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Procedia Materials Science 3 (2014) 1330 – 1335

Procedia Materials Science

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20th European Conference on Fracture (ECF20)

# Numerical modelling of crack propagation in friction stir welded joint made of aluminium alloy

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## Abstract

In this work, fatigue crack propagation in thin-walled aluminium alloy structure with two friction stir welded (FSW) joints has been numerically modelled. Crack propagation in unstiffened part of the structure between two FSW joints is analyzed. Numerical method, so-called eXtended Finite Element Method (*XFEM*) has been used, including software *Abaqus*, as well as *Morfeo*, for modelling and results display. Tensile fatigue loading is applied, with stress ratio $R$=0. The analyzed model is made from aluminium alloy 2024-T351. Material properties in joints zones and geometry measures of *FSW* joint are adopted from available experiments.

Following results are obtained by numerical analysis:

- stress-displacement state in the structure, where special attention is dedicated to the crack tip zone,
- coordinates of the crack front $(x, y, z)$ for every propagation step,
- distributions of stress intensity factors - $K_I$ , $K_{II}$ , $K_{III}$ and $K_{eq}$ along the crack front for each propagation step,
- structural life in form of change of applied number of load cycles, $N$, for each step of propagation.

Besides numerical results, *Abaqus* provides visualization of crack propagation in the structure. On the basis of obtained data, analysis of crack growth stability is done.

*Keywords:* alloy; aluminium alloy; fatigue crack propagation; friction stir welding; structure life, extended finite element method

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Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering
doi:10.1016/j.mspro.2014.06.215

## 1. Introduction

The process of *friction steel welding* - *FSW* was patented in 1991 at the *TWI* (*The Welding Institute, Cambridge, UK*). As a very efficient method of welding both homogeneous and heterogeneous metals, see Johnsen (1999) and Veljić et al. (2012), it quickly found application in many branches of industry. This process is especially important for welding of some aluminium alloys, since conventional welding process are not applicable. The reason for this lies in significant decrease in mechanical properties in welded joint zones, caused by the melting of material. Since the *FSW* procedure takes places in solid state, whereby temperatures in the weld zone does not exceed 500°C, there are no significant changes within the welded material. Application of this relatively new welding process considerably reduces manufacturing costs. Additionally, by applying *FSW*, high quality joints are formed from various materials, with different thickness, shape and dimensions.

Long history of application of Finite Element Method - *FEM* greatly contributed to solving of numerous complex engineering problems. Calculation and analysis of stress-strain state within the structure enables high quality assessment of structural integrity. This contribution is especially significant for structural analysis of important structural parts, i.e. load-bearing components. Long and expensive laboratory tests have been replaced with considerably cheaper software packages for calculation of structures. The application of numerical methods to discretized 2D and 3D structure models, along with laws of fracture mechanics, enabled solving of problems mentioned above in a comfortable way, as shown in Živojinović (2013).

In the case of non-stationary crack calculation, i.e. when its growth within the structure is observed, application of this method is not a simple task. This is due to the need to perform “splitting” of a finite element at the previously formed crack tip for each step of the growth and then generate a new finite element mesh in the same region. Hence, applying FEM becomes far more complicated. However, the method was improved by developing the so-called *eXtended Finite Element Method* (*XFEM*), which enables automatic mesh generation with each new step of the crack growth (by adding special functions to the finite element approximation), see Belytschko and Black (1999) and Giner et al. (2009).

This new method found wide application in some of the existing finite element software packages (including *ABAQUS*, which is used in this work), and it made a significant contribution to structural integrity assessment.

## 2. Numerical modelling of crack propagation in plate with two friction stir welded joints

The process of numerical modelling of crack propagation in *FSW* joint structure consists of the following stages:

1. development of 2D or 3D models, including the modelling of an initial crack (shape, dimensions and location within the structure),
2. defining the materials, i.e. mechanical properties for each welded joint zone, including the base metal;
3. determining the loading (its intensity and type, as well as location),
4. defining the boundary conditions (e.g. connection with the rest of the structure-assembly),
5. generating the finite element mesh, whereby it is important to select the appropriate element type and mesh density. Therefore, the mesh is refined around the initial crack and in the region of its expected further growth.
6. Analysis of the results obtained by the calculation.

As an example of calculation of a non-reinforced thin-walled structure, a plate model with dimensions of 1x20x144 mm was analysed. The plates are made from aluminium alloy 2024-T351. The model consists of plates connected via two *FSW* joints. An initial crack with length of $a_0$ = 3 mm is introduced into the structure between two welded joints, so that it does not disturb the symmetry (Fig. 1), Živojinović (2013).

Within the *FSW* joint, 4 zones can be observed:

a) parent zone-PZ or base material-BM,
b) heat affected zone-HAZ,
c) thermo-mechanically affected zone-TMAZ,
d) nugget-N-part of TMAZ.

Each of the zones mentioned above has different mechanical properties.

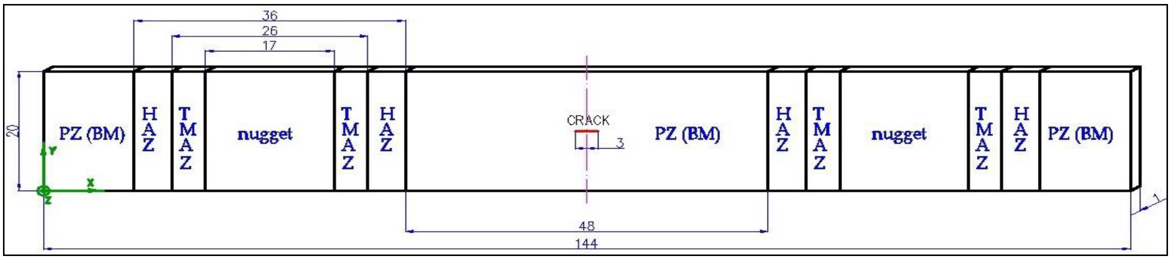

Fig. 1. Plate with two FSW joints.

Modelling of the plate was performed in ABAQUS (Fig. 2). Material properties for each weld zone are adopted from Golestaneh et al. (2009); *Young* modulus $E$ is 68 GPa for all zones, yield strengths are: $\sigma_Y$(nugget)=350 MPa, $\sigma_Y$(TMAZ)=272 MPa, $\sigma_Y$(HAZ)=448 MPa, $\sigma_Y$(PZ)=370 MPa. More detailed material data, like stress-strain relations and constants in *Paris* equation ($C$ and $n$), can be found in Golestaneh et al. (2009) and Živojinović et al. (2013).

The behaviour of a structure with two FSW joints subjected to tensile fatigue load with maximum value of applied stress $\sigma$ =10 MPa and stress ratio $R$ = 0, was analyzed.

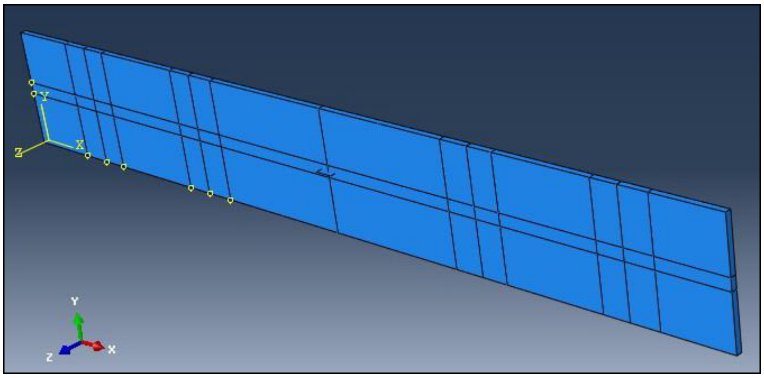

Fig. 2. 3D model of a plate with two FSW joints.

## 3. Results

Particular attention is devoted to the assessment of stability of a crack propagating within the structure.

Based on the calculation performed in *ABAQUS/Morfeo* software, the following data were obtained, Živojinović (2013):

Table 1. Numerical data: change in stress intensity factor with crack growth (left end of the crack).

| left side | $x$ (mm) | $y$ (mm) | $K_I$ (MPa mm$^{0.5}$) | $K_{II}$ (MPa mm$^{0.5}$) | $K_{III}$ (MPa mm$^{0.5}$) | $K_{eq}$ (MPa mm$^{0.5}$) |
|---|---|---|---|---|---|---|
| step 1 | 70.5 | 10 | 44.18988 | 0.200514 | -0.02486 | 44.2608 |
| step 2 | 70.00308 | 10.00454 | 52.57806 | -0.00666 | 0.000707 | 52.70743 |
| step 3 | 69.50551 | 10.00897 | 58.75426 | 0.297365 | 0.014445 | 58.76028 |
| step 4 | 69.00779 | 10.01852 | 66.56618 | 0.086557 | 0.048456 | 66.79225 |
| step 5 | 68.50962 | 10.02932 | 73.35788 | 0.245975 | 0.019613 | 73.32099 |
| step 6 | 68.01248 | 10.04356 | 79.37852 | 0.896758 | 0.035976 | 79.68473 |
| step 7 | 67.51837 | 10.06883 | 87.34881 | -0.21448 | 0.156039 | 87.69121 |
| step 8 | 67.02032 | 10.09214 | 93.18851 | 0.349592 | 0.382237 | 93.36657 |
| step 9 | 66.5252 | 10.11846 | 102.3447 | 1.873158 | 0.505289 | 102.6901 |
| step 10 | 66.02802 | 10.16415 | 105.9199 | 0.749744 | 0.916776 | 106.185 |

Table 2. Numerical data: change in stress intensity factor with crack growth (right end of the crack).

| right side | $x$ (mm) | $y$ (mm) | $K_I$ (MPa mm$^{0.5}$) | $K_{II}$ (MPa mm$^{0.5}$) | $K_{III}$ (MPa mm$^{0.5}$) | $K_{eq}$ (MPa mm$^{0.5}$) |
|---|---|---|---|---|---|---|
| step 1 | 73.5 | 10 | 44.17037 | 0.201249 | 0.015724 | 44.21612 |
| step 2 | 73.99675 | 10.00457 | 52.54249 | -0.07066 | 0.012236 | 52.72886 |
| step 3 | 74.49305 | 10.00773 | 58.57538 | 0.52168 | 0.078838 | 58.6223 |
| step 4 | 74.98649 | 10.01951 | 66.34716 | -0.38624 | -0.18848 | 66.70491 |
| step 5 | 75.48022 | 10.02599 | 73.31177 | 1.147647 | -0.25006 | 73.28491 |
| step 6 | 75.97631 | 10.04676 | 79.34246 | -0.05583 | -1.38131 | 79.82144 |
| step 7 | 76.47105 | 10.06994 | 87.1375 | 0.89349 | -2.39465 | 87.46488 |
| step 8 | 76.9652 | 10.09858 | 92.58274 | 0.469445 | -4.51923 | 93.33622 |
| step 9 | 77.45338 | 10.1519 | 98.58958 | 1.05176 | -9.89855 | 100.1579 |
| step 10 | 77.90766 | 10.18792 | 101.778 | 1.90337 | -11.9482 | 104.624 |

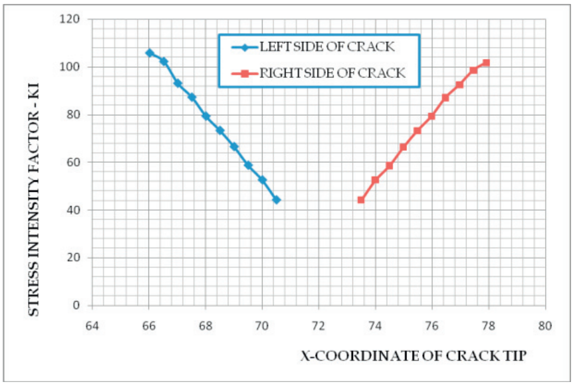

Fig. 3. Change of the stress intensity factor with crack growth.

The above diagram (Fig. 3.) shows a stable, gradual crack growth on both ends.

Table 3. Numerical data: crack growth as a function of number of load cycles - *N*.

| step | $\Delta N$ | $N$ |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 28596.4 | 28596.4 |
| 3 | 18474.3 | 47070.7 |
| 4 | 13115.2 | 60185.9 |
| 5 | 9397.46 | 69583.36 |
| 6 | 7206.67 | 76790.03 |
| 7 | 5592.53 | 82382.56 |
| 8 | 4403.08 | 86785.64 |
| 9 | 3501.64 | 90287.28 |
| 10 | 2874.6 | 93161.88 |

During its stable stage (stable crack growth), the crack propagates within the parent material, and does not reach the remaining zones of the two FSW joints.

## 4. Discussion

Following a certain number of steps, i.e. the period of stable crack growth, a gradual increase in stress intensity factor is observed on both left and right ends of the crack (Fig. 3). After that, unstable crack growth occurs, leading to failure (Table 3 and Fig. 4). Therefore, faster crack growth occurred after a number of load cycles of ≈ 90,000 was applied. The structure maintains its reliability under the given loading, regardless of the existence of a propagating crack. Only if the aforementioned number of load cycles has been applied (with the appropriate safety factor), the replacement of structure parts should be performed for the purpose of maintaining its operational efficiency. Reliability of the designed structure is secured within the calculated period.

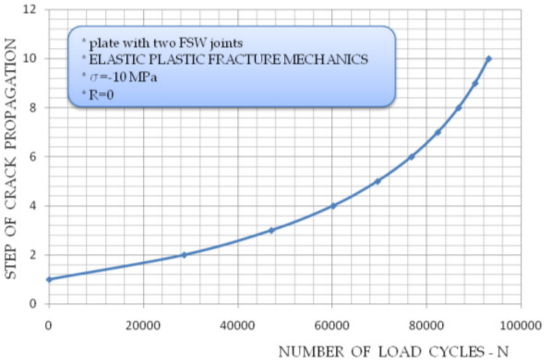

Fig. 4. Crack growth as a function of number of load cycles-*N*.

Following figures (Fig. 5(a)-5(e)) show the distribution of *von Mises* stress within the structure, for several successive propagation steps. A characteristic stress field around the crack tip can easily be noticed. At the same time, the crack growth occurs for the corresponding value - Δ*a*, so-called crack propagation step. All the fields are shown with the scale factor of 100 (due to this fact, the crack opening is clearly visible).

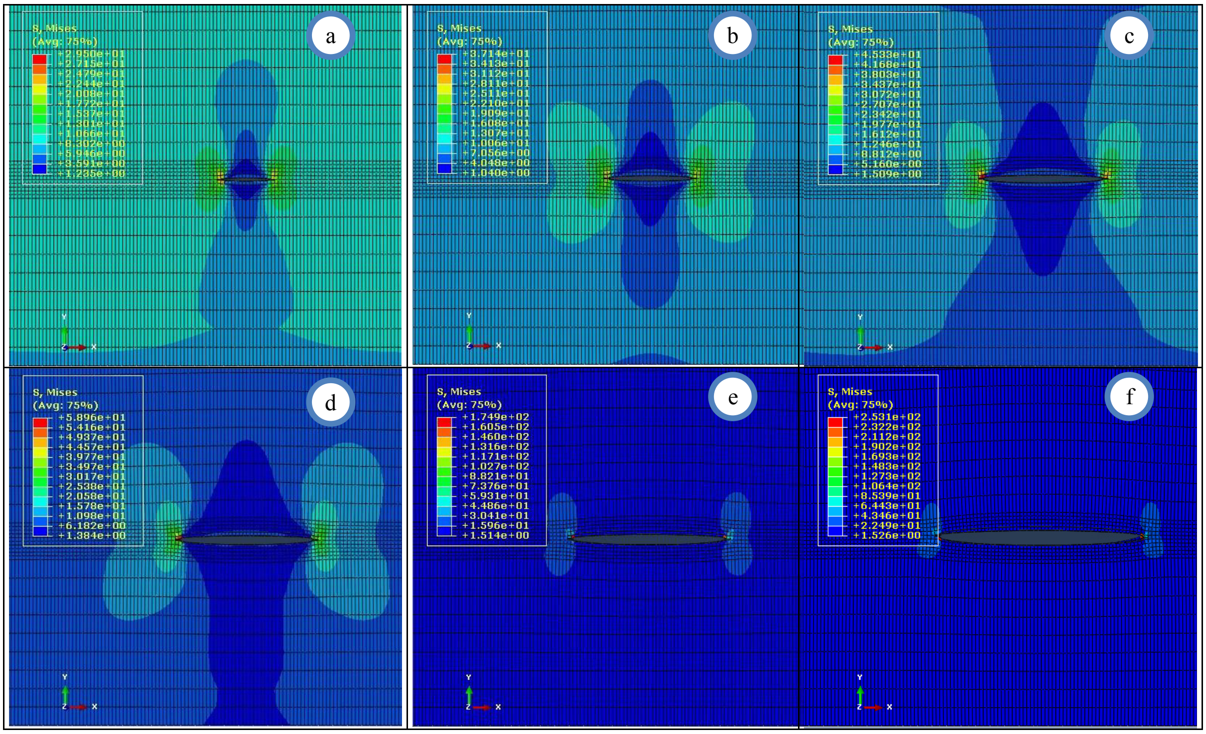

Fig. 5. Crack propagation between two *FSW* joints with *von Mises* stress distribution around the crack tip: (a) step 0; (b) step 2; (c) step 4; (d) step 5; (e) step 6; (f) step 9.

## 5. Conclusions

By analyzing the problems of crack propagation in a plate consisting of two *FSW* joints, the following conclusions have been reached:

- During its (stable) growth, the crack remains within the base material. As it gets closer to the *FSW* joint (*HAZ*), considerable crack growth leading to structure failure starts to occur, before the crack can reach the *HAZ*.
- During the propagation of the crack through the structure, change of its direction can be noticed. Therefore, a combination of crack opening and shearing occurs during its growth, which leads to deforming of the structure as a whole. This phenomenon is related to shear stresses appearing in the structure, and the two additional fracture modes are quantified by corresponding stress intensity factors $K_{II}$ and $K_{III}$.

In the further research, it is necessary to devote particular attention to the following aspects:

- accuracy of properties of the materials, i.e. welded joint zones, as input data.
- accuracy during detection of existing cracks in the structure and/or defining of potential locations where they could appear,
- accurate defining of a real load spectrum during the exploitation period,
- assessment of the right time to withdraw the component from exploitation and replace it.

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