Fatigue Assessment of Friction Stir Welded Joints in Aluminium Profiles

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Doctoral Thesis

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Abstract:

Friction stir welding (FSW) is a low heat input solid state welding technology. It is often used for fabrication of aluminium alloys in transportation applications including railway, shipbuilding, bridge structures and automotive components. In these applications the material is frequently subject to varying load conditions and fatigue failure is a critical issue. In most cases standard codes and fatigue guidelines for aluminium welded joints address only welded structures with conventional welding methods but not those with FSW procedure. In the scope of this thesis fatigue life assessment of friction stir welded components was performed using theoretical approaches along with finite element method (FEM). The further aim of this study was to generate a basis for standardization of fatigue assessment of friction stir welded joints.

Friction stir welded hollow aluminium panels of alloy 6005A are investigated. The panels are used for train wall sides, train floors, deck and bridges. Each panel is made of several profiles that are joined with the friction stir welding method. Fatigue bending tests were performed for profiles in these panels. Fatigue cracks and failure appeared at notches in the profiles. With FEM simulations critical positions for crack initiation and failure were identified. The method of critical distance was used to analyse and estimate the fatigue life. It was shown that the failure location and fatigue limit could be predicted for both base metal and weld location. Choice of welding procedure (clamping condition) can significantly influence the fatigue life. It was shown that for some panels the critical distance method was not able to explain the failure in the weld. In this case fracture mechanics together with residual stress analysis were used successfully to predict the failure.

Assuming homogeneous material properties throughout the weld and the base material, FEM analysis for T and overlap joints as well can provide a reasonable fatigue prediction. This suggests that the same assumption can be extended to complex components for failure analysis of the friction stir welded joints when using the critical distance method.

Fatigue assessment of friction stir welded joints was also performed using standard codes Eurocode 9 and IIW. Fatigue curves of traditional fusion welded joints were used. The results are in reasonable agreement with experimental data and FEM predictions.

Keywords: Friction stir welding, Fatigue, Aluminium alloys, Critical distance, Finite element method, Standard codes
LIST OF APPENDED PAPERS AND AUTHOR CONTRIBUTION IN EACH PAPER

Paper I - Fatigue strength of friction stir welded aluminium profile for train car application.
7th Int. Symp. on Friction Stir Welding, Awaji Island, Japan (2008)
M. Mahdavi Shahri, R. Sandström,

Paper II - Fatigue analysis of friction stir welded aluminium profile using critical distance
M. Mahdavi Shahri, R. Sandström.

Paper III - Critical distance method to estimate the fatigue life time of friction stir welded profiles
M. Mahdavi Shahri, R. Sandström, W. Osikowicz.

Paper IV - Influence of fabrication stresses on fatigue life of friction stir welded aluminium profiles
M. Mahdavi Shahri, R. Sandström.

Paper V - Eurocode 9 to estimate the fatigue life of friction stir welded aluminium panels
Submitted to Engineering Structures Journal for publication
M. Mahdavi Shahri, T. Höglund, R. Sandström.

Paper VI - Effective notch stress and critical distance method to estimate the fatigue life of T and overlap friction stir welded joints.
Submitted to Engineering Failure Analysis Journal for publication
M. Mahdavi Shahri, R. Sandström.

Other Contributions (not included in the thesis)

R. Sandström, S. Waqas, M. Mahdavi Shahri, Slow strain rate tensile testing of friction stir welded Cu-OFP. Research report presented in SKB, Swedish nuclear fuel and waste management Co.


M. Mahdavi Shahri, T. Höglund, R. Sandström, Fatigue life prediction of friction stir welded profile. TMS Annual Meeting, Accepted for oral Presentation, Orlando USA 2012.
**Distribution of work**

**Paper I**

The author of this thesis performed the experiment and did the stress analysis. The author of the thesis also wrote the manuscript. Sandström supervised the work and corrected the manuscript.

**Paper II**

The author of this thesis performed the experiment and did the stress analysis and life prediction. The author of the thesis also wrote the manuscript. Sandström supervised the work and corrected the manuscript.

**Paper III**

The author of this thesis performed the experiment, did the stress analysis for life prediction and wrote the manuscript. Wojciech Osikowicz managed the welding procedure for the panels and commented on the manuscript. Sandström supervised the work and corrected the manuscript.

**Paper IV**

The author of this thesis performed the experiment, wrote the manuscript, and made the stress analysis together with Sandström, who supervised the work and corrected the manuscript.

**Paper V**

The author of this thesis made the evaluation of the results and wrote the manuscript. Torsten Höglund did the stress analysis and supervised the work. Sandström corrected the manuscript.

**Paper VI**

The author of this thesis performed the experiment and did the stress analysis for life prediction. Sandström supervised the work and corrected the manuscript.
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1- Introduction

1.1 The need for fatigue assessment of friction stir welded structures

Good mechanical properties and low weight make aluminium alloys commonly used engineering materials. However, aluminium has traditionally been viewed upon as difficult to weld with conventional fusion welding. Friction Stir Welding is a solid state joining process developed in 1990 [1] and is nowadays frequently used to join aluminium alloys. The FSW process is fast and it can easily be automated. This lowers production time and manufacturing cost. It is also seen to provide superior joint integrity.

In transportation and under varying load conditions fatigue failure is an important issue. There are many factors that make the weld critical under fatigue loading conditions. For instance, stress concentrations such as weld toe and weld root, residual stresses, unfavourable mechanical properties of the weld nugget and potential defects in the weld are major causes of weld failure in service. Weld failure leads to loss of lives and substantial costs each year all over the world.

Guidelines and standard codes such as Eurocode 9 [2] and International Institute of Welding (IIW) recommendations [3] are established for fatigue assessment of aluminium structures and weldments. These recommendations embrace laws and principles regarding fatigue and provide systematic approaches for fatigue assessment of complex structures. For instance the output from modern computer programs or finite element analysis results can be applied directly for life estimation through the use of these codes. The standard fatigue curves presented in the codes are based on experimental investigations and include effects of:

- Local stress concentration due to weld geometries
- Weld imperfections
- Welding residual stresses
- Welding process and metallurgical conditions
- Post weld treatment
- Mechanical properties of the weld nugget

The fatigue curves presented in standard codes address welded structures with conventional welding methods but not those with FSW procedure. For friction stir welding, smooth surface appearance of welded joints, lower level of residual stresses, the absence of filler material in the weld, limited risk of porosity formation and fine-grained equiaxial microstructure provide fatigue strength which is typically higher than those of fusion welds [4],[5].

As the applications for friction stir welding are expanding, demands for fatigue assessment of friction stir welded structures have also increased. Indeed, proper theoretical approaches and standard procedures need to be identified and introduced for fatigue assessment of friction stir welded joint.

Additionally, fatigue strength of friction stir welded joints can be influenced by different welding parameters. It has been a point of interest for many industries to improve the fatigue life via altering the welding parameters.
1.2 Aim of the work

During recent years several investigations have been made of fatigue properties of friction stir welded joints [6]-[12]. The great majority of available data from the fatigue analysis of friction stir welded joints are concerned with uniaxial loading conditions for a simple geometry. In uniaxial loading nominal stress is normally used as reference stress and it is easy to determine. However, fatigue failure is a highly localized phenomenon in engineering components and determining the nominal stress is not always possible due to the complexity of structures and presence of stress concentrators such as notches and cracks. Many approaches based on local parameters [13]-[21] as well as fatigue standard codes have been proposed in order for fatigue assessment of engineering components.

The aim of the thesis was to perform fatigue assessment of friction stir welded aluminium panels covering the following issues:

- Experimental fatigue assessment of friction stir welded profiles
- Capability of critical distance method to estimate the fatigue life for weld location and base metal
- Capability of critical distance method to predict the failure locations in the panels
- Evaluation of residual stresses and their influence on fatigue life
- Influence of welding procedure and clamping condition on fatigue life of friction stir welded joints
- Applicability of Eurocode 9 and IIW recommendations for fatigue assessment of friction stir welded joints

Fig. 1. An aluminium panel of train wall side. Two extruded profiles are welded by friction stir welding technique; weld line can be seen in the centre of the panel.
2- Overview (A) - Friction Stir Welding

2.1 Friction stir welding and process parameters

FSW is a solid-state joining process that was invented in 1991 at the Welding Institute (TWI), UK. A non-consumable rotating tool interacts with the work pieces and frictional heating plasticises the material. Movement of the rotating tool along the welding direction produces the joint. Maximum temperature is 0.7 to 0.9 of the melting temperature and a large temperature gradient is avoided [22].

Figure 2 shows a schematic diagram of the FSW process. The rotating tool including a shoulder and a probe (pin) is rotated and fed at a constant traverse speed into the line between two pieces of material, which are pushed together. Shoulder is in contact with the work piece surface in order to generate necessary heat. Heat is formed between the tool shoulder and the work pieces. The material is softened, as the tool moves along the weld line and the material is stirred by the pin and two pieces are welded.

![Fig. 2. Schematic illustration of the friction stir welding process](image)

Correct parameters are needed to perform the welding. There are at least five important factors:

*Tool rotation and travel speeds*

There are two tool speeds in friction stir welding; the traverse speed along the joint line and the rotation speed. These parameters are of considerable importance and must be chosen properly. Increasing the rotation speed or decreasing the traverse speed will result in an increase of the temperature in the weld. To produce a good weld it is important that the material is hot enough to plasticize the material around the tool. If the material is not hot enough then voids and other defects may be produced in the weld and if the weld is too hot, the weld nugget may collapse [23].
Tool geometry and material

Tool geometry is an important factor as a good tool can improve both the weld quality and the welding speed. Tool material should be sufficiently strong and wear resistant at the welding temperature. Hot work tool steels are usually used for welding aluminium alloys within the thickness range of 0.5 - 50 mm but more advanced tool materials are necessary for other applications such as metal matrix composites or higher melting point materials [24][25]. Geometry of pin and shoulder has been found to have strong effect on the formation of stir zone.

Tool tilt and plunge depth

The plunge depth is the lowest point of the shoulder under the surface of the welded plate and it is a critical parameter for weld penetration. It increases the pressure below the tool and helps the good forging of the material at the rear of the tool. Tilting the tool by 2-3 degrees, so that the back part of the tool is lower than the front, assists this forging process. The plunge depth needs to be chosen correctly, both to provide the necessary downward pressure and to get the proper weld penetration [22].

Welding force

During welding there are a number of forces that will act on the tool. A downwards force to fix the position of the tool and the traverse force. A torque is also required for tool rotation.

Pre-heating and pre-cooling

High melting points material such as steel and titanium may have difficulties to gain enough softening and plasticity through heat produced by the welding tool. In order to get a good material flow pre-heating can be used. For low melting point material cooling can be used in order to reduce grain growth of recrystallised grains.

2.2 Fatigue properties of friction stir welds

In the past few years, several investigations have been done on stress-number of cycle (S–N) behaviour and fatigue crack propagation (FCP) behaviour of FS welds[26]-[39]. These studies show that fatigue strength of FS welds in general are lower than those of the base metal, i.e., the FS welds are susceptible to fatigue crack initiation, however in some cases the fatigue limit was reported comparable to those of base metal [36][40]. It is also observed that the fatigue strength of the FS welds is higher than those of fusion welds such as MIG and laser welds [29][36]. Typical S–N curve for FS weld, laser weld, MIG weld, and base metal of 6005Al-T5 are shown in Fig. 3. Fine grain microstructures of FS welds contribute to the higher fatigue strength compared to fusion welds.

Several other studies were conducted to evaluate the crack propagation and fatigue threshold for friction stir welds. Ericsson and Sandström [41] showed that crack propagation rate in friction stir weld 6082 matches that of the parent material at high load ratio R. Similar results were reported by Donne et al [38] for FS welds of 2024Al-T3 and 6013Al-T6. They observed that at lower loads or lower R-ratio of 0.1, the resistance to fatigue crack propagation of the FS welds were higher compared to those of the base metal and at higher R-ratios of 0.7–0.8, base materials and FS welds exhibited similar propagation behaviour. Fig. 4 shows crack propagation rate at R=0.8 in the weld zone, HAZ and base material of AA6082. Similarly, other investigations [27][36][37][39] showed that FS weld zone exhibited significantly lower
fatigue-crack growth and much higher fatigue threshold, $\Delta K_{th}$, at a stress ratio of 0.1 in both air and 3.5% NaCl solution compare to base metal.

Fig. 3. S–N curves of base metal, FSW weld, laser weld and MIG weld for 6005Al-T5, FS welds presents fatigue strength higher than MIG and laser welds [28].

Fig 4. Crack propagation rate at R=0.8 in weld, HAZ and base material of AA6082[41].
The reason for low fatigue crack growth and high threshold value compared to base metal is attributed to the presence of compressive residual stress in the weld and roughness induced crack closure. The overall good fatigue properties of friction stir welds are attributed to fine grain microstructure, the smooth appearance of the weld and low tensile residual stresses in the weld area [22].

2.3 Residual stress in friction stir welds

Compressive and tensile residual stresses are important factors in fatigue assessment. In fusion welding, complex thermal and mechanical stresses are involved in the welding process and residual stresses can reach the yield strength of the base material, but in friction stir welding residual stresses are low due to low level of heat input. Tensile residual stresses have been measured at magnitudes of 20-50 % of base material yield strength. It is known that residual stresses in FS welds are normally higher in the longitudinal direction than in transverse (same as fusion welds). For both longitudinal and transverse directions stresses exhibit an “M” like distribution across the weld. The peak tensile longitudinal residual stresses normally appear in the HAZ. Residual stresses in base metal or weld nugget might be compressive. Fig. 5 shows typical distribution of residual stresses across the weld region. As can be seen, residual stresses are higher in HAZ but lower in base metal and weld nugget[22],[42].

![Fig. 5. Typical distribution of residual stresses across the FS welded region [42].](image)
Rigid clamping is used in FSW and this exerts higher restraint on the welded plates compared to conventional welding processes. These restraints impede the contraction of the weld nugget and heat-affected zone during cooling thereby resulting in generation of residual stresses. Normally in HAZ residual stresses are higher than in other regions. Tensile residual stresses in the HAZ were found to decrease with decreasing transverse and rotational weld speed (1000-300 mm/min and 2500-1000 rev/min) [43]. This is explained by the lower cooling rates. Indeed clamping force and welding speed can be used to control the level of residual stresses in the weld and HAZ for FSW. Consequently residual stress exerts a significant effect on the post weld mechanical properties, particularly the fatigue properties. In addition to thermo-mechanical residual stresses in the welded area, load applied by clamping force and welding tool can produce local plastic deformation. These strains mainly appear close to notches, cracks and other stressed locations in the component. Residual stresses left after plastic deformation can influence the behaviour of cracks or notches close to the weld and result in shorter fatigue life. Mahdavi Shahri and Sandström showed that residual stresses due to plastic deformation close to crack tip resulted in fatigue failure in the weld, see paper IV.

Donne et al. [44] investigated residual stress distribution through the thickness of FSW 2024Al-T3 and 6013Al-T6 welds by using different measurement techniques such as X-ray diffraction, neutron diffraction and high-energy synchrotron radiation. It was observed that residual stress distribution across the welds was similar at the top and root sides of the welds.

2.4 Friction stir welds flaws

Common defects in fusion welding such as hot cracking, porosity and slag formation are not normally present in friction stir welds. However, conventional welding defects such as void or lack of penetration or surface irregularities can still be present. Process parameters such as tool pressure, rotational and welding speed, pin and shoulder geometries are crucial factors to control temperature and material flow and therefore formation of flaws. For instance if the tool pressure is too low, enough heat will not be generated and this will lead to lack in bonding or when the welding speed is too high unwedded grooves in the weld may appear. Here follows a list of common types of flaws that can appear in friction stir welds [45],[46].

**Tunnel defects** – Flaws that are volumetric and contains no material. When the traverse speed is too high or the rotation speed is too low the temperature will not be high enough, voids can be formed in the weld. The tilt angle may also affect the occurrence of tunnel defects, too small or too big angles can cause this defect.

**Lack of penetration** – Poor alignment of the welding tool, short pin, inadequate plunge depth resulting in lack of penetration. Lack of penetration can be a potential source for fatigue crack.

**Kissing bonds** – Kissing bonds are entrapped oxide and they are formed due to low temperature and limited act of forging by welding tool. Indeed the materials of the joined parts have only slight contact and little mixing. These defects are very difficult to trace and the weld may have the appearance of a defect free weld, but has poor mechanical properties when tested.

**Nugget collapse** - can occur if the temperature is too high during the welding process.

**Surface flash**- is a result of tool pressure on the weld nugget.
Common flaw types which can be generated in friction stir welding process are illustrated in Fig. 6.

![Common flaw types which can be generated in friction stir welding process](image)

**Fig.6.** Common flaw types which can be generated in friction stir welding process[46]

### 3- Overview (B) - Fatigue Assessment

#### 3.1 Strategies for fatigue assessment

Fatigue failure occurs when the structure is subjected to variable loading condition and the amplitude of the load is below what is required to cause static failure. Normally for fatigue assessment of any material two alternative assumptions are made [47]:

1- Material is free of any initial defect and crack initiation is started at a defect free position.
2- The material contains initial defects (like cracks) and failure is initiated from the defect position.

If the first assumption is applied then the fatigue initiation life can be estimated from the cyclic stress state. Indeed the stresses should be calculated analytically or numerically and then fatigue life is found by correlating each stress state to the number of cycles which cause the failure in the material. If the second assumption is applied, the stress intensity factor for the crack is used to predict the crack propagation life.

Material data in engineering design is derived using these two assumptions by testing small scale specimens, since testing on full scale components could be very expensive or even impossible. However, using test data obtained from small scale it is not always sufficient for fatigue assessment of a component. The component geometry can be very complex and it is not always possible to use the material data directly to determine the fatigue life of complex
component. When it comes to fatigue assessment of welded structure it is even more complicated. For instance:

- The difficulty of defining material properties, which vary throughout the weld and the heat affected zone (HAZ)
- The presence of residual stresses
- The difficulty of defining the weld geometry: radius at the toe or weld root
- The difficulty of defining a FE model for the weld geometry which is sufficiently precise

In order to overcome aforementioned problems standard codes such as IIW and Eurocode 9 were established for fatigue assessment (initiation and propagation) of complex or welded structures. There are mainly four methods to predict fatigue of welded components that are used in standard codes:

- Nominal Stress
- Structural Stress
- Effective Notch Stress
- Linear Elastic Fracture Mechanics (LEFM)

Below, brief descriptions of the methods as recommended by IIW are given. More detailed description of the methods can be found in Radaj and Sonsino[48].

### 3.1.1 Nominal Stress

The nominal stress is the average stress in a welded joint and can be calculated using elementary theories of structural mechanics. For a simple structure it is easy to define the nominal stress. Fig. 7 shows the nominal stress in a beam-like component. As can be seen in the diagram linear stress is calculated and weld toe stress at (z) is ignored.

For complex structures the nominal stress can be more difficult to determine or sometimes impossible to define. Even with finite element methods it may not be straightforward to determine nominal stresses for complex structures. By definition finite element methods determine notch stresses and not nominal stresses. No global code or program is yet designed to determine the nominal stresses from finite element analysis and it is up to the designer to interpret the nominal stress. Some designers assume that the stress at some distance from stress concentration (depends on plate thickness) is the nominal stress.

In the IIW recommendations, S-N curves for 81 different structural details of welded joints are compiled. The S-N curve is identified by its fatigue strength of the part at 2 million load cycles.
Fig. 7. Nominal stress calculation at the vicinity of weld toe. Nominal stress is defined by axial load $P$ and bending moment $M$ in the section and the weld toe stress at $(z)$ is ignored [2].

3.1.2 Structural Stress

The Structural or Hot-Spot stress comprises all stress raising effects of a structural detail but not stress concentrations due to the local weld profile i.e. membrane stress plus the linear shell bending stress. The non-linear stress peak is not included, see Fig. 8.

The method is mainly used when the nominal stress is difficult to define. Structural stress is usually determined by a finite element analysis (FEA) based on IIW recommendations or the strain from strain gauges is recorded at specified distances from the weld toe. These stresses (strains) are then extrapolated to the weld toe using a two or three point formula which is specified by IIW. There are uncertainties regarding the reference points (Fig. 8) and extrapolation equation. The reference points can be selected at absolute distance from the weld toe. Distance of reference points from the weld toe can be also defined as function of plate thickness, as explained in the IIW recommendations. The method is normally valid if the failure occurs at the weld toe. The designer has to verify if weld will fail in the weld toe and not from the root or inner defects and identify what procedure is appropriate for extrapolation. The final assessment is performed by a direct comparison of structural stress with universal Woehler S–N curves.
Fig. 8. Definition of structural stress. By choosing two or three reference points, the stress can be extrapolated to the weld toe [3]

3.1.3 Effective Notch Stress Method

The irregularity of the weld toe and the root configuration is normally difficult to assess as an ordinary notch in the structure due to non-linear material behaviour or scatter of the weld shape parameters. It has been shown in many investigations that these irregularities can be replaced by an effective radius. For structural steels an effective notch root radius of \( r = 1 \text{ mm} \) has been verified to give consistent results for fatigue assessment [49][50][51]. The effective notch stress can be determined by FEM and then corresponding fatigue life can be obtained by using the Woehler S–N curves in the IIW recommendations. Recent investigations have shown that the method can also be applied to aluminium structures. It has been shown that for thin wall aluminium structures (with thickness \( t < 5 \text{ mm} \)) that reference radius of 0.05 mm can be used for fatigue assessment [52]. However, the effective notch stress concept for thickness \( t < 5 \text{ mm} \) has not been yet introduced into the IIW recommendations. Fig. 9 shows the principle of applying a notch radius of 1 mm on weld toes and roots. All the weld irregularities and stress concentrations are replaced by a fictitious radius.
3.1.4 Fracture Mechanics Method

Fracture mechanics is a method that is used to predict the behaviour of cracks or crack-like imperfections in solids subjected to fatigue loading. Fracture mechanics for welded structures is used with the assumption of an initial crack in the material. To use this method knowledge of stress state in the vicinity of the crack is required. FEM is normally useful to determine such a data. The stress intensity factor is a suitable measure of the crack tip conditions. If the stress intensity factor is known the fatigue life can be determined by integrating the Paris power law[65]:

\[
\frac{da}{dN} = C(\Delta K)^m
\]

where \( C \) and \( m \) are material constants and \( \Delta K \) is the range of the stress intensity factor. Equation (1) presents the crack growth per cycle as a function of the stress intensity factor. If stress distribution around the crack tip is known, the growth of the crack can be estimated in the structure. Figure 10 shows the crack growth per cycle as a function of the stress intensity factor range.

When the stress intensity factor is below a certain value, there is no crack growth. This value is a material dependent parameter and called threshold value for fatigue growth \( (\Delta K_{th}) \). In Fig. 10, region I is the threshold region, region II is the stable crack growth region and region III is the unstable crack growth region. If the stress intensity factor exceeds the fracture toughness value of the material then fracture will occur.
3.2 Critical distance method

As it was mentioned in previous sections, to perform the fatigue assessment of aluminium weldment many guidelines and standard codes such as Eurocode 9 and IIW recommendations can be used in order to perform the fatigue life assessment and optimum design of welded structures. For fatigue assessment of welded joints using these guidelines, the first step is to define a reference stress suitable for estimating fatigue strength. The next step is to use the reference S-N curve for life estimation. However, it is known that standard codes only address the technological and geometrical aspects (including defects). For instance in Eurocode 9 and IIW recommendations, the same fatigue strength is assumed for aluminium alloys regardless of chemical composition and mechanical properties of different alloys. This assumption results in conservative estimates due to the well-known fact that different aluminium series are characterised by different fatigue strengths. Although the technological and geometrical aspects such as stress concentrations play a major role to determine the overall strength taking material properties in to account could be a great advantage. A theory of critical distance [53] has been developed during recent years. This method will be discussed in the thesis. The method is able to take the material properties in to account. Therefore it is of interest to use this method when doing fatigue assessment of specific locations with specific material properties such as weldment and in particular friction stir welded joints. This method is also applicable for fatigue assessment of stress concentrations such as sharp notches, cracks and blunt notches.

Many other investigations have been made in order to correctly assessing stress concentration phenomena in weldments. Fatigue assessment methods as the N-SIF approach [54]-[56] the Strain Energy Density (SED) parameter[57], the Fictitious Notch Radius approach [58] are some recent development in this area.
3.2.1 Background

The critical distance method is used to predict the fatigue limit. Fatigue limit can be measured from plain specimens in tension but can not be used for most engineering components because they usually fail from stress concentration. Stress concentrations are usually appearing around geometric features. If the geometric feature is a blunt notch then its nominal fatigue limit may be reduced as much as the stress concentration factor $k_t$. However this approach can not always be used. For instance, when the radius of curvature approaches zero, the maximum stress approaches infinity. This gives rise to complex behaviour for small features. Indeed material may not fail even in the presence of high stress around notches.

A number of investigations have been made in order to predict this behaviour. It has been found that high strength of small notches is due to the fact that the stress concentration is limited to small volume of material. In this approach stress at a single point or averaged over a given distance or area is considered. The early work of Neuber suggests that the averaged stress around the notch root should be used for fatigue assessment [61]. Peterson [60] simplified this further and proposed that the appropriate stress can be found at a point at a certain distance from the notch root. Taylor[59] extended Neuber's and Peterson's theories and proposed that the critical distance method can be used for a body containing a crack, see Fig 11. The key parameter in this method is the critical distance $L$ [61]:

$$L = \frac{1}{\pi} \left( \frac{\Delta K_{th}}{\Delta \sigma_0} \right)^2$$

Fig.11. Representation of point method and area method for notch stress calculation [59].

where $\Delta K_{th}$ is the fatigue threshold stress intensity factor and $\Delta \sigma_0$ the fatigue limit for uniaxial specimens. Contrary to IIW recommendations and Eurocode 9, material properties of each specific material can be taken into account.

The critical distance method indeed unifies the approaches for fatigue assessment of notch and crack (fracture mechanics). As shown in Fig. 11, the method is applied for a blunt notch
and a sharp crack. This is important because normally a blunt notch and a crack should be assessed in different ways.

### 3.2.2 The effect of small defects

One of the advantages of the critical distance method is its ability to predict fatigue behaviour of small defects. It is known that linear elastic fracture mechanics is normally applicable for long cracks and cannot be used for short cracks and small defect size in the material (normally below 0.1 mm). This was first observed by Pearson [63]. This is due to the fact that short crack behaviour is anomalous. Indeed the short crack threshold is not the same as for long cracks. Fig. 12 shows the schematic behaviour of short cracks. It can be seen in the diagram that LEFM does not work for small defect size.

However, it has been shown that the theory of critical distance and other critical distance methods such as Elhaddad empirical law [64] can be used to predict the fatigue limit for small size defects. Fig. 13 shows predictions of the fatigue limit as a function of crack length. The material is a common medium-carbon steel, at R=−1. The point method, line method and area method is used by Taylor [61] to predict the fatigue limit for short crack. The figure also shows the El-Haddad empirical law prediction. Predictions by LEFM are valid only for long cracks.

![Schematic representation of short crack behaviour](image-url)

**Fig.12.** Schematic representation of short crack behaviour [63].
Fatigue cracking of metallic materials takes place in three steps: micro level, meso level and macro level. A micro crack is located within a single grain, a meso crack in a couple of grains and a macro crack passes through many grains. Formation of micro crack in a single grain can be derived from the theory of cyclic deformation in single crystals [65][67]. Indeed formation of persistent slip can result in initiation. If the applied cyclic loadings are high enough the micro crack can break through the microstructural barriers and become a meso crack. Indeed material morphology to analyse the formation of short crack is very important and plasticity plays a primary role in the primary initiation and propagation level. But when the crack is long enough, it is assumed that the material become homogeneous and isotropic and linear–elastic stress fields drive the crack propagation [67]

According to the classical Kitagawa–Takahashi’s [66] diagram (see Fig. 14) cracks can be classified as short when their half-length, \( a_0 \), is less than \( L \). Conversely, they are long when \( a_0 \) is greater than \( L \). Here \( L \) is a material parameter and can be calculated as presented in equation (2). Indeed the importance of critical distance method is to link from the less severe notch (plain specimen) to the most severe notch (long crack) and its capability for fatigue assessment from microstructural up to macro level defects.
3.2.3 The effect of R ratio

It has been found that critical distance value is almost constant as the local value of the load ratio, $R$, changes. $\Delta K_{th}$ and $\Delta \sigma_0$ are material constants (in equation 2) so it is expected that $L$ value should be a constant as well. It is known that both $\Delta K_{th}$ and $\Delta \sigma_0$ change with $R$ value. However it is shown by Taylor [53] that despite the changes in these two properties with $R$, the value of $L$ is changed to a smaller extent.

It is also shown by Taylor [53] that even if the $L$ value shows slight changes for some material at different $R$, by assuming constant $L$, fatigue prediction is still accurate and the value of critical distance does not need to be known with great precision. It is because the notch root stress is not a strong function of distance. Table 1 shows calculated $L$ value for different materials at different load ratio. As can be seen in the table the critical distance value tend to be remain fairly constant [67]. For notched specimens of cast iron Taylor showed that the critical distance method is able to predict fatigue limit at different load ratios [53]. Fig. 15 shows predicted fatigue limit using point method for cast iron. The critical distance method takes the effect of load ratio in to account.
3.2.4 The effect of notch radius

It is well known that the fatigue limit is influenced by the radius of a notch. Fig. 16 shows some typical data on the effect of notch root radius on fatigue limit. The material is 0.15% carbon steel and fatigue tested with load ratio $R=-1$. As can be seen in the figure, the fatigue limit remains constant below a certain value of notch radius which is 1 mm in this case. As the notch radius increases, the fatigue limit will increase. The concept is used in failure analysis; indeed by increasing the radius of sharp notches to a blunt notch, the possibility of having fatigue failure will decrease. The figure shows prediction made using the point method. The stress analysis in this case is made with FEM but some other method such as Creager and Paris can also be used for stress analysis around the notch. As illustrated in Fig 16 critical distance (point method) has predicted the fatigue limit accurately for different radius. This concept is very important because the critical distance method indeed can be used as a powerful tool for designing of notch component against fatigue failure.

If the notch radius is much smaller than $L$, then it is expected that the notch radius has no effect on fatigue limit prediction since the reference stress is assessed a long way from the
notch tip. In paper II of this thesis two models were presented for the interface notch of a weld, one with zero radius and the second model with finite radius (equal to 2, 10, and 50 μm). The point method (PM) was used to estimate the fatigue limit for each case. It was observed that fatigue limit was the same for both models. Fatigue limit was predicted correctly and the fatigue analysis has not been affected by high local stress gradient or singularity of the stress field at the tip of the notch since the chosen radii were much smaller than 0.2 mm which is the $L$ value for the material. This finding suggests that if the radius of a notch is small enough then it can be changed to zero without altering the outcome.

Fig.16. Effect of notch root radius on fatigue limit, prediction using point method [68]

### 3.2.5 Multiaxial fatigue

In many applications in engineering components, the stress state is complex. When using the critical distance method for uniaxial loading, a line should be drawn perpendicular to the direction of the first principle stress at the point of maximum stress and then stress is assessed as shown in Fig.11. Taylor and Susmel [69] have investigated the application of theory of critical distance to predict the fatigue limit under multiaxial loading condition. They have conducted experiments for wide range of materials using specimens with sharp notch and loaded in tension at various angles of inclination in order to simulate multiaxial loading condition. The point and line methods were used in the same way as for uniaxial testing specimen at the vicinity of sharp notches and the first principle stress was used as the stress parameter. It was found that both the point method and the line method give a good prediction. For multiaxial loading using Susmel–Lazzarin critical plane criterion [70] increases the accuracy of the result. This method is in principle a critical distance method but the stress parameter is a shear stress. Fig 17 shows experimental fatigue limit in terms of
maximum shear stress amplitude, $\tau_a$, versus predicted fatigue limit $\tau_{A,\text{Ref}}$ for notched specimens under multiaxial loading.

### Multiaxial Fatigue Data

![Graph](image)

**Fig. 17.** Predicted and experimental fatigue limit for notch specimens under multiaxial loading using Susmel–Lazzarin critical plane method [70]

#### 3.2.6 Application of TCD for fatigue assessment of weldments

As mentioned, the critical distance method has the ability to take material parameters into account for fatigue assessment. $\Delta K_{th}$ is the fatigue threshold stress intensity factor and $\Delta \sigma_0$ the fatigue limit for uniaxial specimens. This is very important when it comes to fatigue assessment of weldments because materials properties in welded region are different from those in base metals. Current procedures of fatigue assessments for welded joints assume homogenous material properties. Taylor [71] determined the material properties at the vicinity of failure location in a weldment and then used these data for fatigue assessment. The other important aspect is fatigue assessment of weld beads such as weld toe and weld root with sharp notches. For instance, Taylor used a simple model of a weld bead as a triangular prism with zero radii at its edges as shown in Fig 18. Stress at the critical distance can easily be determined even using modestly fine mesh. Indeed no extra fine mesh is required at the vicinity of the weld beads since stresses on the notch tip is not used in the analysis.
Fig. 18. T-shaped weld specimen: fatigue failure occurred from the corner of the weld bead as indicated in agreement with the FE model [71].

It was mentioned that the critical distance method can be used for fatigue assessment of multiaxial loading states which is an advantage for complex welded structure as well. In the current thesis the critical distance method has been used for fatigue assessment of friction stir welded components for the first time. In the next section a summary of the work will be given.
4. Summary of appended papers

Paper I: Fatigue strength of friction stir welded aluminium profile for train car application

The purpose of paper (I) was to investigate fatigue strength experimentally and identify stress concentration locations in a friction stir welded aluminium panel under full scale testing. This panel is used for railway car walls. It is made from two profiles which are welded in the centre with joint geometry called half overlap. The panel shape is a frame rib structure, Fig 19. The joint type is a combined lap-butt joint and a sharp interface notch is formed after welding close to the weld nugget. The possibility of crack initiation and propagation from the blunt notches in the base metal and also crack initiation from the sharp interface notch in the FS welded joints under cyclic loading condition were investigated. FEM modelling of loading conditions was carried out and the stress distribution in the panel was investigated.

With FEM simulations critical positions for crack initiation and failure were identified in the parent metal and in the weld. The fatigue failures always occurred at the major stress concentrations in full agreement with the finite element simulations. These positions were all at narrow radii in the base metal. Failure appeared in seven different positions in the profiles as illustrated in Fig. 19. Highest stress was observed in the weld interface sharp notch but fracture never occurred in the welds although cracking could be observed in some specimens there. Cracks initiated from the interface notch at the weld root and propagated to the weld nugget but the propagation stopped after a short distance. This is shown in Fig 20.

Fig.19. Stress concentrations on radii locations in the panel under 3-point bending test.
Fatigue failure was observed in seven different locations. Example of fatigue failure is illustrated for position 1.

![Fatigue failure example](image1.png)

**Fig.20.** Crack initiated from interface tip and propagated to weld (stir zone) under 3.2 kN load and after $10^5$ cycles

**Paper II: Fatigue analysis of friction stir welded aluminium profile using critical distance**

The purpose of paper (II) was to predict the fatigue limit and to evaluate the fatigue strength of the weld location of the panel investigated in paper (I).

Finite element method stress analysis combined with the theory of critical distance was used to estimate the fatigue limit for weld interface notch and blunt notches in the panel section. It was discussed in section 3.2.1 that the critical distance method as a unifying method can be used to estimate the fatigue strength of a crack like imperfection as well as a blunt notch or other features in the component. This capability of the critical distance method was used to compare the fatigue limit of a blunt notch and a crack like imperfection directly and to identify failure locations. As mentioned in paper I, despite of the high stress concentration in sharp notch interface in the weld root failure never appeared there. The reason for this can be easily understood considering stress–distance curves. Fig. 21 shows the stress–distance curve for a blunt notch at position (1) in the base metal and weld interface notch. When the notch (1) is at its fatigue limit (stress at the critical distance is equal to the fatigue strength of the plain specimen) then the equivalent stress at the critical distance for the weld root is lower than the fatigue limit of the plain specimen. According to critical distance this means that failure will not happen at the weld interface notch despite the high stress gradient at the tip of notch.

It was also observed in experiments that the weld never failed. Since the radius of the interface notch is much smaller than the critical distance value $L$, choosing different notch radii does not influence the far field stress. As can be seen in Fig 21, stress at the critical distance for notch radius of 10 and 50 µm is similar.

The point method (PM) was used to determine the fatigue limit for other features and stress concentration features in the panel and fatigue strength was obtained in the term of load range at 2 million cycles (by choosing the stress equal to fatigue limit of plain specimen at the
critical distance). Table 2 shows the prediction of the fatigue strength for each notch compared with the experimental results.

![Stress–Distance Curve](image)

**Fig. 21.** Stress–distance curve for position (1) and weld interface notch. Despite the high stress gradient at the tip of the weld interface notch, stress at the critical distance for interface notch is lower compared to position 1.

**Table 2.** Prediction of the fatigue strength for different location of profile at 2 million cycles.

<table>
<thead>
<tr>
<th>Position</th>
<th>Experimental fatigue limit</th>
<th>Point method prediction (PM)</th>
<th>Deviation from experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch 1</td>
<td>2.05 kN</td>
<td>1.85 kN</td>
<td>9%</td>
</tr>
<tr>
<td>Notch 2</td>
<td>1.91 kN</td>
<td>1.77 kN</td>
<td>7%</td>
</tr>
<tr>
<td>Notch 3</td>
<td>1.98 kN</td>
<td>1.92 kN</td>
<td>3%</td>
</tr>
<tr>
<td>Notch 4</td>
<td>2.26 kN</td>
<td>1.61 kN</td>
<td>28%</td>
</tr>
<tr>
<td>Notch 5</td>
<td>2.08 kN</td>
<td>1.87 kN</td>
<td>10%</td>
</tr>
<tr>
<td>Notch 6</td>
<td>1.88 kN</td>
<td>1.58 kN</td>
<td>16%</td>
</tr>
</tbody>
</table>
Paper III: Critical distance method to estimate the fatigue life time of friction stir welded profiles

Friction stir welded panels are produced with two main joint geometries: half overlap and hourglass. These two geometries are shown in Fig. 22. The aim of this paper was fatigue assessment of different weld geometries under different loading condition. The other aim of the paper was to study the influence of welding procedure and clamping condition on fatigue life of friction stir welded panel.

Guidelines and standard codes such as Eurocode 9 and IIW recommendations are available for fatigue assessment of aluminium structures and weldments. However, these may not be proper for complex geometries since it is not always obvious how to determine the reference stresses. Effective notch stress concept for thickness $t < 5$ mm has not yet been introduced by IIW, while the gauges of aluminium panels in this study are only 2–3 mm.

It was shown in the present paper that critical distance method can be used for fatigue assessment under different loading condition regardless of where the failure occurs in the panels. Figure 23 shows S-N diagram and critical distance prediction for different joint geometries. Series B presents the prediction for hourglass shape panel simultaneously welded on lower and upper part of the panel. Series C and D are predictions for half overlap joints, which are loaded differently. Series C failed in base metal but series D failed in the weld; however, for both group predictions were acceptable. No sample of series B failed in the weld.

It was also observed that clamping procedure and applied force by the welding tool in friction stir welding of hollow aluminium profiles can significantly alter the fatigue life. All samples of hourglass shape which had not been welded simultaneously (series A) failed in the weld. The fatigue crack initiated from the sharp interface notch and propagated through the welded nugget. Thus complete fracture occurred in the weld. This was explained by the presence of residual stresses around the crack tip in series A. For series A a fracture mechanics approach along with residual stress analysis has been used in this case to analyze the failure, but presence of residual stresses was not incorporated into the stress analysis of critical distance method for fatigue life prediction.
Fig. 22. Schematics of weld geometries after joining process, (a) 1– hourglass shape, (b) 2 – half overlap (truss); Weld nuggets are shown schematically by black areas. The arrow shows the location of interface notch.

![Stress range versus number of cycles to failure for series B, C and D. Prediction for a critical distance of 0.19 mm and 0.11 mm fits with uniaxial data.](image)

Fig. 23. Stress range versus number of cycles to failure for series B, C and D. Prediction for a critical distance of 0.19 mm and 0.11 mm fits with uniaxial data.

Paper IV: Influence of fabrication stresses on fatigue life of friction stir welded aluminium profiles

Effects of clamping conditions on the fatigue life of friction stir welded joints have been studied to much lesser extent compared to many other parameters which are involved in the friction stir welding process. The aim of paper IV was to investigate how clamping conditions can influence the fatigue life. As mentioned in paper III two welded hourglass shape panels presented totally different fatigue life when the welding procedure was altered, see Fig 24.

It was found that the applied force by the welding tool can produce local plastic deformation and residual stresses close to notches resulting in fatigue failure of the weld. Residual stresses were modelled using Comsol Multiphysics. Superposition techniques were used to take the residual stresses into account. Stress intensity factor $K_L$ associated with applied stress was calculated and added to stress intensity factor $K_R$ associated with the residual stress. In this way an effective stress ratio could be calculated. When the residual stresses affect the mean stresses or stress ratios, this actually influenced the crack initiation, propagation, and closure.

In the present paper it was shown that the failure in the weld and low fatigue strength in one
series of hour glass shape panels could be explained by taking into account the effect of stress ratio.

![Graph showing load range vs number of cycles to failure for series A and B](image)

**Fig. 24.** The experimental results of the fatigue test, load range vs. number of cycles to failure for series A and B

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**Paper V: Eurocode 9 to estimate the fatigue life of friction stir welded aluminium panels**

Eurocode 9 is a European standard that covers the design of building and engineering structures made from wrought and cast aluminium alloys. Paper V compares fatigue test results from friction stir welded joints with fatigue curves of traditional fusion welded joints which are presented in Eurocode 9. In this paper the capability of Eurocode 9 for estimating the fatigue life time of FS welded extruded aluminium profiles is investigated. Eurocode 9 estimates the fatigue life on the basis of the nominal stress; however, determining the nominal stress in complex structures is normally difficult. Instead nominal stress strategy can be used simply with no need of FEM computation; therefore it is extremely cost effective and time saving if there is a way to use the nominal stress strategy. At the initial stage of designing a complex component the nominal stress method can also be used to roughly estimate the fatigue life of components. Prediction results from Eurocode 9 for hollow aluminium welded panels were conservative in all cases; both for base metal and weld location the deviations from the experiment fell between 8-15 % of experimental results. Fig 25 shows experimental
and predicted fatigue life for the panels. As can be seen in the figure all predictions were conservative for the panels.

![Figure 25](image_url)

**Fig. 25.** Experimental and predicted fatigue life

**Paper VI: Effective notch stress and critical distance method to estimate the fatigue life of T and overlap friction stir welded joints**

The interface notch is a general characteristic of friction stir welded joints and appears in many types of FS welds. As interface notch is a location that fatigue failure can occur. However, the aluminium panels in papers I-IV did not fail in the interface notch except in one case. In order to predict fatigue failure under complex loading conditions, fatigue of T and overlap joints were modelled. For both types of joint, failure occurred in the weld nugget initiated from the interface notch, Fig 26.

It was shown that the FE analysis can still provide a reasonable fatigue prediction for friction stir joints when using the critical distance method, assuming homogeneous material throughout the weld and the base material. Two material properties $\Delta K_{th}$, the fatigue threshold stress intensity factor and $\Delta \sigma_0$, the fatigue limit were used to estimate the fatigue life at interface location. For friction stir welded material $\Delta K_{th}$ and $\Delta \sigma_0$ are close to those of base metal. Assuming homogeneous material throughout the weld and the base material a good prediction can be obtained. The same procedure was applied on an actual component. It was shown that deviation for predicted result was less than 15% of the experimental results for failure location in the weld.
Fig. 26. Experimental and predicted fatigue
5. Conclusions

Friction stir (FS) welded aluminium panels with different geometries have been fatigue tested. Stress analysis of the panels was performed with FEM. Fatigue assessment was performed using different strategies.

- All geometrical features including sharp interface notches and blunt notches or features with unknown geometries in the panels were finely analysed and problem of fatigue were addressed using the critical distance method.

- The critical distance method has been used successfully and introduced as a proper method for fatigue assessment of these types of the panels made out of aluminium profiles.

- In all panels except in two cases, the predicted fatigue limit for the weld was higher than for other notches in the profile. This suggests a good strength and design for weld location from a fatigue point of view for existing panels.

- The problem of fatigue assessment of thin wall structures was addressed. The critical distance method was used successfully for plate thicknesses< 5mm.

- Tensile residual stresses due to unbalanced clamping force or downward force can appear very close to the crack tip and significantly influence the fatigue life.

- Fatigue S-N curve in Eurocode 9 can be used to approximately predict the fatigue of life friction stir welded material.

- Assuming homogeneous material throughout the weld and the base material in FE analysis still can provide a reasonable fatigue prediction for friction stir joints.

- Fatigue data generated in the thesis can be introduced into standard codes in order to use as reference S-N curves for friction stir welded profiles.
6. Acknowledgments

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