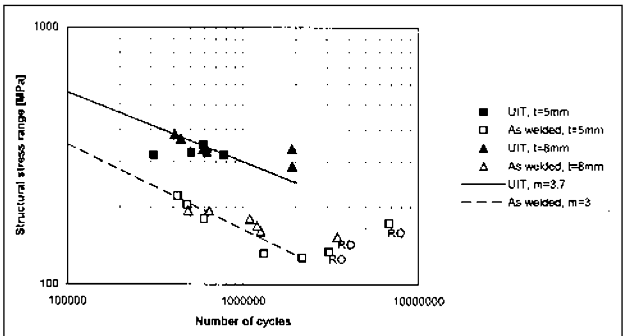

Fig. 5.1. Structural stress comparison between as-welded and UI-treated test series, R = 0.1.

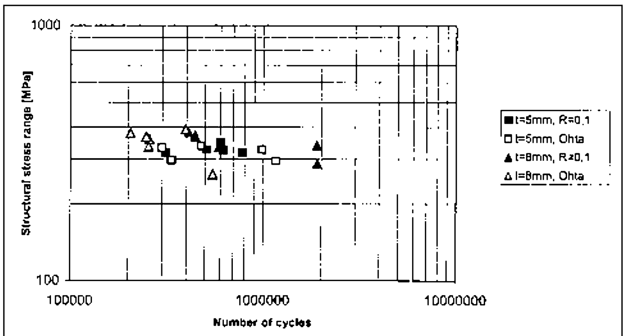

Fig. 6.1. Structural stress comparison between R = 0.1 and Ohta – test series, UIT.

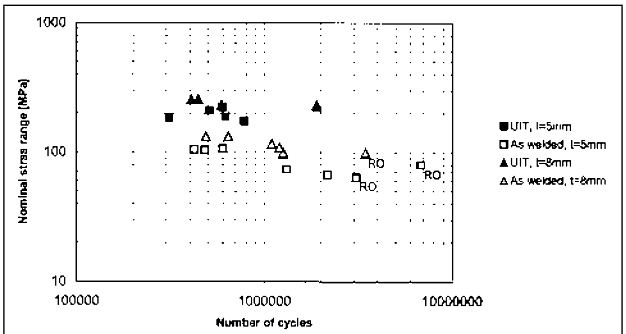

Fig. 5.2. Nominal stress comparison between as-welded and UI-treated test series, R = 0.1.

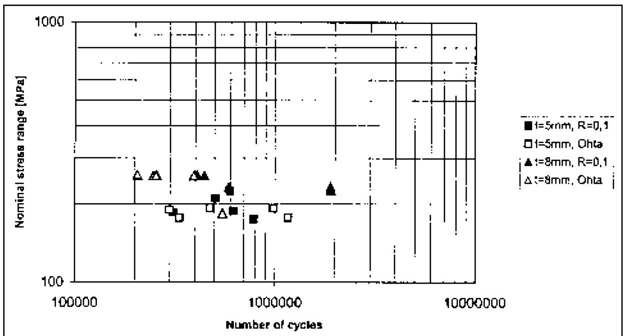

Fig. 6.2. Nominal stress comparison between R = 0,1 and Ohta – test series, UIT.

m is the slope of the S-N curve (assumed m = 3 for welded structures),

Ci is the fatigue capacity of specimen *i*,

$C_{50\%}$ is the computed mean fatigue capacity of test series, $C_{95\%}$ is the characteristic fatigue capacity of the test series,

n is the number of test specimens, and

$FAT_{95\%}$ is the characteristic fatigue class based on 95% survival probability.

Results of the statistical analysis for the six sets of data are presented in Tables 4 and 5. According to Table 4, the as-welded fatigue strength for both material thicknesses was greater than the hot spot design value of 100 MPa indicating that the welds were somewhat stronger than average even prior to UIT. However, the strength of ultrasonic impact treated welds based on m = 3 was 46% higher than the fatigue class for as-welded specimens. Traditional residual stress improvement methods, i.e., hammer peening, have been included in design recommendations of International Institute of Welding. It is recommended that for structures with plate thickness larger than 25 mm, the benefit for hammer peening is assumed to be a factor of 1.5 on allowable stress range [15]. This value is consistent with values obtained in this study.

Table 5 provides a comparison of UIT treated welds tested at both R = 0.1 and according to the Ohta-method. As seen in the table, the fatigue class of R = 0.1 data sets are 19% higher than fatigue class for Ohta-method data sets. This degree of difference is consistent with design recommendations summarised by Hobbacher [16].

"*In case of S-N data, proper account should be taken of the fact that residual stresses are usually low in small-scale specimens. The results should be corrected to allow for greater effects of residual stresses in real components and structures. This may be achieved either by testing at high R-ratios, e.g. R = 0.5 or by testing at R = 0 and lowering the fatigue strength at 2 million cycles by 20%*"

Table 4. Structural fatigue classes $FAT_{95\%}$ of welded and treated series (m = 3), R = 0.1.

	UIT	AW	UIT / AW
t = 8 mm	172	115	1.50
t = 5 mm	160	110	1.45
8 mm / 5 mm	1.08	1.05	

Table 5. Structural fatigue class $FAT_{95\%}$ comparison between thickness and R-ratio (m = 3), UIT.

	R = 0,1	Ohta-method	R = 0.1 / Ohta-method
t = 8 mm	172	145	1.19
t = 5 mm	160	135	1.19
8 mm / 5 mm	1.08	1.07	-

High stress ratio fatigue testing did not erase the degree of fatigue improvement obtained in the UIT treated welds. The method therefore should be useful, therefore, also for improvement of large-scale structures.

From these tables it is seen that the 8 mm thick specimens had consistently greater fatigue strength that did the 5 mm thick specimens. This result is somewhat contrary to what is expected. However, it can be noted that the stress values are based on structural stress. The structural stress concentration factor used for the 5 mm thick specimens was 1.7 as compared to only 1.4 for the 8 mm thick specimens. In other words, based on nominal stress the thinner specimens had greater fatigue strength. The difference in strength is small and has not been further investigated here.

It should be noted that statistical analysis of the UIT treated specimens was done using an assumed slope of 3. This is a conservative estimate. For long lifetimes the fatigue strength improvement tends to be much greater. The effect of free slope has been presented in Table 6. Because there was only a small difference in the measured fatigue strength of 5 and 8 mm thick specimens, these data have been integrated to produce the values from Table 6. In the as-welded condition, the free slope m = 2.8 is close to the assumed slope of SN - curve for welded structures m = 3. The fatigue class based on free slope is 66% greater for UIT treated welds than for as-welded specimens.

6 CONCLUSIONS

This paper presents Ultrasonic Impact Treatment as a means of improving the fatigue strength of welded joints. Fatigue tests on 5 mm and 8 mm longitudinal non-load carrying joints in both the as-welded and UIT treated condition have been performed. Stress values are recorded as structural stress ranges, which have the advantage in that potential secondary bending stresses are also taken into consideration and specimens with different geometries are more easily compared.

Statistical evaluation indicates that the fatigue class of ultrasonic impact treated welds was about 46% higher than the fatigue class for as-welded specimens based on the recommended fixed SN curve slope, m = 3. This is similar to IIW recommendations for other improvement techniques. Based on free slope regression analysis the increase of fatigue strength is clearly higher. Free slope regression analysis of UIT treated welds produced m = 3.8. In that case the fatigue strength improvement at 2×10^6 cycles is 66%.

Table 6. Structural fatigue strength based on free and fixed (m = 3) slope regression analysis.

	m	$FAT_{50\%}$	$FAT_{95\%}$
AW, R = 0.1 free slope	2.8	135	109
AW, R = 0.1 fixed slope	3	130	111
UIT, R = 0.1 free slope	3.7	249	184
UIT, R = 0.1 fixed slope	3	232	162

The effect of specimen thickness on fatigue strength was only slight. The fatigue class of specimens $t = 8$ mm is 5-8% higher than fatigue class of specimens $t = 5$ mm. The cause of this difference has not been investigated.

Fatigue strength based on low mean stress testing ($R = 0.1$) is about 19% higher than the measured fatigue strength at a high mean stress obtained using the Ohta-method ($\sigma_{max} = f_y$). This value is similar to that expected for as-welded structures and indicates that UIT does not loose its effectiveness for large fabricated structures that have yield magnitude reactive residual stress states.

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Appendix 1

UIT: ultrasonic impact treatment, AW: as welded
T: thickness of specimen [mm]
R: σ_{min} / σ_{max}, Ohta: $\sigma_{max} = f_y$
$\Delta\sigma_{hs}$: structural stress range [MPa]
$\Delta\sigma_{nom}$: nominal stress range [MPa]
N: number of cycles
Observation: F-failure at weld tœ/treated groove

	T	*R*	$\Delta\sigma_{hs}$	$\Delta\sigma_{nom}$	*N*	Observation
UIT	5	0.1	349	224	596082	F
UIT	5	0.1	318	186	310170	F
UIT	5	0.1	324	188	620074	F
UIT	5	0.1	327	210	505913	F
UIT	5	0.1	318	175	781200	F
UIT	5	Ohta	333	190	298108	F
UIT	5	Ohta	338	193	473704	F
UIT	5	Ohta	327	192	980692	F
UIT	5	Ohta	297	177	333199	F
UIT	5	Ohta	295	177	1163070	F
AW	5	0.1	180	107	599377	F
AW	5	0.1	221	105	422755	F
AW	5	0.1	127	67	2173795	F
AW	5	0.1	132	74	1313035	F
AW	5	0.1	204	104	480284	F
AW	5	0.1	173	80	6814655	Run-Out
AW	5	0.1	134	64	3086407	Run-Out
UIT	8	0.1	288	225	1902884	F
UIT	8	0.1	369	257	441958	F
UIT	8	0.1	383	257	407610	F
UIT	8	0.1	335	232	488203	F
UIT	8	0.1	338	232	1892369	F
UIT	8	Ohta	360	258	256226	F
UIT	8	Ohta	392	257	393186	F
UIT	8	Ohta	367	257	247240	F
UIT	8	Ohta	379	259	205424	F
UIT	8	Ohta	336	257	254817	F
UIT	8	Ohta	261	184	545583	F
AW	8	0.1	193	132	485897	F
AW	8	0.1	193	132	640024	F
AW	8	0.1	161	99	1257193	F
AW	8	0.1	180	116	1091393	F
AW	8	0.1	169	109	1199013	F
AW	8	0.1	153	99	3453562	Run-Out