Influence of Spectrum Loading on the Fatigue Strength of Improved Weldments

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Abstract

Fatigue life improvement techniques have shown a considerable benefit to the fatigue strength of welded joints. Most of these investigations have been performed under constant amplitude loading where an effect of parent plate yield strength has been observed. However, under realistic service conditions the loading, for the vast majority of load carrying structural components, is not constant amplitude. Once real load spectra are used, the situation becomes more complicated due to relaxation and redistribution of residual stresses. In order to improve the current knowledge, several fatigue test series have been carried out under spectrum loading. These tests combine different fatigue life improvement techniques such as hammer peening, shot peening, grinding and TIG-dressing together with different type of random loading. The present paper considers only the results obtained from TIG-dressed specimens.

The paper addresses the degree of improvement for different combinations of spectrum parameters for a wide range of plate yield strengths. Correlations have been made between fatigue test results and fatigue crack growth calculations based on a strip yield model where consideration is given to the influence of the residual stress field on fatigue crack growth. The model used shows the relative importance of initial flaw sizes, residual stresses, stress concentrations and their reciprocal influence. X-ray and neutron radiography were used to study relaxation of residual stresses experimentally.

It is found that reasonably good life predictions are obtained both under constant amplitude and spectrum loading.

1 Introduction

Fatigue of welded joints is basically regulated by various codes. Still, these codes treat neither spectrum loading nor post weld treatment in any detail. Yet, almost all engineering components and structures are subjected to spectrum loading during their service lives. One of the main drawbacks in the application of the fatigue life improvement methods is the variation in the quality of the process as well as the uncertainty of the degree of improvement for each specific process. One big step ahead in this direction has been achieved with the publication of the Specifications for Weld Toe Improvement.[1]

Also, there is currently a strong demand for increasing the nominal design stress level. However, welding always introduces initial defects removing the time for crack initiation. Fatigue crack growth is essentially independent of material strength and therefore there is no beneficial effect of using higher strength steels in fatigue loaded applications. The only remedy to this appears to be applying post weld treatment in order to increase the fatigue lives of high strength steels. The main challenge is currently to combine such beneficial post weld treatment with general spectrum loading.

To date there is very scarce information, if any, on fatigue life improvement methods combined with variable amplitude fatigue loading. Most of the information available on this subject refers to constant amplitude loading. The main task of the present paper is to illustrate the effect of different spectrum parameters as well as the influence of parent plate yield strength on the level of improvement produced by TIG-dressing.

This paper summarises part of the fatigue testing being performed in an on-going inter-Nordic study. Experimental results are shown for DOMEX 350XPE and 590XPE, cold forming HSLA-steels, both in the as-welded and the TIG-dressed conditions. The tests include also two quenched and tempered extra high-strength steels, namely WELDOX 700 and 900, studied under the same conditions. Testing

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was performed under both constant amplitude and spectrum loading, but this presentation concentrates on variable amplitude fatigue loading.

Residual stress measurements were performed continuously by means of X-ray diffraction to determine the initial distributions and their relaxation under spectrum loading. Measurements have also been carried out by neutron diffraction to study the through-thickness distribution.

This paper also includes fracture mechanics modelling of certain chosen experimental combinations of the parameters involved. This modelling was done in order to quantify the influence of the various parameters involved in the overall fatigue behaviour under complex loading. The model accounts for local stress concentration, residual stress distributions, residual stress relaxation, applied stress levels, spectrum shape and the weld-induced defect distribution.

2 Experimental Procedure and Test Results

2.1 Material and Test Specimens

All experimental results presented in this paper were obtained from non-load carrying fillet weld fatigue test specimens. These consisted of 80 x 700 mm plates, containing a 140 x 140 mm longitudinal attachment on each side, MAG welded by one pass fillet weld, with no weld preparation. The same welder has manufactured all the test specimens for all the test series at SSAB Oxelösund AB Laboratories, in order to keep the scatter of weld- and TIG-dressing quality under a controlled level. Weld- and TIG-parameters are given in Refs 2, 3. Material characteristics are presented in Tables 1 and 2.

2.2 Fatigue Testing

Fatigue testing included constant amplitude and spectrum loading. The spectrum was a randomised sequence created within each block of 500,000 cycles by employing a draw without replacement routine. The blocks were repeated without reseed until fracture occurred. This gives an entirely randomised sequence until failure. The spectra used, SP2 and SP3, were used previously for similar testing together with other spectra with related but different parameters.[4] SP2 is tension dominated and has a mean stress equal to $0.5\sigma_{max}$, a stress ratio $0 < R < 0.9$ and an irregularity factor equal to one. SP3 has the same range pair distribution as SP2 but the mean stress is zero, resulting in a tension/compression spectrum.

Table 1 – Mechanical Properties of the Steels Studied

Steel	*R_{eH} [Mpa]*	*R_m [Mpa]*	*A_5 [%]*	*Charpy-V -40°C [J]*
DOMEX350YP	398	503	34	-
DOMEX590XPE	615	747	31	27
WELDOX700	780	850	12	L:40 t:27
WELDOX900	900	1010	12	T:27

Table 2 – Chemical Composition of the Steels Studied

Steel	*C*	*Si*	*Mn*	*P*	*S*	*Al*	*Nb*	*CE_{IIW}*
DOMEX350YP	0.058	0.02	0.62	0.009	0.01	0.042	0.014	0.18
DOMEX590XPE	0.09	0.21	1.63	0.11	0.02	0.03	0.024	0.41
WELDOX700	0.15	0.44	1.32	0.012	0.002	0.099	0.060	0.37
WELDOX900	0.17	0.22	1.40	0.020	0.003	0.060	0.030	0.56

2.3.1 ***Measuring Residual Stresses by X-ray Diffraction.*** In the case of the TIG-dressed specimens it is very difficult to define the exact location of the fusion line. Therefore it was decided to make residual stress measurements relative to the end of the attachment. The locations of longitudinal measurement points were in the symmetry plane at 13 mm (estimated weld toe region), 23 mm, 33 mm and 63 mm from the attachment. Measurements across the specimen width were all located 13 mm ahead of the attachment. They were performed at 0 mm, 6 mm, 12 mm and 24 mm in the transverse direction on each side of the symmetry line, see Fig 3. The radiated area was approximately 4 X 6 mm. In all cases the longitudinal stress component was measured. In order to study residual stress relaxation, testing was interrupted at predeterminated number of load cycles, at which point the specimens were removed and subjected to X-ray diffraction measurements before testing was continued. This was done several times during the fatigue testing of each specimen. Most of the relaxation takes place close to weld toe where stress concentration is largest. The main part of relaxation process occurs under the first 100.000 cycles for the tested spectrum. This is in accordance with results in Ref. 5 there 50% or more of the initial stresses were relaxed within 8% of the total life of the specimen.

2.3.2 ***Measuring Residual Stresses by Neutron Diffraction.*** A fatigue test specimen in the TIG-dressed condition was also used to study the through-thickness distribution of residual stresses at the weld toe region. These measurements have just started and only preliminary results are presented. The neutron diffraction measurements were carried out with a dedicated neutron diffractometer, REST, at the R2 reactor in Studsvik, Sweden. The Fe (211) reflection planes were used to obtain strains in the normal, transverse and longitudinal directions. The gauge volume, 2 x 2 x 2 mm^3, defines a lateral resolution of stresses in the order of 2 mm.

The results of fatigue testing are presented in Figures 1 and 2. Fatigue lives are plotted versus maximum stress in the load spectrum. This is to illustrate clearly the significance of TIG-dressing on fatigue lives for each test condition. However, it does not allow direct comparison of the results obtained for the various load spectra with constant amplitude loading.

The improvement in fatigue life was considerable for the load spectra used when compared with the improvement obtained under constant amplitude fatigue loading. When considering constant amplitude fatigue loading TIG-dressing of the weld toe leads to an improvement in fatigue life of approximately four times for all load levels. When considering spectrum loading TIG-dressing of the weld toe leads to an improvement in fatigue life of 8-15 times depending on the applied load. Note that higher effects can be seen at longer fatigue lives.

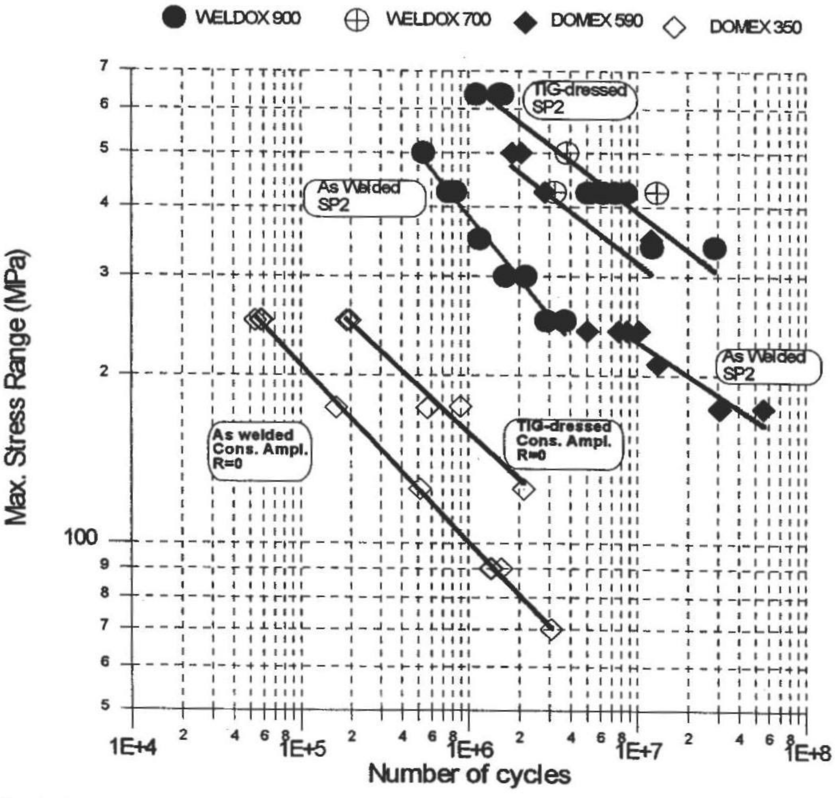

Fig. 1—Relative fatigue life/strength improvement for different test conditions.

2.4.1 ***Some Considerations Regarding Parent Plate Yield Level.*** The quantity of fatigue test results is still very limited. Nevertheless, some influence of parent plate yield level on the fatigue strength of TIG-dressed specimens can be observed. The higher yield level shows the highest fatigue strength.

The present modelling of welding induced residual stress fields is mainly based on an elastic-plastic crack closure fatigue crack propagation analysis model.[6,7] The influence of the residual stress fields on fatigue crack growth is accounted for by a residual stress intensity factor concept. Such stress intensity factors are determined by the residual stress distributions at the crack site using a 3D weight function method.[8] The residual stress intensity factor represents the influence of residual stress fields on the crack growth quantitatively, and will be added to the stress intensity factors caused by the cyclic loading. The redistribution of residual stress fields is well represented by the procedure of calculating the residual stress intensity factors by the superposition principle under elastic considerations. Crack tip plastic deformation under both applied load and residual stress is accounted for in the elastic-plastic crack growth analysis model. The numerical model used to predict fatigue crack propagation is a strip yield model based on Dugdale-Barenblatt assumptions but extended to leave plastically deformed material in the wake of the extending crack tip. This model was previously developed and was shown to be applicable both for plane stress and plane strain conditions by incorporating a variable constraint factor.[6] A constraint factor $\alpha = 1.73$ was used in the present crack growth analysis model, based on comparison with elastic-plastic FEM calculations,[9] to account for the three dimensional effect at the crack tip essentially leading to plane strain conditions.

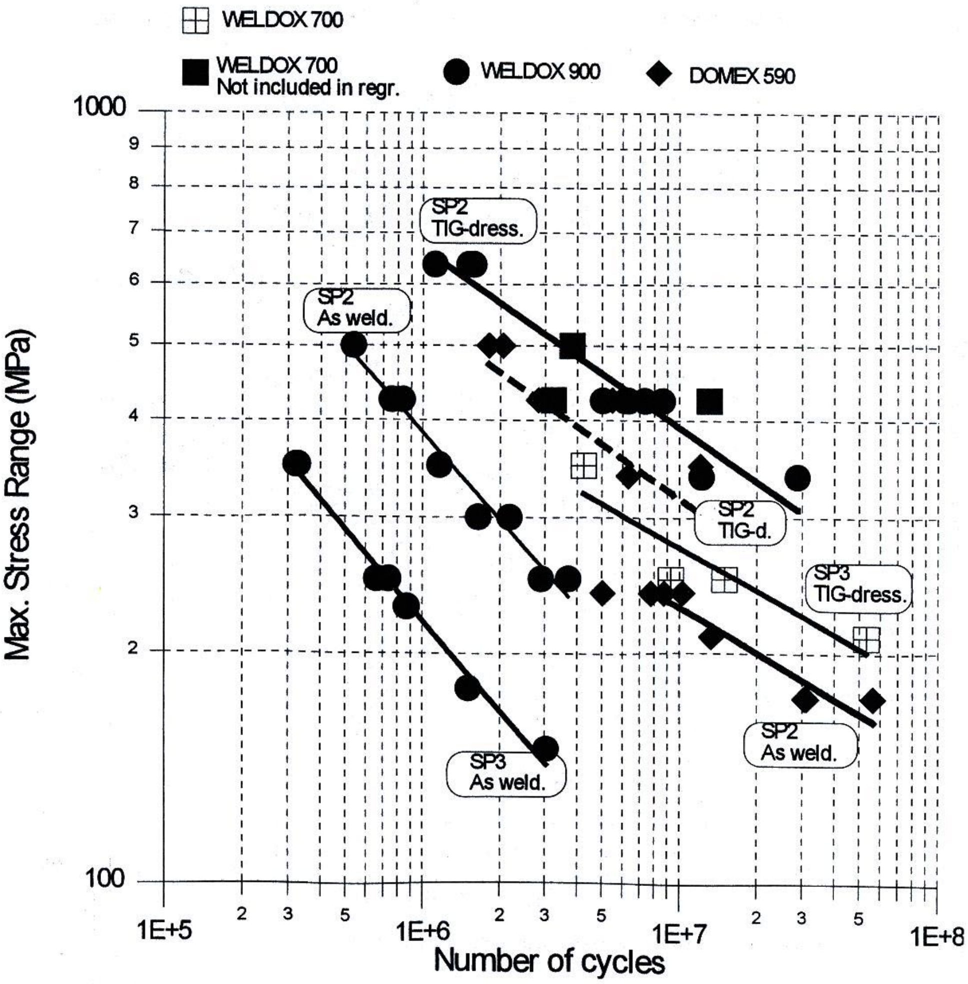

Fig. 2—Fatigue test results for different spectra in as-welded and TIG-dressed condition.

3.1 Elastic Stress Distributions

A finite element 3D solid model was created both for the as-welded specimen and the TIG-dressed specimen to analyze the stress distributions in the weld toe region. The weld toe radii were obtained from measurements on several specimens and average values of 0.14 mm and 7.0 mm were used for the two cases, respectively. The linear elastic computations reveal such high local stresses that plastic deformation will occur for the load levels applied in the testing, especially for the specimens in the as welded condition. The stress concentration factor is around $K_t \approx 6$ for the as-welded specimens and $K_t \approx 1.8$ for the TIG-dressed specimens. These results were presented in Ref. 4.

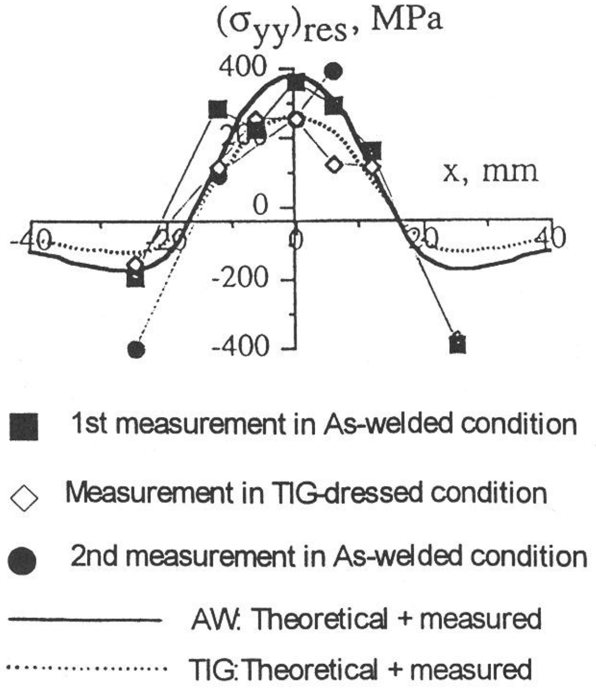

Fig. 3—Initial longitudinal residual stress distribution across specimen width at weld toe yield.

3.2 Residual Stress Distributions

The neutron diffraction measurements are shown in Figure 4. These values are, at the surface, in agreement with x-ray measurements. As already mentioned, the local elastic stress concentration is high enough to cause local yielding. Together with residual stresses plastic deformation will occur that leads to redistribution of the initial residual stresses when the structure is unloaded. To simplify the residual stress analysis, elastic perfectly plastic constitutive behaviour is assumed and the through-thickness initial residual stress is estimated using an empirical method. It is assumed that the plastic deformation changes only the local stress distribution. The average of the through-the-thickness stress will be equal to the average of the linear stress result so that the requirement of equilibrium is satisfied.

It has been shown[4] that the residual stresses had approximately reached saturation level at around 10^5-1.5 X 10^5 cycles. The same procedure as above is used to evaluate through-the-thickness redistributed residual stresses for different load levels. These values are used in the evaluation of fatigue crack growth.

3.3 Computed Fatigue Crack Propagation

The numerical model described above was used to predict fatigue crack growth under spectrum loading. This was done assuming residual stresses as discussed above. The computations show that residual stresses significantly reduce fatigue life.

Compared to the predicted results for constant amplitude loading, the main difference is that the residual stress has negligible effect on the fatigue lives for spectrum loading over a considerable range of initial crack sizes. The residual stress still influences the critical crack size as becomes obvious at the right end of all the curves in Figure 5. Although residual stress has some effect on the fatigue life of the as-welded specimens, it has almost no effect on the fatigue life of TIG-dressed specimens.

Another comparison of predicted spectrum behaviour is shown in Figure 6 for both as-welded and TIG-dressed specimens under two different stress levels. The most significant improvement in the fatigue lives of TIG-dressed specimens is for small initial crack sizes. In this region the fatigue life curves, for as-welded versus TIG-dressed specimens, diverge. This is the same behaviour as already observed in the experimental fatigue life results shown in Figure 1 and 2. This clearly confirms the notion that life improvement by TIG-dressing is particularly relevant in the long life regime, where also the need may be most prevalent. It was confirmed previously [2,3] that initial flaw sizes become substantially smaller following TIG-dressing.

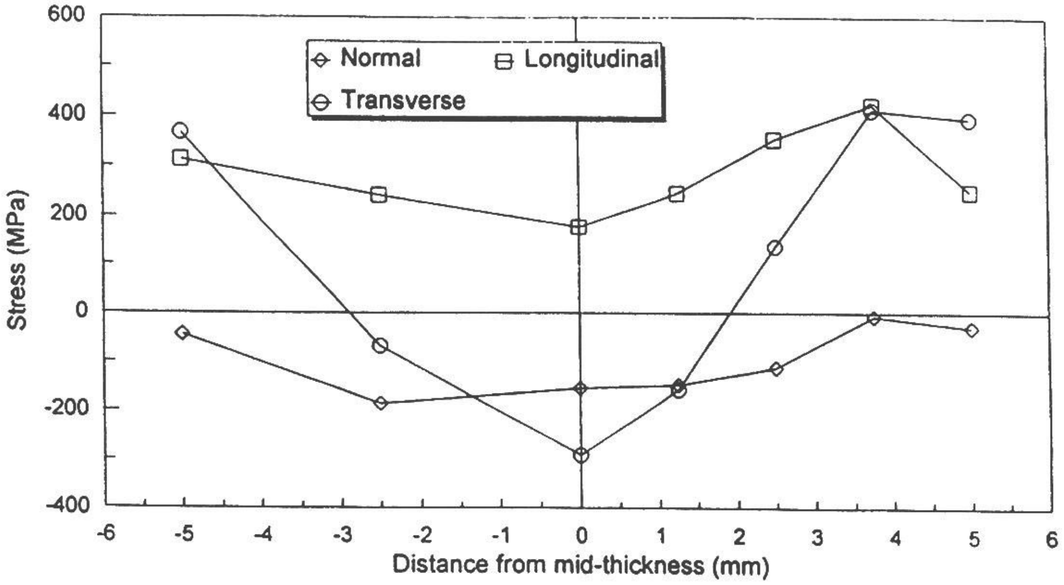

Fig. 4—Depth profile of stresses at weld toe location.

4 Discussions and Conclusions

It is shown that a significant increase in fatigue strength is achieved by the use of the TIG-dressing life improvement technique.

For the load spectra studied (tension dominated as well as tension/compression type) this positive effect is even larger than under constant amplitude loading.

For low strength steel the life improvement achieved is approximately constant irrespective of applied load level. For higher strength steel the degree of life improvement becomes larger than for low strength steels. Further more, there is a clear indication of a load level effect on the high strength steel results. The degree of life improvement is largest at lower applied stress levels, i.e., at long fatigue lives.

These experimental observations are also confirmed by fracture mechanics modelling. Here, it was shown that the largest effect of the TIG-dressing is to reduce the elastic stress concentration.

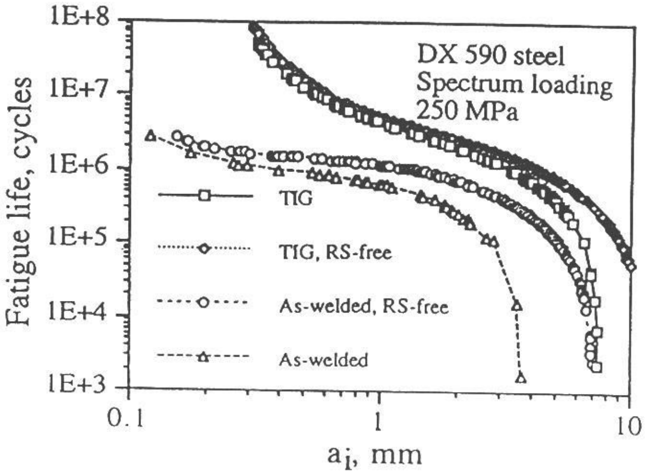

Fig. 5—Predicted spectrum crack growth life for different initial flaw sizes.

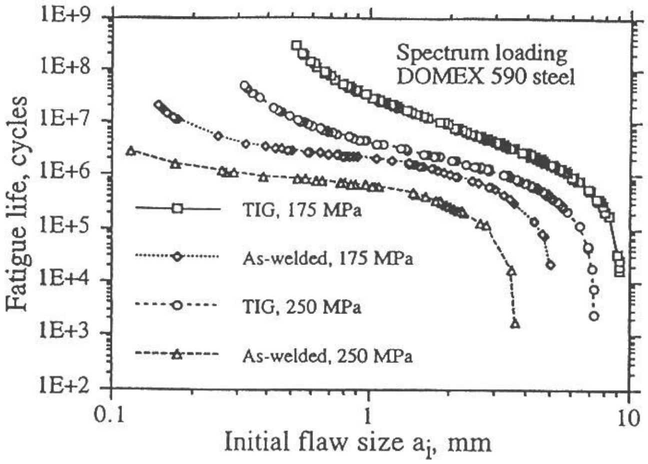

Fig. 6—Predicted spectrum crack growth life for different load levels.

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