Fracture mechanics based estimation of fatigue life of welds
A. Krasovskyy*, A. Virta
Wärtsilä Switzerland Ltd, Zürcherstr. 12, 8401-Winterthur, Switzerland

Abstract

This paper presents a mechanism based approach for lifetime prediction of welded joints, subjected to a multiaxial non-proportional loading. Assuming the existence of crack-like flaws after the welding process, the stage of a fatigue crack initiation becomes insignificant and the threshold for the initial crack propagation can be taken as a criterion for very high cycle fatigue (VHCF) whereas crack growth analysis can be used for low and high cycle fatigue (LCF, HCF). The proposed deterministic method, which is based on the welding process simulation, thermophysical material modeling and fracture mechanics, considers the most important aspects for fatigue of welds. Applying worst case assumptions, fatigue limits derived by this method can be then used for the fatigue assessment of complex welded structures. The capability of the approach is validated by S-N curves provided at the Recommendations of the IIW.

© 2014 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of the Politecnico di Milano, Dipartimento di Meccanica

Keywords: fatigue, residual stresses, welding simulation, fracture mechanics, weight function method

1. Introduction

The importance of welding for the modern structural engineering cannot be emphasized enough. Different techniques are currently applied in the industrial environment offering almost unlimited possibilities regarding manufacturability with high cost effectiveness. At the same time the requirements on welded structures are increasing and so the requirements on the design methods. In order to fulfill their functionality many welded structures must stand a cyclic loading in different regimes during the whole lifetime. The bounds between different fatigue regimes are rather conditional and depend on many factors. In this work, the bound between very high cycle and high cycle fatigue (VHCF and HCF) is defined by the knee point on the S-N curve and is typically for steels...
around $10^6 \div 10^7$ cycles. Low cycle fatigue (LCF) defines the area on S-N curve, where the loading leads to a significant plastic deformation of material and is below $10^4$ cycles.

Practical experience and experimental observations show that fatigue damage generally originates from weld notches (toe or root). The fatigue behavior of the whole structure is therefore dominated by local stress concentrations in the vicinity of the welding fusion line, which is considered to be the weakest link.

During arc welding, the high thermal impact induces alterations in the microstructure and material properties of the weld metal and the surrounding heat affected zone. Surface conditions on the weld notch are typically poor, including many randomly distributed defects and small cracks, which can be seen as additional stress raisers. Moreover residual stresses are inevitably present after the welding as a result of plastic deformation induced by non-homogeneous thermal expansion, liquid-to-solid transformation and phase transformations in the solid state [1, 2]. The biggest challenge for a product development in industrial environment is how to achieve a compromise between an accurate lifetime prediction and a fast calculation procedure for the entire welded structure in order to be able to perform a design optimization in affordable amount of time. Design codes such as those presented in the IIW recommendations [3] can greatly reduce the analysis effort in the design of welded structures providing a suitable balance between computational accuracy and ease of use. However the proposed S-N curve approach is rather generalized in respect of material or welding process. Various assumptions have to be made in a conservative way so that the full cost and weight optimization potential cannot be achieved.

For less conservative fatigue estimation and a better understanding of interactions between welding and fatigue behavior a coupled analysis of welding process, operational loading and mechanism based failure modeling can be performed.

2. Specifics of the fatigue of welds

Estimating the fatigue resistance of welded joints requires a conservative assumption that cracks on weld seam are present after the welding process. In this case, the stage of a fatigue crack nucleation is relatively insignificant [4, 5] and the threshold for the initial crack propagation can be taken as a criterion for VHCF whereas crack growth analysis can be used for HCF and LCF. Fig. 1 illustrates the differences between the S-N curves for welded and non-welded structures: while for non-welded metals with good surface condition and small size of inclusions a considerable amount of lifetime has to be spent for a crack initiation, crack growth is dominant for welds.

![Fig. 1 Typical S-N curve and crack growth diagram with three areas representing crack initiation, crack propagation and fracture.](image)

Since weld notches are the highest loaded areas on a weld seam, one can assume that the surface crack-like defects are the most critical. Depending on the material properties and the size of initial defects fatigue limits can be predicted by means of fracture mechanics. For instance, in marine 2-stroke diesel engines the maximum allowable depth of cracks or crack-like defects, identified by non-destructive testing, is 1 mm. Therefore, as the worst case, a semi-elliptical surface crack with a depth $a$ of 1 mm and an aspect ratio $a/c = 0.1$ in the vicinity of the weld notch can be assumed as the most critical defect [3, 5].

For the sake of simplicity only linear elastic fracture mechanics (LEFM) is considered in this study. This is legitimate for the case where the initial size of the surface crack is larger than 0.5 mm and belongs to the long crack range [7, 8].
Characterization of weld seam for an accurate fatigue assessment requires information about residual stresses, microstructure and mechanical properties. Nowadays, the thermomechanical simulation of welding process can significantly facilitate this and provide more understanding of the relevant phenomena and their dependencies [9, 10, 11]. However a reliable welding simulation is very demanding, not only in respect of calculation time but also regarding a comprehensive description of the material behavior [2].

Welding induced residual stresses can have either a beneficial or a harmful effect on the lifetime, depending on sign, magnitude and distribution with respect to the load-induced stresses. Using commercial software for welding simulation, it is possible to predict them accurately for idealized boundary conditions at laboratory or for simple geometries. However, for many real welded structures with complex geometry and welding sequence, local stress state can be significantly affected during the assembling stage. Another aspect, which has to be taken into account, is an alternation of residual stresses due to cyclic loading or high temperature. All mentioned difficulties related to the accurate prediction of residual stresses, make it currently impossible (at least quantitatively) to use the information for lifetime prediction. For the derivation of macroscopic fatigue limits therefore, stress ratio R=0.5 [3] has to be used as a worst case assuming high positive residual stresses.

3. Fatigue crack analysis

Due to the presence of weld notches, which act as stress concentrators, the through-thickness stress distribution is very inhomogeneous and a classical approach for calculation of the stress intensity factors is no longer valid. An accurate solution by using FE-analysis is in contrast quite time consuming. Convenient and efficient seems to be the weight function method. In [12] the stress intensity factors for semi-elliptical surface crack for both points A (on the plate surface) and B (deepest location of the crack front) subjected to Mode I loading can be obtained by integrating the product of the stress range distribution $\Delta \sigma(x)$ in the anticipated crack plane and the weight function $m(x,a)$:

$$\Delta K_{A,B} = \int_0^a \Delta \sigma(x)m_{A,B}(x,a)dx$$ (1)

According to [13] the maximum validity of the weight function method is up to the size of crack of 80% of the plate thickness.

In order to perform fatigue assessment for complex parts in a reasonable amount of calculation time a worst case assumption in regards to the through-thickness stress distribution has to be made. Assuming Mode I as a dominant for crack growth, the most critical stress state is the one with the highest range of the maximum normal stress, means when the entire section is under the tension.

In order to study the effect of plate thickness on stress distribution a parametric FE-analysis was performed using a 2D plane strain model for plate thicknesses varying from 10 - 50 mm. The radius on the weld toe was chosen to be 1 mm which corresponds to the effective notch stress concept [3]. Fig. 2 represents normed by the peak stress $\sigma_{peak}$ distribution over the normed plate thickness coordinate $x/t$.

If the initial crack size is large compared to the depth of the stress gradient, i.e. the initial crack size covers the steepest stress gradient, the radius of the weld toe do not affect significantly to the crack growth rate in the depth.
direction. For the case of the initial crack depth of 1 mm, the influence of the notch radius size on the crack propagation in the depth direction is therefore assumed negligible.

The dimensionless distribution can be described by exponential law as a function of the plate thickness in the following form:

\[ \Delta \sigma(x) = \Delta \sigma_{\text{peak}} f(x, t) \]  

(2)

From (1) and (2) one can get the range of the stress intensity factor as a function of the peak stress range:

\[ \Delta K_{A, B} = \Delta \sigma_{\text{peak}} \int_0^a f(x, t) m_{A, B}(x, a) \, dx \]  

(3)

Flaws and crack-like defects on weld seams can propagate under fatigue loading if the stress intensity factor is above its threshold value \( \Delta K_{\text{th}} \). If \( \Delta K \) is below that value, an effectively infinite fatigue life can be obtained.

Murakami [14] proposed a model that predicts the fatigue crack propagation threshold at the loading ratio \( R_K = -1 \) for small initial defects (short crack range) \( \Delta K_{\text{th}-1} \), assuming the crack opening mode, or Mode I, as a dominant. He found a correlation between the material hardness \( H_V \), the effective area of the defect projected onto the plane normal to the first principal stress, \( \text{area} \), and the fatigue strength:

\[ \Delta K_{\text{th}-1} = 3.3 \times 10^{-3} (H_V + 120)(\sqrt{\text{area}})^{1/3} \]  

(4)

Expression (7) has been successfully validated for different classes of materials. However, it seems to work well only in the short crack regime. For the long crack range, which is more relevant for welds, it is no longer valid [15].

In order to extend the applicability of Murakami's model, Chapetti [16] proposed the upper bound for it:

\[ \Delta K_{\text{th}-1} = -0.01239 H_V + 15.5 \]  

(5)

Combination of (7) and (8) provides the general threshold value:

\[ \Delta K_{\text{th}-1} = \min \{ \Delta K_{\text{short}}^{\text{th}-1}, \Delta K_{\text{long}}^{\text{th}-1} \} \]  

(6)

The mean stress sensitivity which includes effect of residual stresses and loading asymmetry over one cycle can be described as a function of the mean stress intensity factor \( K_m \):

\[ \Delta K_{\text{th}} = f(K_m) \]  

(7)

Now using information about the through-thickness stress distribution, fatigue limit can be derived by the weight function method. Substituting the range of stress intensity factor on the left side in (6) by its threshold value from (10) one can derive a limit for stress range in VHCF regime, which is related to the peak stress on notch surface:

\[ \Delta \sigma_{\text{wR}}^{\text{VHCF}} = \max \left\{ \int_0^a f(x, t) m_A(x, a) \, dx, \int_0^a f(x, t) m_B(x, a) \, dx \right\} \]  

(8)

For regimes of the high and low cycle fatigue crack propagation is the dominating damage mechanism. In this case \( \Delta K \) from external load exceeds its threshold value and crack growth up to the critical crack size (specified by the structural requirements) must be modeled in order to predict lifetime. In terms of the linear elastic fracture mechanics (LEFM) crack growth in both directions can be described by the Paris power law:

\[ \frac{da}{dN} = C(\Delta K_A)^m; \quad \frac{dc}{dN} = C(\Delta K_B)^m \]  

(9)

where \( N \) is a number of loading cycles, \( C \) and \( m \) are the material constants. For the sake of simplicity only the standard Paris law, which is not able to consider effect of the loading ratio \( R_K \), will be considered here.

Criterion for damage must be fracture toughness \( K_{ic} \) and the critical crack size \( a_f \), dictated by validity of the Glinka’s weight function method \( a_f = 0.8 \, t \). The total life can be calculated as:

\[ N = \frac{1}{C_m} \int_{a_f}^{a_0} \frac{da}{(\Delta K_A)^m} \]  

(10)

Combining (4) and (14) one can derive the allowable stress range for the HCF and LCF regimes:
\[
\Delta \sigma_{wR}^{HCF} = m \left[ \frac{1}{C N} \int_{a_0}^{a} \int_{0}^{a} f(x,t) m_A(x,a) dx \right]^{m} da
\] 

(11)

Since the proposed here method for fatigue assessment of welded joints based on LEFM it has to be applied to the cases with moderate plastic strains. Otherwise an effective crack size corrected by the plastic zone size or inelastic fracture mechanics is required.

Real welded structures have a random defect orientation and are typically subjected to a complex loading. For a general case of multiaxial and non-proportional loading [17], one can formulate a fatigue criterion based on the critical plane approach as follows:

\[
\max_{\phi, \theta \in [0, \pi]} |\Delta \sigma| \leq \Delta \sigma_{wR}
\] 

(12)

The right side of this equation is a fatigue limit specified for a specific number of cycles and stress ratio. The left one can be expressed as the maximum value of the normal stress range \(\Delta \sigma_n\) over all plane orientations, defined by spherical coordinates \(\phi\) and \(\theta\).

4. Estimating fatigue limits

Based on the theory and assumptions in chapter 3 as well as on the results from the welding simulation one can now derive an S-N curve for S235JR. Due to the undisclosed research, material data are taken from the literature or calculated by software JMAtPro and the validation of the results is done by the fatigue limits from IIW. For that purpose the effective notch stress concept can be chosen. FAT 225 represents a survival probability of 97.7% at stress ratio \(R = 0.5\). Since FAT 225 defines fatigue limits for the effective notch stress concept with notch radius of 1 mm through-thickness stress distribution provided in chapter 3 can be used.

For the calculation of crack growth material constants from [18] for S235JR (base material) at \(R = 0.5\) were used: \(C = 9.71E -9\) and \(m = 2.71\). For the calculation of the stress intensity threshold hardness HV213 was taken. Plate thickness was selected to be 10 mm. Resulting S-N curve compared to the one from IIW can be seen on Fig. 3.

![Fig. 3 Fatigue limits for welds from IIW and predicted by the crack growth calculation.](image)

Considering that the slope of the IIW-curve after \(10^7\) cycles is rather controversial, predicted endurance limit (defined by knee point) and the stress level at the knee-point of IIW-curve are similar: 145 MPa in case of LEFM and 132 MPa from the IIW. But in opposite to IIW, predicted by the presented here approach limits can be derived for particular material, welding process and stress state.

5. Conclusions

The emphasis throughout this study has been to formulate and validate an accurate fatigue approach for welded structures, in order to achieve the full cost and weight optimization potential for industrial applications. It has been...
shown that lifetime prediction can be successfully done by performing a coupled analysis of the welding process simulation and operational loading using fracture mechanics based fatigue model. The fatigue criterion associated with a threshold for crack propagation and crack growth rate in combination with the critical plane approach is able to accurately predict the fatigue behavior. The proposed approach is a powerful method for the fatigue assessment as well as for a better understanding of the influence of different aspects which affect the fatigue resistance of welded structures.

References