# ESTIMATION OF FATIGUE LIFE IMPROVEMENT FOR ULTRASONIC IMPACT TREATED WELDED JOINTS

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## Abstract

It is commonly observed that complex fabricated structures subject to fatigue loading fail at the welded connections. Some problems can be corrected by improved detail design but fatigue performance can also be improved using post-weld improvement methods. Ultrasonic impact treatment (UIT) is a relatively new and efficient post-weld improvement method. The current study presents experimental fatigue strength data of non-load carrying attachments in the as-welded and UIT treated condition. Treated welds were found to have about 50% greater fatigue strength. This improvement in strength has been modelled using the local strain approach. Material parameters in the highly cold-worked UIT treated zone have been derived using the Uniform Material Law for fatigue analysis. The stress concentration was computed using FE analysis and mean stress estimates were based on X-ray diffraction measurements of the residual stress state at in the treated zone. The predicted degree of improvement was in excellent agreement with the experimentally measured improvement.

## 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, bridges, ships, cranes and rotating equipment are a few examples of heavily fatigue loaded complex welded structures. During cyclic loading, the weakest point in fabricated structures is normally the welded joints themselves. Welds represent regions of global stress concentration, very high local stress concentration, and normally possess high tensile residual stress. A good method to improve fatigue resistance of welded joints is to increase the normally very short crack initiation period observed in weld. Methods for increasing the initiation period with some improvement method can generally be divided to two categories: methods that modify the stress distribution near the weld to produce beneficial compressive residual stress and methods that modify the local geometry of the weld toe to eliminate the initial defects and decrease the local stress concentration.

The International Institute of Welding has been active in defining both procedures and design guidelines for common post-weld treatment methods including grinding, TIG dressing, and shot and needle peening [1]. Ultrasonic impact treatment is novel post-weld improvement method, which removes weld toe effects, decreases tensile stresses and reduces the stress concentration in the fatigue critical region [2].

In this study, the constant amplitude fatigue strength longitudinal attachment in the as-welded condition is compared with the fatigue strength following ultrasonic impact treatment. Two specimen thicknesses, 5 mm and 8 mm, have been used for studying the thickness effect of UIT. The material used is structural steel S355 J0.

The analytical estimation of crack initiation period following ultrasonic impact treatment is calculated according to the local strain approach. Material parameters in the highly cold-worked UIT treated zone have been derived using the Uniform Material Law for fatigue analysis [3].

## Ultrasonic impact treatment

Ultrasonic impact treatment is a novel treatment method originally developed in the former Soviet Union for use in shipbuilding and submarine construction. When properly applied, the method is able to provide a more gradual weld metal to base metal transition reducing the local stress concentration. The area being treated is highly plastically deformed which has the effect of both work hardening the material and introducing favourable compressive residual stresses. UIT can be used to improve fatigue strength and form a so-called “white-layer” possessing high corrosion fatigue resistance [2].


FIGURE 1. The 27 kHz ultrasonic impact treatment equipment.

FIGURE 2. The performance of ultrasonic impact treatment.

## Analysis methods

### *Statistical analysis of the test data*

Data has been evaluated according to statistical methods for fatigue testing developed within the International Institute of Welding. 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. The statistical analysis of test series has been calculated according to equations (1) - (5). First, the fatigue capacity of each test specimen, *i*, in a sample is calculated using equation (1) where *m* is the slope of the S-N curve and is here assumed to be 3. $N_i$, $C_i$ and $\Delta\sigma_i$ are the number of cycles to failure, fatigue capacity, and applied stress range for specimen, *i*. In equation (5), the fatigue class *FAT* has been presented as $FAT_{95\%}$.

$$\Delta\sigma_i^m \cdot N_i = C_i = FAT_i^m \cdot 2000000 \tag{1}$$

The mean value of fatigue capacity is computed by (2) where *n* is the number of test specimens in the sample.

$$\log C_{50\%} = \frac{\sum \log C_i}{n} \tag{2}$$

The standard deviation, *s*, of the fatigue capacity of the sample is.

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

The characteristic value of fatigue capacity, $C_{95\%}$, is.

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

The characteristic fatigue class is.

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

### *Uniform material law for fatigue*

The analytical calculation of crack initiation period of ultrasonic impact treatment is based on local strain approach. The local strain approach to fatigue analysis was developed largely within the Society of Automotive Engineers Committee on Fatigue Design and Evaluation in the 1970-1980's. The original purpose of the local strain approach is fatigue life assessment of structures without welds. The local strain method was chosen because the ultrasonic impact treatment demolishes the initial crack-like defects caused by welding and a common analytical method of fracture mechanics is not applicable. The flow chart for fatigue life analysis used in this study is presented in Fig. 3.

Application of the local strain approach requires numerous material parameters than must be defined by strain controlled fatigue testing. The Uniform Material Law (UML) was developed in Germany as a means of approximating the material variables used in the local strain approach without the relatively expensive material tests.

Several parameters of Fig. 3 and Tab. 1 are based on the ultimate tensile strength $R_m$. This is not specifically known for the UIT treated material but can be estimated based on hardness. The Brinell hardness (HB) has been measured from the bottom of the UI-treated groove.

$$R_m = 3{,}45 \cdot HB \qquad (6)$$

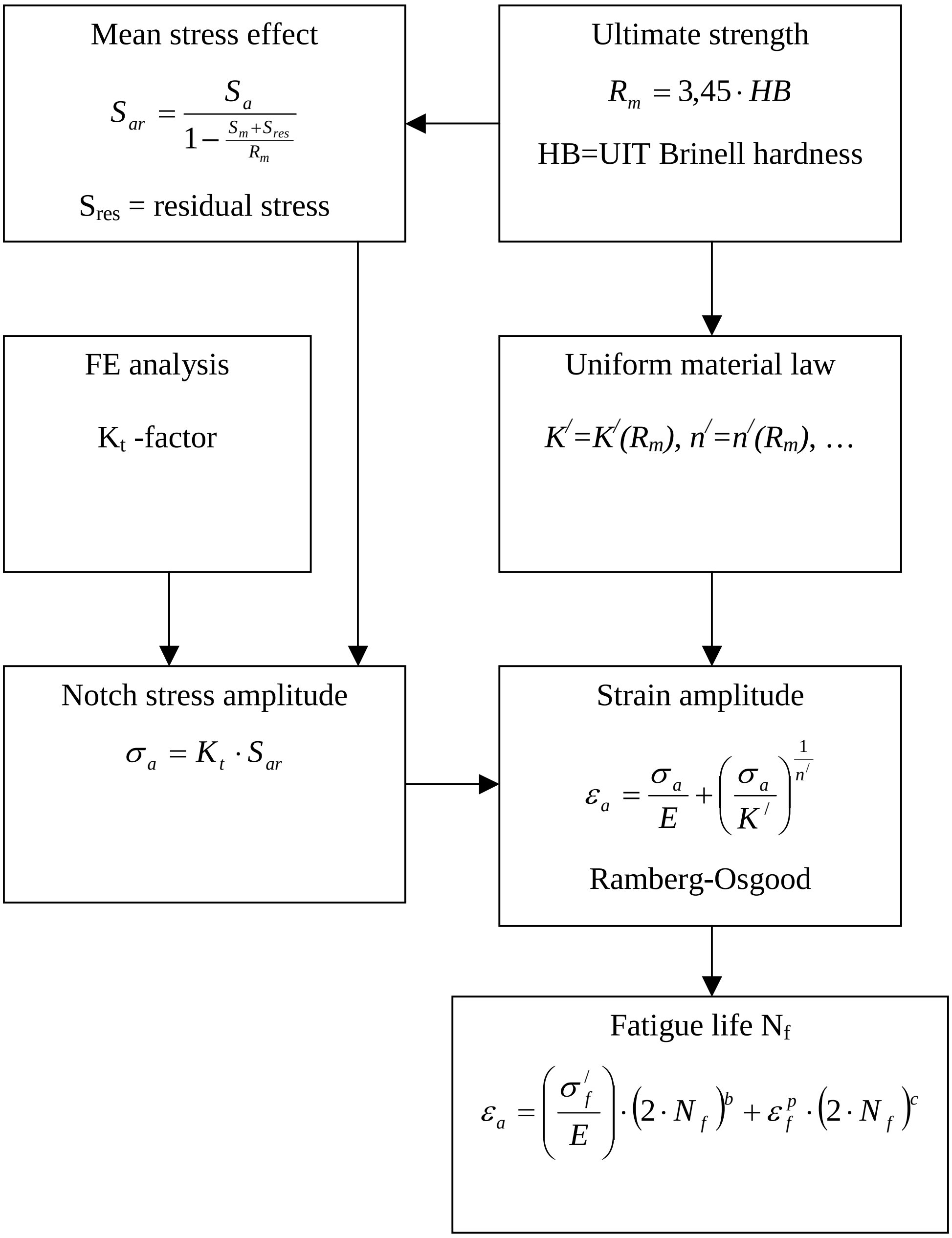


FIGURE 3. Flow chart for fatigue life analysis.

TABLE 1. Coefficients and exponents based on the uniform material law (UML).

| | Unalloyed and low-alloy steels | Aluminium and titanium alloys |
|---|---|---|
| $\sigma'_f$ / MPa | $1{,}5 \cdot R_m$ | $1{,}67 \cdot R_m$ |
| b | -0.087 | -0.095 |
| $\varepsilon_f^p$ | $0.59.\psi$ | 0.35 |
| c | -0.58 | -0.69 |
| $K'$ / MPa | $1{,}65 \cdot R_m$ | $1{,}61 \cdot R_m$ |
| $n'$ | 0.15 | 0.11 |

According to UML the dimensionless value in Eq. (7) is related to the ultimate strength $R_\mathrm{m}$ and elastic modulus $E$.

$$\begin{aligned} &\psi = 1{,}0 && \text{if } R_m / E \leq 3 \cdot 10^{-3} \\ &\psi = (1{,}375 - 125 \cdot R_m / E) && \text{if } R_m / E > 3 \cdot 10^{-3} \end{aligned} \tag{7}$$

Consideration of mean stress and residual stress is accomplished by modification of the corrected nominal stress range $S_\mathrm{ar}$ as presented in (8), where $S_\mathrm{a}$, $S_\mathrm{m}$ and $S_\mathrm{res}$ are nominal stress range, nominal mean stress and residual stress.

$$S_{ar} = \frac{S_a}{1 - \frac{S_m + S_{res}}{R_m}} \tag{8}$$

The local stress amplitude is nominal stress amplitude ($S_\mathrm{ar} = S_\mathrm{ar} / 2$) multiplied by $K_\mathrm{t}$.

$$\sigma_a = K_t \cdot S_{ar} \tag{9}$$

The strain amplitudes have been calculated with the Ramberg-Osgood relationship.

$$\varepsilon_a = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{K'} \right)^{\frac{1}{n'}} \tag{10}$$

The initiation fatigue lives have been defined based on strain amplitudes.

$$\varepsilon_a = \left( \frac{\sigma'_f}{E} \right) \cdot \left( 2 \cdot N_f \right)^b + \varepsilon_f^p \cdot \left( 2 \cdot N_f \right)^c \tag{11}$$

## Experimental and numerical methods

Longitudinal attachment fatigue test specimens were fabricated from S355 J0 structural steel using 8 mm thick plate. The test specimen geometry and dimensions are shown in Fig. 4. The specimen type has a relatively small region of high stress concentration so the location of expected fatigue crack initiation is more predictable than for many other weld geometries.

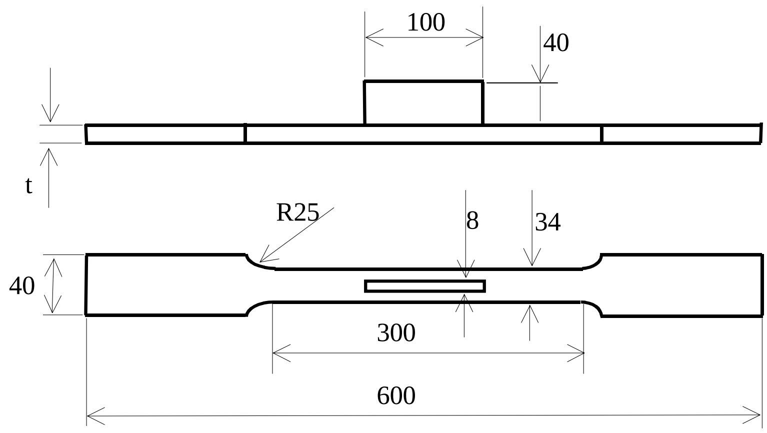


FIGURE 4. Longitudinal attachment specimen for axial tension fatigue tests, $t$ = 8 mm.

UIT has the benefit of producing a smooth weld metal to base metal transition. The finite element analysis was needed for calculating the local stress and the stress concentration factor, $K_t$, at the ultrasonic impact treated region near the end of the longitudinal attachment. The theoretical stress concentration factor is assumed to be the notch stress divided by nominal stress. The finite element model of ¼ of original size is shown in Fig. 5. The computed stress concentration factor was $K_t$ = 2,39 when the thickness of material is 8 mm.

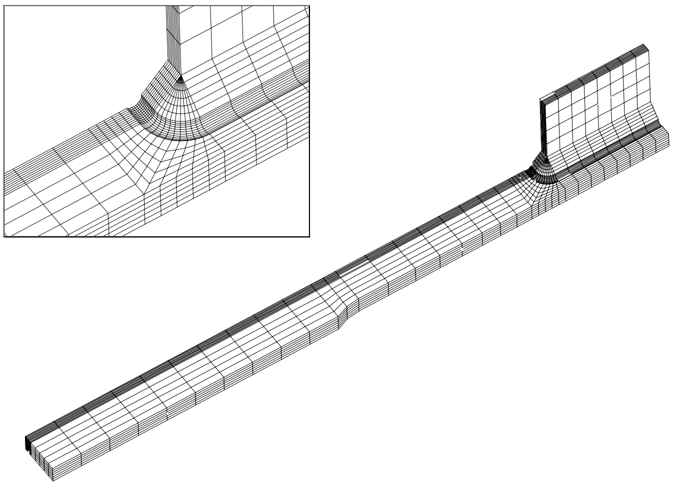

FIGURE 5. Finite element model of longitudinal attachment specimen.

One of the main advantages of the UIT method is its ability to induce high compressive residual stress in the region of the weld. The surface residual stresses developed as a result of ultrasonic impact treatment have been measured using X-ray diffraction. The purpose of X-ray measurement was to find the interaction between residual stresses and the state of treatment. The state of treatment was quantified as the total treatment time over some area of the weld. When computing the fatigue crack initiation life using UML the beneficial effect of compressive mean stress can be considered. The measured transverse residual stress of $S_{res}$ = -205 MPa has been used to the value of residual stress in the UML calculations.

## Results and discussion

The characteristic fatigue classes $FAT_{95\%}$ reported in Tab. 2 are calculated using structural stress values. The structural stress, which is often called hot spot stress, includes the stress concentration effects of the detail, but not the local non-linear stress peak caused by the notch at the weld toe. The stress ratio is $R$ = 0.1.

TABLE 2. Comparison between treatment condition and thickness of material, m=3.

| | UIT | AW | UIT / AW |
|---|---|---|---|
| $FAT_{95\%}$ (8 mm) | 172 | 115 | 1.50 |
| $FAT_{95\%}$ (5 mm) | 160 | 110 | 1.45 |
| 8 mm / 5 mm | 1.08 | 1.05 | |

The fatigue strength of ultrasonic impact treated test series is 45-50 % greater than for the as-welded test series. This means that fatigue life is approximately $1{,}45^3$ = 3 times longer in the ultrasonic impact treated state. From Tab. 2 it can also be seen that the 8 mm thick specimens had consistently greater fatigue strength than 5 mm thick specimens. The difference in strength is, however, quite a small.

The theoretical fatigue life calculation has been applied to ultrasonic impact treated test series of parent material thickness 8 mm. The fatigue life of structures can be considered in two stages: crack initiation (nucleation) and crack propagation to final fracture (crack growth). In some situations, the initiation may be the most significant part of fatigue life. In the case of ultrasonic impact treatment both stages must be taken account into fatigue life estimations.

The comparison between test results and two-stage approach has been presented in Fig. 6 and Tab. 3. The crack initiation part is estimated according to uniform material law. The crack propagation is assumed to be comparable to the mean life of 8 mm specimens in as-welded conditions ($FAT_{50\%}$ =134, $FAT_{95\%}$=115) as seen in Tab. 2. The complete fatigue life estimation of two-stage analysis is initiation life + propagation life. The experimental fatigue strengths have been presented according to nominal stress range $S_a$ and fatigue life of experiments $N$.

TABLE 3. Slope of S-N curve and mean fatigue strength of two-stage approach.

| | $m$ | $FAT_{50\%}$ |
|---|---|---|
| Test results | 6.00 | 198 |
| Initiation | 11.20 | 215 |
| Propagation | 3.00 | 134 |
| Initiation + Propagation | 8.94 | 220 |

As seen in Fig. 6, most of the test data lies below the two-stage fatigue life estimation. Because of that, the two-stage fatigue life is fairly good estimation for calculating the theoretical mean life of ultrasonic impact treated specimens.

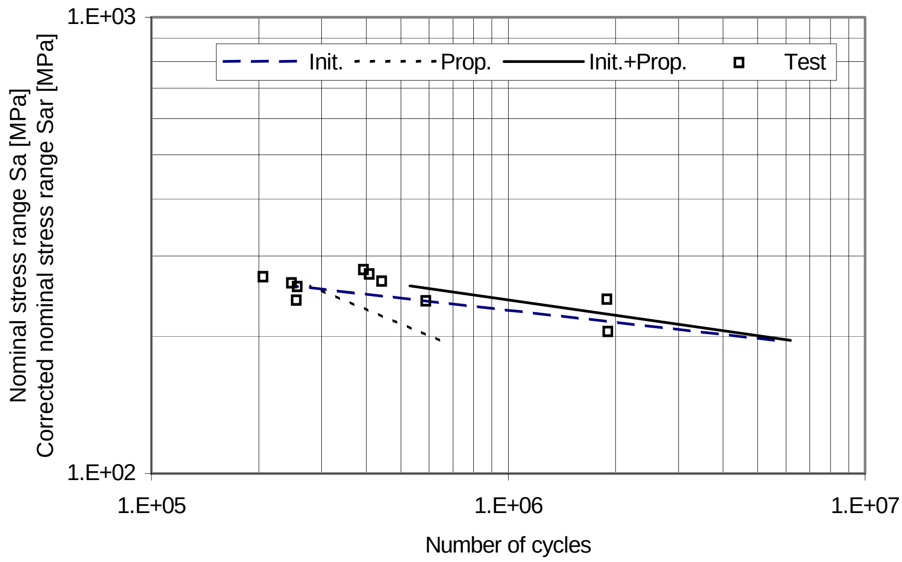


FIGURE 6. Graphical presentation of two-stage method and fatigue test results.

## Summary

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 has 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 50 % higher than the fatigue class for as-welded specimens based on the recommended fixed S-N curve slope, $m = 3$. This is similar to IIW recommendations for other improvement techniques.

The effect of specimen thickness on fatigue strength was only slight. The fatigue class of specimens $t = 8$ mm is 5 - 8 per cent higher than fatigue class of specimens $t = 5$ mm.

The theoretical calculation gives rather accurate approximation for mean fatigue life of ultrasonic impact treatment. The uniform material law were utilized for defining the coefficients for local stress approach.

## References

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