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The Effect of Weld Profile and Geometries of Butt Weld Joints on Fatigue Life Under Cyclic Tensile Loading

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The fatigue life of welded joint was calculated based on numerical integration of simple Paris' law and a reliable solution of the stress intensity factor (SIF). The initial crack length (a_i) was assumed to be equal to 0.1 mm in case of weld toe. This length was satisfactory for different butt joints geometries. The comparisons with the available data from standards and literature were demonstrated. It was shown numerically that the machining of weld reinforcements will increase the fatigue life. The increase of plate thickness decreases the fatigue strength (FAT) and the number of cycles to failure when using the proportional scaling of crack length. The validation processes of the current calculations have been shown. Therefore, it can be concluded that it will prevent the unnecessary waste of time consumed to carry out the experiments.

Keywords butt joints, FAT, fatigue life, fatigue strength, weld design, weld joint, weld toe crack

1. Introduction

Butt weld joints may contain some defects developed during the fabrication processes. Regardless of these defects, fracture mechanism which is used to predict the fatigue life of the welded joints supposes that cracks already exist. Many applications in the structural areas involve welded components, which have to be properly designed to avoid fatigue failure. Although considerable fatigue data exist for welded joints in structural steels and aluminum as provided by International Institute of Welding (IIW) (Ref 1, 2) and British Standard Institution (BSI) (Ref 3), the fatigue life design data for welded joints of different materials are very sparse.

The recommended standards also do not include the effects of different geometries, for example, regarding the toe radius; BSI does not consider that the weld toe radius is constant (Ref 4). Therefore, the assessment of welded joints is a major industrial problem. The reason is that the welds tend to become regions of weakness in a structure because of stress concentration effects, poor material properties, and the difficulty of defining material properties, which vary throughout the weld and heat-affected zone (HAZ). Moreover, geometry has a major influence on fatigue strength (FAT) producing scatter of results which leads to uncertainties about the magnitude of cyclic failure stresses.

Another reason for motivation of the current study is the time that fatigue testing machines, particularly those needed to test relatively large specimens require to apply cyclic loads at frequencies typically in the range 5-15 Hz. Clearly this means that the generation of fatigue test data can be a lengthy process, even for one type of specimen, and one particular stress ratio. Indeed it takes 8-24 days to apply 10^7 cycles. Therefore, most test series are normally confined to fatigue lives of less than 10^7 (Ref 5). Thus, the determination of fatigue life of welded joints is quite a complex problem. All the theories and models have to be verified and corroborated by experimental data.

Therefore, it is suggested that for the safe fatigue design of welded components practice, fracture mechanics should be used with the calculated crack parameters from this study. Thus, the ability for studying the effect of weld profile on fatigue life could be demonstrated.

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2. Fracture Mechanics-Based Method

The majority of crack initiation occurs at geometrical discontinuities such as weld toe and weld defects. Since the linear elastic fracture mechanics (LEFM) approach always gives conservative results of the fatigue life time when compared with those of modern experimental data of weldments (Ref 6), fracture mechanics is an approach used to determine propagation life, while strain life approach is used to determine initiation life. Therefore, total life is the sum of these two lives.

Linear elastic fracture mechanics (LEFM) can be used to predict fatigue life, FAT, and the crack growth to its final size (a_f). For welds in structural metals, crack initiation occupies only a small fraction of the life, and it can be assumed to be negligible in contrast to the unwelded butt joints. Therefore, this method is suitable for assessment of fatigue life, inspection intervals, and crack-like weld imperfections that are likely present in weld joints. Initial cracks used in fatigue analyses are often in the range of 0.05-0.2 mm (Ref 7). Engesvik (Ref 8) analyzed the fatigue life of welded joints and concluded that it may be dubious to apply LEFM at crack depths less than 0.1 mm. Nevertheless, this value can vary depending on the welding operation parameters, geometry, and material properties. In some other literature, (a_i) is usually measured or assumed to be approximately equal to 0.1-0.2 mm for welds (Ref 4).

BS7910 (Ref 3) recommended that the initial flaw size (a_i) be between 0.1 and 0.25 mm. The life is assumed to be finished when (a_f) reaches half the sheet thickness (Ref 4, 9). The critical crack size is kept at half of the plate thickness as in laboratory conditions.

The uncertainty of initial crack lengths is incredible and leads to serious problem. Thus, for this study, an initial crack depth of weld toe crack of 0.1 mm was used (Ref 10-13). In this study, the LEFM approach which estimates the crack propagation life (N_P) was used to calculate the total life (N_T) of the welded joints.

2.1 Calculation of Fatigue Life Using Paris' Law

To predict fatigue crack propagation, numerous empirical or semi-empirical equations have been proposed to relate fatigue crack growth rate data with stress intensity factor (SIF) range. Among the proposed equations, the Paris-Erdogan relationship (Eq 1) is commonly accepted and used in practice for a wide range of mode-I cracks (Ref 14). This relationship is given as

$$\frac{da}{dN} = C(\Delta K_I)^m \quad \text{(Eq 1)}$$

where C and m are material-dependent constants. The Paris' model, which is used to calculate fatigue life in FRANC2D (Ref 15), is very simple and might not be appropriate for some materials, nonzero load ratios, and very high or very low SIF ranges. In many cases, it is more appropriate to extract SIF versus crack length history computed within FRANC2D and use this information with a more sophisticated growth model (Ref 16).

Equation 1 is the most common equation for welded joints and also the one for which the most material data are available.

In practice, the fatigue life equation is solved by splitting the crack growth history into a series of crack increments, Δa, in which Δa is determined according to the stability of the a-N curve.

After dividing the crack path into (n) increments, between (a_i) and (a_f), the number of cycles N_j for each increment (between the size a_j and the size $a_j + \Delta a$) can be calculated. The crack length vector and the calculated SIF are transferred to Excel and integrated numerically. Then, the number of cycles to reach given crack depths is calculated by numerical integration of Eq 1 as follows:

$$dN = \frac{1}{C(\Delta K_I)^m}\, da \Rightarrow \int_0^N dN = N_p = \int_{a_i}^{a_f} \frac{da}{C(\Delta\sigma\sqrt{\pi a}F(a))^m} \quad \text{(Eq 2)}$$

where $\Delta\sigma$ is the stress range, and $F(a)$ is the geometry factor.

Then, the total life N can be calculated by summation of N_j for each increment as

$$N = \sum_{j=1}^{n} N_j = \sum_{j=1}^{n} \frac{\Delta a}{C(\Delta K_I)_j^m} \quad \text{(Eq 3)}$$

where j is the step's number. A numerical integration for a crack growth rate was carried out at various stress levels, and the results of fatigue life were recorded to determine the S-N curve.

2.2 Backward Calculation of Fatigue Strength

Armed with knowledge of the SIF, and K_I at different crack depths, it was possible to make polynomial curve fits of $K_I(a)$. Numerical integration of Paris' law (Eq 1) was carried out using a polynomial equation of SIF to establish the a-N curve. SIFs at different loading have been scaled to calculate the expected fatigue life for different stress ranges and to develop the S-N curve.

A FORTRAN language program was developed to carry out the numerical integration of Paris' law at various stress ranges. The initial crack (a_i) was changed to get characteristic and mean FAT values.

DOMEX 550 MC, the high strength hot-rolled steel, with minimum yield strength of 550 MPa, and a minimum and maximum tensile strengths of 600 MPa, and 760 MPa, respectively, was used in the current model.

If the correct constants (C, and m) for steel were not available, then the BSI7910 (Ref 3) and IIW (Ref 1, 2) recommendations were used; see Table 1.

According to IIW, all FAT values were given as characteristic values, which are assumed to have a survival probability (reliability) of at least 95% (i.e., 5% failure probability) within two standard deviations (SDs) equal to 0.178 calculated from the mean value of a two-sided 75% confidence interval level (Ref 1, 2). The initial crack length should be considered in the determination of the fatigue life of welded joints. Emphasis is laid on how to choose growth parameters C, m, and a_i. With backward calculations, a_i has been determined and found to be in agreement with the FAT95% according to characteristic values of C and m. In case of FAT50%, a new value of $C_{50\%}$ is needed to be determined, which is equal to $C_{95\%}$ + 2SD. Both curves of these FAT values are plotted and shown in Fig. 1 using the straight line equation with slop m:

$$\log N = \log C - m \times \log \text{FAT} \quad \text{(Eq 4)}$$

Then, the characteristic FAT95% is calculates by

$$\text{FAT95\%:} \quad \log(2 \times 10^6) = \log C_{95\%} - m \times \log \text{FAT95\%} \quad \text{(Eq 4.1)}$$

Table 1 Characteristic value of recommended materials' parameters for steel

BSI 7910 (Ref 3)	IIW (Ref 1, 2)
$C_{95\%} = 5.21 \times 10^{-13}$, and $m = 3$	$C_{95\%} = 5 \times 10^{-13}$, and $m = 3$
Units used are in N and mm	

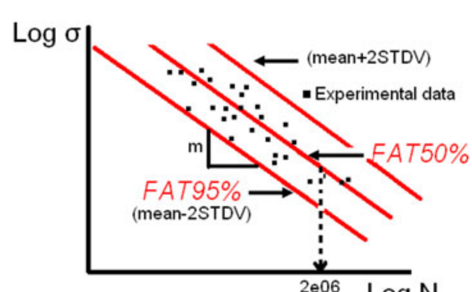


Fig. 1 S-N curve (Ref 13)

The mean FAT50% is then

$$\text{FAT50\%:} \quad \log(2 \times 10^6) = \log(C_{95\%} + 2 \times \text{SD}) - m \times \log \text{FAT50\%} \quad \text{(Eq 4.2)}$$

Finally, the *S-N* curves are obtained (Fig. 1) according to

$$N = (\text{FAT95\%}/\Delta\sigma)^m \times (2 \times 10^6) \quad \text{(Eq 5)}$$

$$N = (\text{FAT50\%}/\Delta\sigma)^m \times (2 \times 10^6) \quad \text{(Eq 6)}$$

The mean values of material constants for steel have been calculated and given in Table 2 as well as in (Ref 10-13). The value of $C_{50\%}$ is only 8.5% larger than that from BSI 7910 which is given as equal to 2E−13 (Ref 3). These values can be used to calculate FAT50% for new notch cases.

According to the current procedure (i.e., backward calculations), a_i value was changed to just fit the curve of FAT95% which is plotted using Eq 5, and shown in Fig. 1. Then, these determined values (C, m) from Table 1 and a_i can be used to find FAT95% for new notch cases which have the same crack classifications (weld toe or weld root crack). The curve of FAT50% has been plotted using Eq 6 and values of $C_{50\%}$ and m equal to 2.17E−13 and 3, respectively (see Table 2).

3. Simulation of Fatigue Crack Growth

FRANC2D software (Ref 15) has been used to find appropriate solutions of SIF for the butt weld joints using LEFM. It is found that SIF obtained by FEM gives better crack growth direction and SIF solutions as compared with analytical calculations formulas (Ref 10-13). These results have been conclusively proven. Also current FE models are in good agreement with the experimental data in the literature.

Table 2 Mean values of recommended materials parameters for steel

BSI 7910 (Ref 3)	Current study
$C_{50\%} = 2 \times 10^{-13}$, and $m = 3$	$C_{50\%} = 2.17 \times 10^{-13}$, and $m = 3$
Units used are in N and mm	

In general, the behavior of crack path propagation (CP) in FRANC2D is almost the same as compared to the available experimental results (see Fig. 2). The FEM simulation by FRANC2D shows that the maximum stress intensities develop when the plane of the crack is normal to the direction of the primary tensile stress (opening mode). However, as the plane of the crack tilts further away from the mode-I tensile loading, the structural member, in the form of a plate or a similar configuration, will lose its ability to support the external load.

Figure 2 shows the comparison between the simulated and real experimentally tested specimens, where *W* is the reinforcement width (weld bead width), and *H* is the reinforcement height (weld bead height). Fatigue crack growth was simulated under the opening mode-I which is usually assumed in fracture mechanics.

In the previous studies by the authors (Ref 10-13), rules have been given for estimation of crack growth direction, a_i, C, and m. The values of C and m in the case of characteristic values of FAT95% (5% failure probability) were determined from well-known rules.

It has been shown that fatigue crack growth behaviors of welded joints are highly dependent not only on the materials and load conditions but also on the weld geometry such as weld toe angle, weld toe radius, plate thickness, and width of reinforcements (Ref 18). Nguyen and Wahab (Ref 19) used LEFM to present the effects of tip radius of undercut at weld toe, weld toe radius, flank angle, plate thickness, and edge preparation angle on the fatigue crack propagation life. The current study highlighted on the reinforcement and on the sheet thickness effects. Cracks are presented at weld toe where high residual tensile stresses are introduced by the welding processes because of expansion and shrinkage of weldment during heating and cooling, misalignment, and microstructural variation in weldment and HAZ, see Fig. 2.

3.1 FEM Modeling

Since weld geometry conditions may differ in various weld joints, traditional empirical relations become invalid in some cases, and new models may have to be created for local stress distribution and accurate SIF calculation. Therefore, the determination of accurate SIF solutions for the correct weld geometry conditions is of practical significance for structural design and fatigue life evaluation of welded structures.

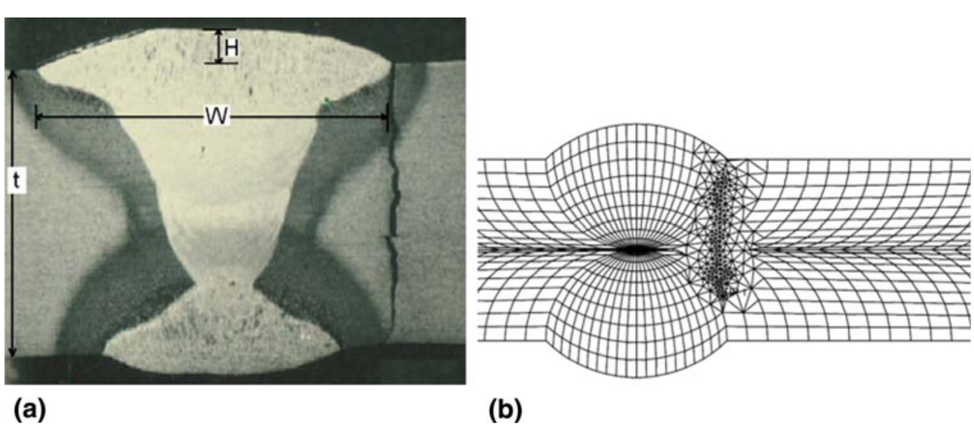


Fig. 2 Transverse butt weld joints: (a) experimental crack growth (Ref 17); (b) crack growth simulation by FRANC2D

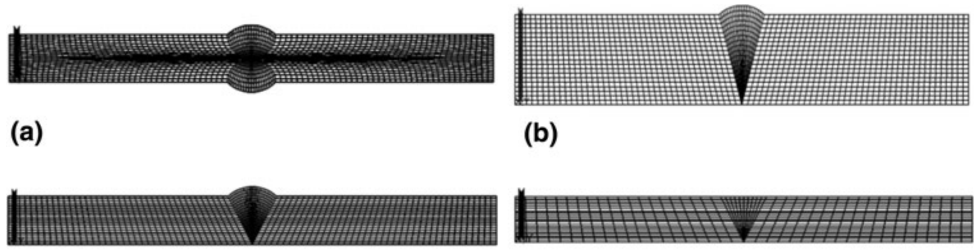
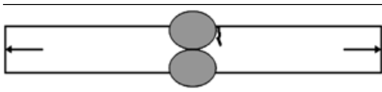
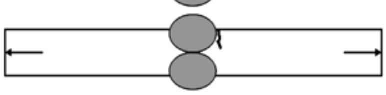
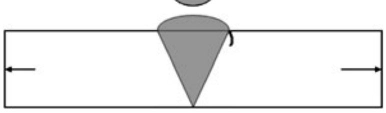
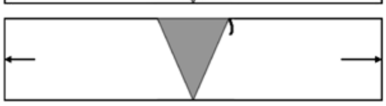


Fig. 3 Butt weld joints: (a) unmachined X-groove (t = 10 mm); (b) unmachined V-groove (t = 20 mm); (c) unmachined V-groove (t = 10 mm); (d) machined V-groove (t = 10 mm)

Table 3 FAT of steel from standards based on experimental fatigue test (MPa)

Geometry	IIW (Ref 1, 2)	GL (Ref 20)	Conditions
	100	90	Transverse butt weld made in shop in flat position. Max. Weld reinforcement is (1 mm + 0.1 × W) or toe angle ≤30°
	80	80	Transverse butt weld not satisfying previous conditions
	Not available	71	Transverse butt weld from one side, full penetration
	125	112	Transverse butt weld ground flush to plate

The material type used for the base and weld metal was steel, so values of E were chosen as 210 GPa. Figure 3 shows the FE models that were used in this study with approximated geometries for the total joints length equal to 100 mm. The, as-machined weldments were taken into consideration.

3.2 Experimental Measurements

The results obtained in this study are compared with the experimental results from IIW (Ref 1, 2), BSI (Ref 3), and Germanische Lloyd GL (Ref 20). These standards were based on the experimental fatigue testing under tensile cyclic loads. Table 3 shows some values of FAT from different standards.

According to BSI, IIW, GL, and the National Institute for Materials Science (NIMS) (Ref 21), the initial crack length is non-measurable as of now and no guidance is found. Also, there are other weld profiles and geometries that have not been presented yet.

Based on the previous study (Ref 13), the initial crack length was determined. Therefore, the calculation of fatigue life of new geometries and profiles can be estimated using the current numerical approach.

4. Results and Discussion

Numerical analysis of 2D, complete penetration butt joints was performed to determine the effects of weld profile and geometries on fatigue crack propagation life under cyclic tensile loading.

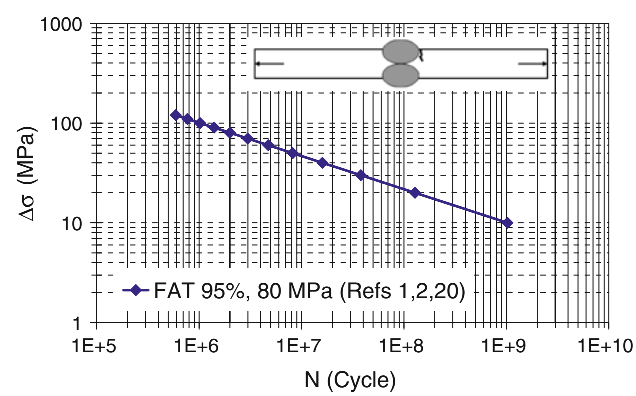


Fig. 4 *S-N* curve for X-groove unmachined butt weld, W = 10 mm, H = 2 mm, and t = 10 mm, (C_{char} = 5E−13, m = 3)

4.1 S-N Curves

Butt welds with different thickness and weld reinforcement were presented to show the validity of the current approach to calculate the fatigue life.

Transverse butt weld made in shop floor in flat position with toe angle more than 30° (see Fig. 3a) has a FAT equal to 80 MPa from IIW case 213 (Ref 1, 2) and GL, type No. 3 (Ref 20), see Fig. 4. Figure 5 shows the fatigue life calculation for this case using numerical integration of Paris' law. Initial crack length equal to 0.1 mm is confirmed with the FAT value taken from IIW and GL. Therefore, it can be concluded to use this crack length for other cases of butt welds, single-, or double-side welds.

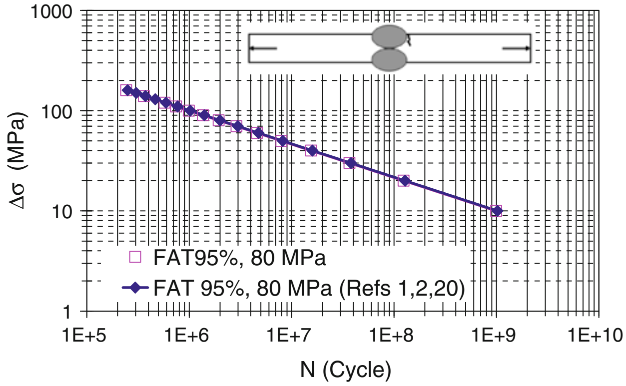


Fig. 5 *S-N* curve for X-groove unmachined butt weld compared with the FAT value 80 MPa from standards, $W = 10$ mm, $H = 2$ mm, and $t = 10$ mm, ($C_{char} = 5E-13$, $m = 3$)

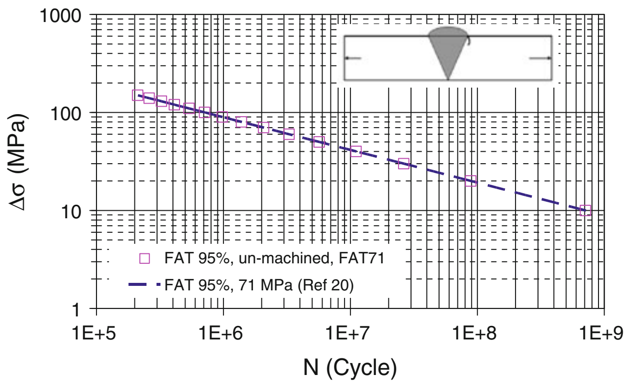


Fig. 6 *S-N* curve for V-groove unmachined butt weld, $W = 10$ mm, $H = 2$ mm, and $t = 20$ mm, ($C_{char} = 5E-13$, $m = 3$)

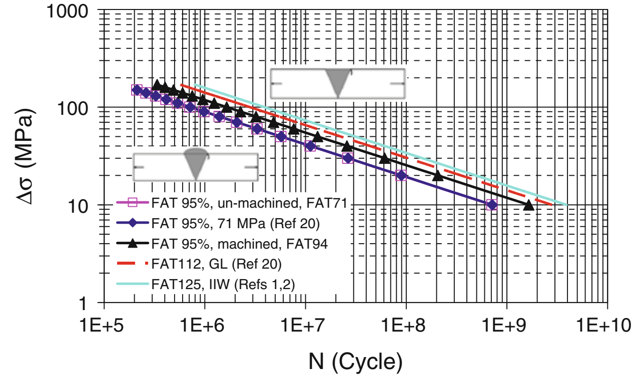


Fig. 7 *S-N* curves for V-groove unmachined and machined butt weld, $W = 10$ mm, $H = 2$ mm, and $t = 20$ mm, ($C_{char} = 5E-13$, $m = 3$)

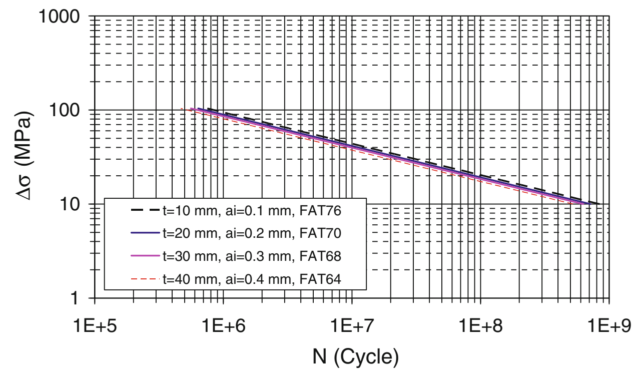


Fig. 8 Characteristic *S-N* curves for V-groove unmachined butt weld, $W = 10$ mm, $H = 2$ mm, and $t = 10$-40 mm, ($C_{char} = 5E-13$, $m = 3$)

The *S-N* curve for single groove butt weld with sheet thickness 20 mm, weld reinforcement width 10 mm and height 2 mm (Fig. 3b, c) are presented in Fig. 6. This calculated FAT value agrees well with those recommended from GL type No. 6, FAT 71 MPa (Ref 20).

Owing to the effect of stress concentration, the FAT and life decrease with the presence of a weld reinforcement. Therefore, the complete removal of the weld bead reinforcement (see Fig. 3d) has been reported to give improved fatigue performance in condition of free surface from crack like scratch after machining. The machining processes for fillet weld are having high influence on FAT and fatigue behavior of joints. The flash grinding increases the FAT to 91 MPa, while it was 71 MPa (Ref 20) in the case of weld reinforcement, because of reduction of stress concentration at weld toe; see Fig. 7. An increase in endurance limit is also observed in the joint area of flash butt-welded joints after the weld flash has been removed (Ref 22).

The decrease in FAT between smooth plates (machined butt weld) and notch plate (unmachined butt weld) can be defined in terms of the stress concentrating factor (K_t) as follows:

$$K_t = \frac{\text{FAT}_{\text{machined}}}{\text{FAT}_{\text{unmachined}}} \quad \text{(Eq 7)}$$

FAT-values for machined transverse butt weld joints are equal to about 94 MPa (see Fig. 7); then, K_t is equal to 1.33.

According to IIW and GL, FAT-values are equal to 125 MPa, and 112 MPa, respectively (see, Fig. 7). These values are higher than the FAT94 which are calculated in this study. The reason is that the effects of scratch in machined joint have been reduced in reality. Therefore, the initial crack equal to 0.1 mm, which was used for the weld toe crack, will give a lower fatigue life.

As the thickness of plates is reduced, the fatigue strength and life will increase in case of proportional scaling of the weld toe crack length (i.e., $a_i = 0.1$, 0.2, 0.3, and 0.4 mm for thicknesses 10, 20, 30, and 40 mm, respectively). These results have been confirmed by others researchers (Ref 23-25); see, Fig. 8.

4.2 Verifications with Standards

The design class F is recommended to be used commonly for the design of butt-welded joints of the predicted scatter band of *S-N* curves in Ref 19 as shown in Fig. 9.

For reference, the design life and mean life of relevant full penetration arc-welded butt joint fatigue classes as specified in BSI5400 and BSI7608 (Ref 26, 27), respectively, are also shown in Fig. 9. Class D welds are shop floor welds made in flat position using specific arc welding processes. Class E welds are out of position welds made by other processes including submerged arc welding. Class F welds are welds made on a permanent backing strip, and certain classes of fillet welds.

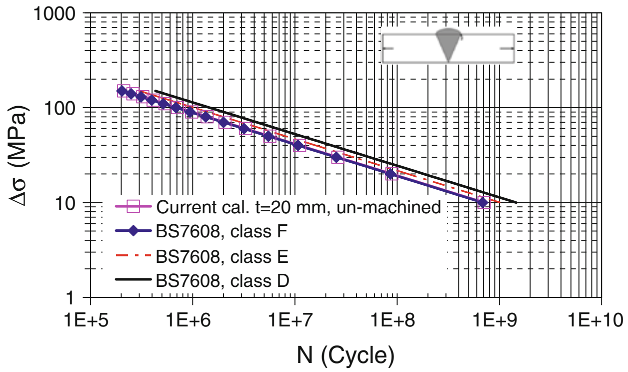


Fig. 9 Comparisons between different fatigue design data (FAT95%) and the current calculation (a_i = 0.1 mm, C_{char} = 5E−13, m = 3)

Figure 9 shows the comparison of different design data of fatigue test for butt welds. Therefore, a high-quality-welded butt joint would be expected to be assigned to class D (Ref 28); see Fig. 9.

According to the current study, the fracture mechanics approach has given more conservative fatigue life and FAT as compared with BSI7608. Therefore, it is suggested that for safe fatigue design of critical welding practice, fracture mechanics should be used with crack parameters which are calculated in this study.

The current results agree well with the literature which used LEFM and FEA and those based on experimental tests (Ref 6, 18, 19, 23, 29, 30).

5. Conclusions

Fracture mechanics has been used to find the accurate prediction of fatigue life of welded joints. It can be used to determine FAT of unknown notch cases of welded connections.

The entire fatigue process in fillet-welded joints has been modeled by pure fracture mechanics approach. The simple version of Paris' law has been adopted. In this study, the initial crack depth and growth rate parameters have been determined according to backward calculations to calculate FAT. The new values of FAT have been calculated according to the predicted existence of an initial crack. Therefore, the proposed initial crack length is expected to give good results. An initial crack size equal to 0.1 mm was used for all joints that have weld toe crack, and this length is typical when arc welding is used and consistent for different welding processes. These initial crack length values are applicable for all types of joints which have the same crack type. The machining processes for fillet weld are having high influence on FAT and fatigue behavior of joints. In this study, the flash grinding increases the calculated FAT to 94 MPa while it was 71 MPa. As the thickness of plates is reduced, the fatigue strength and life will increase in case of proportional scaling of the weld toe crack length. This study shows the possibility of simulating different geometries and calculating the fatigue life for welding joint geometries not listed yet in previous recommendations to provide the fatigue life strength, and thus save the time and costs that are needed for experimental testes.

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