The influence of small voids on the fatigue strength of friction stir welds in the aluminium alloy AA6061-T6

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Flat rectangular profiles of the aluminium alloy AA6061-T6 were friction stir welded to butt joints. Welding parameters outside the process window generated a random mixture of good welds and welds with small voids. These voids approximately reduced the tensile strength by 10%, the ductility by half, and the fatigue strength by 20% as compared to void-free welds. Voids can easily be detected on fracture surfaces. Void-free specimens have approximately 10% lower fatigue strength if the fatigue crack extends over a corner of the specimen cross section as compared to a semi-elliptical fatigue crack.

Key words: Fatigue testing, friction stir welding, aluminium alloy

1 Introduction

Joints made by Friction Stir Welding (FSW) have a high static strength and a good fatigue performance [1-3]. However, the fatigue strength can be strongly reduced by flaws present in the friction stir (FS) welds [4-8]. Several types of defects and flaws have been found and classified, as discussed for example in [5, 9]. The distinction made in the present report between 'defect' and 'flaw' is that a defect definitely inhibits the joint from fulfilling its function whereas a flaw is an imperfection that might or might not be tolerated. A defect is thus one type of flaw.

In an investigation of the fatigue strength of FS welds in AA6082-T4, welds with flaws denoted "lack of fusion or pores" were studied [10]. All fatigue cracks started at such flaws. The fatigue strength of the weld at 2 million cycles of axial testing was 50% of the fatigue strength of the parent material. In the present study, we aim to look at the consequences of comparatively small flaws. Even good FS welds contain local stress concentrations, the most severe one often being on the edge of the weld track. The higher the load of the fatigue test, the more sites will be activated. During low-load, high-cycle fatigue testing, though, often only a single crack is initiated [11]. While the fatigue life can be prolonged by milling the surface flush or by other suitable surface treatment [12], this is rarely done in industrial FSW. Since our research is application-oriented, we investigate joints with as-welded surfaces.

The single-side FS welded butt joints investigated here are asymmetric since the welding occurred from one side only. The sense of welding tool rotation in combination with the direction of the linear tool movement introduces another asymmetry between the so-called advancing and retreating sides. The advancing side is the side of the weld where a point on the circumference of the shoulder of the FSW tool has the highest velocity relative to the welded material. These two asymmetries are relevant for the fatigue strength of the weld because they lead to an asymmetric distribution of defects [9] as well as to asymmetric residual stresses [13].

Highly non-symmetrical joint configurations, such as tee and lap joints and joints without welding through the complete thickness, exhibit much poorer fatigue resistance than butt joints. In highly non-symmetrical joints, structural stress concentrations can be very strong and may dominate over local stress concentrations such as those occurring at weld flaws [14]. The common designations for the different zones within and around the FS weld are shown in Figure 1. The weld nugget consists of fully recrystallized material and was occupied by the tool during welding. The thermo-mechanically affected zone (TMAZ) corresponds to the plastically deformed material that surrounds the weld nugget. Finally, the heat affected zone (HAZ) is composed of material with altered microstructure due to the thermal cycle of the welding process.

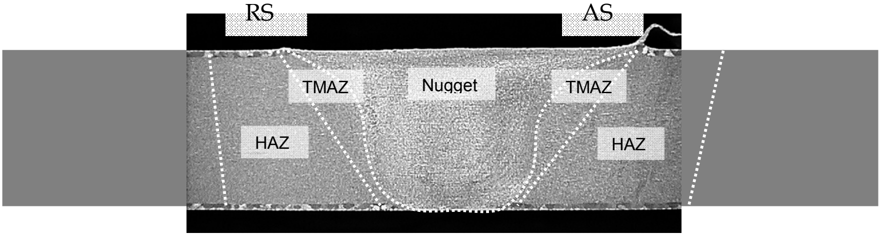

Figure 1: Zones of the friction stir weld – weld nugget, thermomechanically affected zone (TMAZ), and heat affected zone (HAZ). The advancing side (AS) and the retreating side (RS) of the weld are also indicated.

2 Experimental procedure

Flat rectangular profiles of the aluminium alloy AA6061-T6 in ¼ inch thickness were produced at a Sapa plant in North America, with the composition shown in Table 1. Due to storage, and especially due to shipping of the profiles over the Atlantic Ocean, they have had the opportunity to grow a thick layer of native oxide.

Table 1: Composition of the aluminium alloy AA6061 from this investigation

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.68	0.22	0.28	0.02	0.89	0.06	0.02	0.01

All concentrations are given in wt%.

500 mm long profiles were FS welded to butt joints at Sapa Technology using an in-house 5-axis TOS milling machine. The samples were welded in position control, with the weld track parallel to the direction of profile extrusion. Other welding parameters are given in Table 2.

Table 2: Tool and parameters used for friction stir welding of AA6061-T6 profiles

Tool	"5651", 5 mm pin diameter, 13 mm shoulder diameter
Tool tilt	2°
Welding speed	700 mm/min
Tool angular velocity	1900 rotations/min

Hammer bend tests with the root side of the weld under tension were conducted on selected samples of all welds and indicated that the joints had been welded through the complete material thickness. The bending radius during these hammer bend tests was almost zero.

The tool selected for the trials was somewhat smaller in diameter than 5651-tools used typically for ¼ inch of aluminium gauge and is normally used for 5 mm aluminium gauge. The pin length, however, was adjusted to fit the material thickness of ¼ inch. Special care was taken in order to produce welds with no or minimum underfill. The forging pressure on the material might have varied due to tolerances in profile thickness and shape in combination with the position-controlled mode of welding. The combination of these conditions led to a varying joint quality, including good welds and welds with small voids.

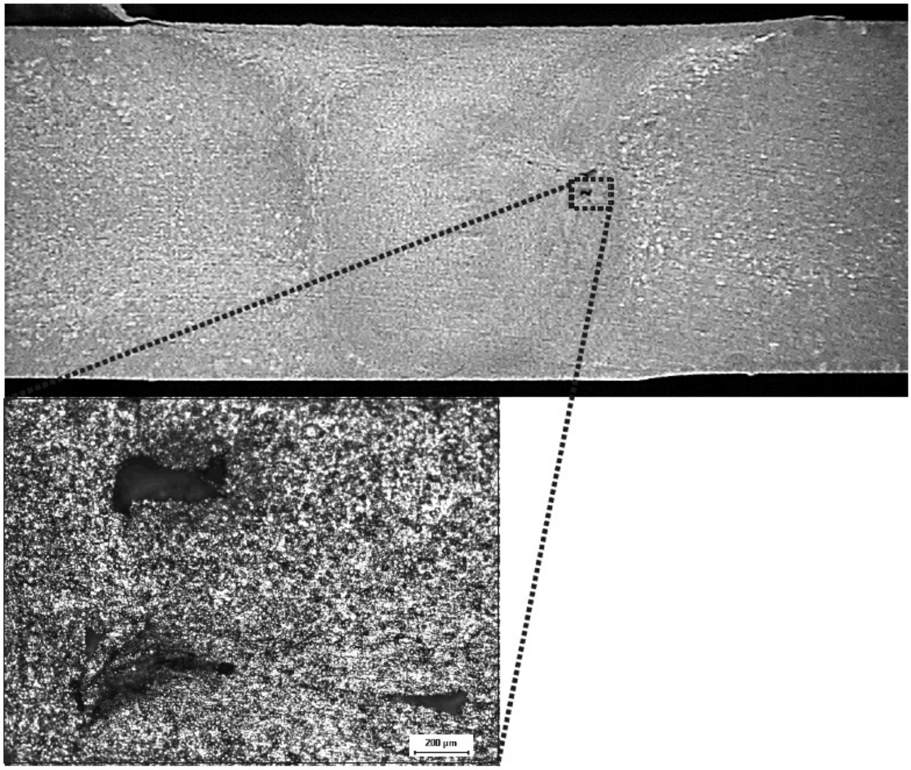

Figure 2: Friction stir weld with running void in aluminium alloy AA6061-T6

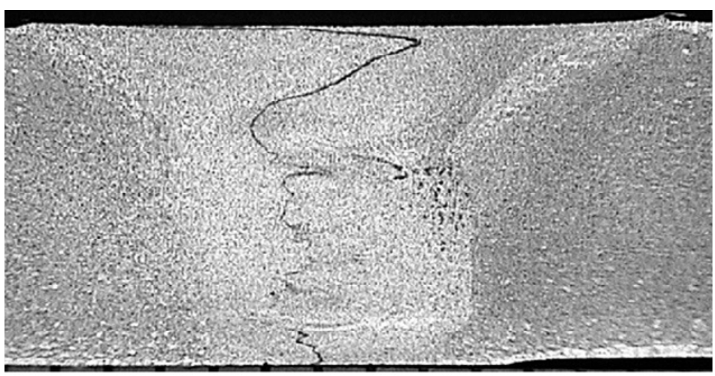

Figure 3: Cross section of friction stir weld in aluminium alloy AA6061-T6 after etching in caustic soda. The dark line corresponds to a band of small, finely distributed oxide particles of approximately 1 µm in diameter.

Some of the FS welded joints in AA6061 exhibit small voids running along the welds, as shown in Figure 2. Such a void coincides with a point that looks like a singularity in the material flow within the weld. This position of the void, close to the transition from the nugget to the thermo-mechanically affected zone (TMAZ) is typical for FS welds [9]. Voids can occur because of insufficient forging pressure, too low rotational speed in relation to the speed of welding, or too large gaps between faying surfaces.

Etching of weld cross sections in caustic soda makes visible bands of very small, finely distributed oxide particles of approximately 1 µm in diameter, as shown in Figure 3. These bands of oxide particles are very pronounced in the FS welds of the present investigation, which is probably due to the assumed thick layers of native oxide on the profile surfaces.

Tensile testing was carried out on a Zwick 1478 testing device according to EN10002-1:2001.

Axial stress-controlled fatigue tests were performed on a resonant testing device (Amsler Vibrophore) at around 100 Hz testing frequency. The load ratio R = 0.5 was chosen according to the recommendation in the new European standard [15]. For FS welds, the load ratio can significantly influence the fatigue strength [16] since transverse residual stresses in short FS welds are small [4].

3 Results and discussion

Tensile test results for parent materials and friction stir welds are given in Table 3. Proof strengths of void-free FS welds [1] are slightly above 50% of the respective parent material proof strength. The tensile strength reaches almost 80% of the value of the parent material. Within the group of specimens with FS welds, voids slightly reduce the mechanical strength values and strongly reduce the elongation values (normalized to the gauge length of the measurement), as depicted in Figure 4. The reduction in strength, slightly below 10%, corresponds roughly to the height of the void containing zone in relation to the total specimen thickness (Figure 2).

[1] Since a specimen with a weld is not homogeneous in its mechanical properties, its yield strength is not well defined by the regular tensile test. This should be considered when proof strengths measured on welded specimens are measured and discussed.

Table 3: Tensile test data of parent material and friction stir welds of aluminium alloy AA6061-T6

Type of specimen	$R_{p0,2}$ (MPa)	R_m (MPa)	A_{50} (%)	A_g (%)	Remarks
Parent material, ⊥ ED (n = 2)	298 [297-298]	318 [318-318]	(6.2) [5.7-6.6]	(4.9) [4.5-5.3]	Fracture outside gauge length
Parent material, | | ED (n = 2)	279 [278-279]	313 [313-313]	14.5 [14.2-14.8]	10.2 [10.1-10.2]	
Friction stir weld (n = 14)	167 [164-170]	251 [247-254]	6.5 [6.3-6.9]	4.2 [4.1-4.5]	No flaw visible on fracture surface
Friction stir weld (n = 6)	161 [151-165]	228 [218-236]	2.8 [2.3-3.5]	2.3 [1.9-3.0]	Running void visible on fracture surface

The numbers n of specimens are given in parentheses behind the respective specimen types. Mean values are given for all tensile test quantities, ranges of measured values are given in brackets below the respective mean values. The parent material specimens were taken perpendicular and parallel to the extrusion direction (ED).

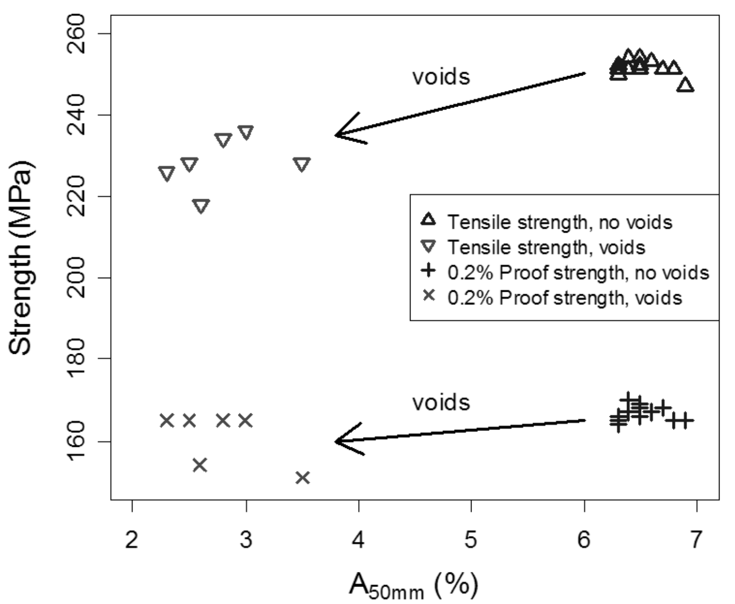

Figure 4: Influence of voids on proof strength, tensile strength, and elongation to fracture of friction stir welds in AA6061-T6

Most specimens without voids fractured at the edge of the weld track. Fractures mostly passed through the heat-affected zones which are the mechanically weakest regions. Voids in FS welds were opened during the tensile test and fracture was initiated there. Figure 5 shows fracture surfaces and side views of two selected specimens.
FS welds without voids exhibited a strong shear deformation before fracture occurred as shown in Figure 5. This deformation did not occur in specimens with running voids and the resulting elongations were thus much shorter.
Stress amplitude-fatigue life curves are shown in Figure 6. All specimens with voids (or crack nucleation at the root, as in one single case) failed earlier than all other tested specimens. The voids locally raise the stress amplitude during fatigue testing and are thus expected to significantly reduce the time for fatigue crack nucleation. Since voids also reduce the static tensile strength, the final unstable fracture already occurs at a

a)

b)

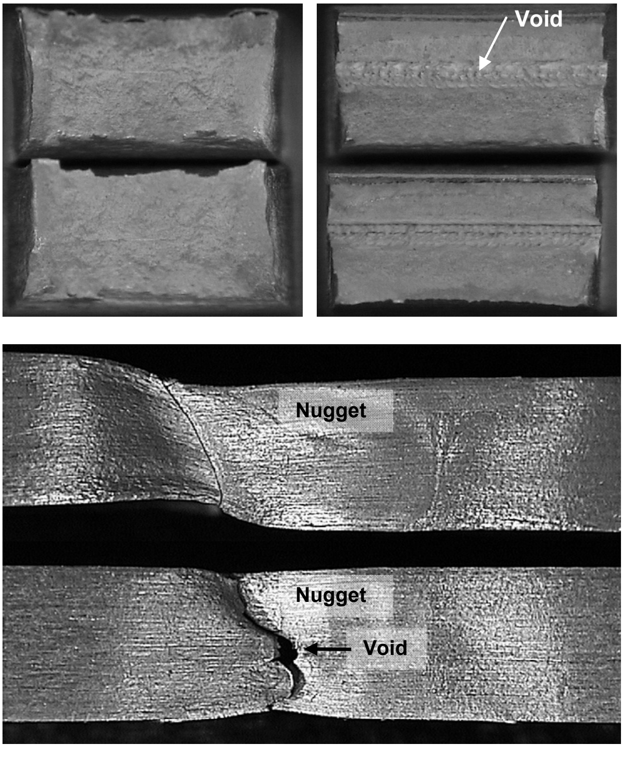

Figure 5: Fracture surfaces a) and side views b) of tensile test specimens with friction stir welds in aluminium alloy AA6061-T6. The void-free specimen failed in the heat-affected zone while the specimen with a running void failed inside the weld nugget.

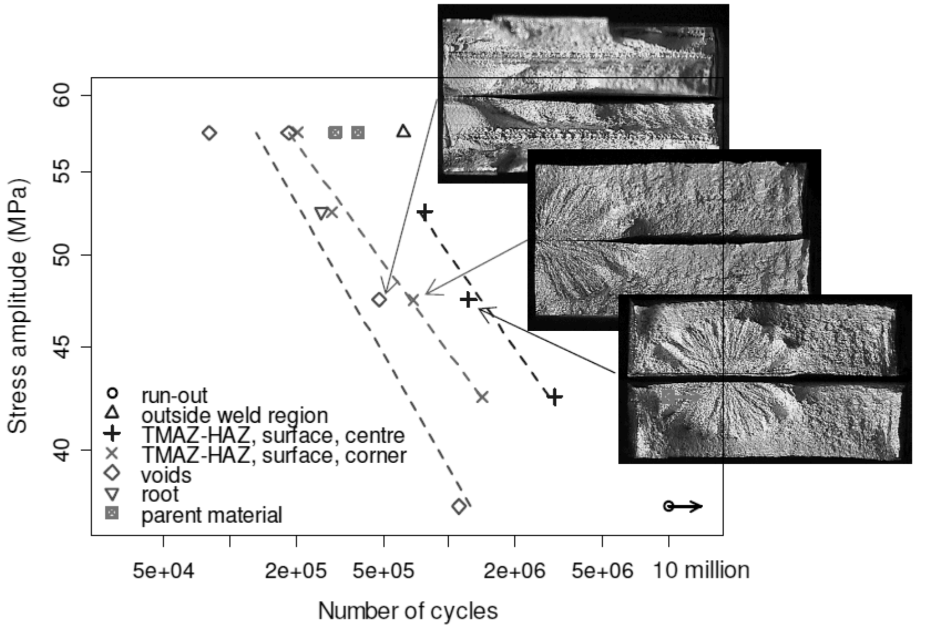

Figure 6: Stress amplitude-fatigue life data for friction stir welds in aluminium alloy AA6061-T6. Power-law lines were fitted to those specimens that had the same type of crack nucleation and growth. Locations of crack nucleation, or other information on the specimens, are given in the legend. Fracture surfaces of three selected specimens are also shown.

comparatively short fatigue crack length.

The dotted lines indicate power-law fits [2] for groups of specimens that failed with the same failure mode. Quantitative comparisons of fatigue strengths between these groups of specimens should be drawn with respect to the power-law lines, not between single data points. The two shifts between neighbouring power-law lines in Figure 6 correspond to approximately 10% change in fatigue strength for each shift.

As shown in Figure 7, fatigue test specimens that failed due to the presence of voids can easily be identified by their fracture surfaces. The main difference as compared to tensile test specimens with voids is that the fatigue test specimens also exhibit a region of fatigue crack growth. This region can be distinguished from the region of the unstable final

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[2] $\ln(N) = a + b \ln(\Delta\sigma)$, where N is the number of cycles to failure, $\Delta\sigma$ is the stress amplitude, and a and b are constants.

fracture by its higher flatness. Figure 7 also shows how the area of the fatigue fracture surface decreases when the stress amplitude is increased.
In the void-free specimens, fatigue cracks nucleated at one of the edges of the weld track, as shown for one example in Figure 8. These edges are not smooth such that some locations along the edge are especially prone to the nucleation of a fatigue crack. If the crack nucleates close to a corner of the specimen cross section, the fatigue life is shorter than if the fatigue crack fracture surface does not include such a corner, compare Figure 6. During cyclic loading of the specimen, cyclic plastic deformation occurs. The cyclic deformation is expected to be larger close to a corner of the cross section, due to the presence of two free surfaces. The time for crack nucleation should therefore be shorter if a suitable location for crack nucleation at the edge of the weld track exists close to a corner of the specimen cross section. It is the time for crack nucleation that is expected to dominate the total fatigue life

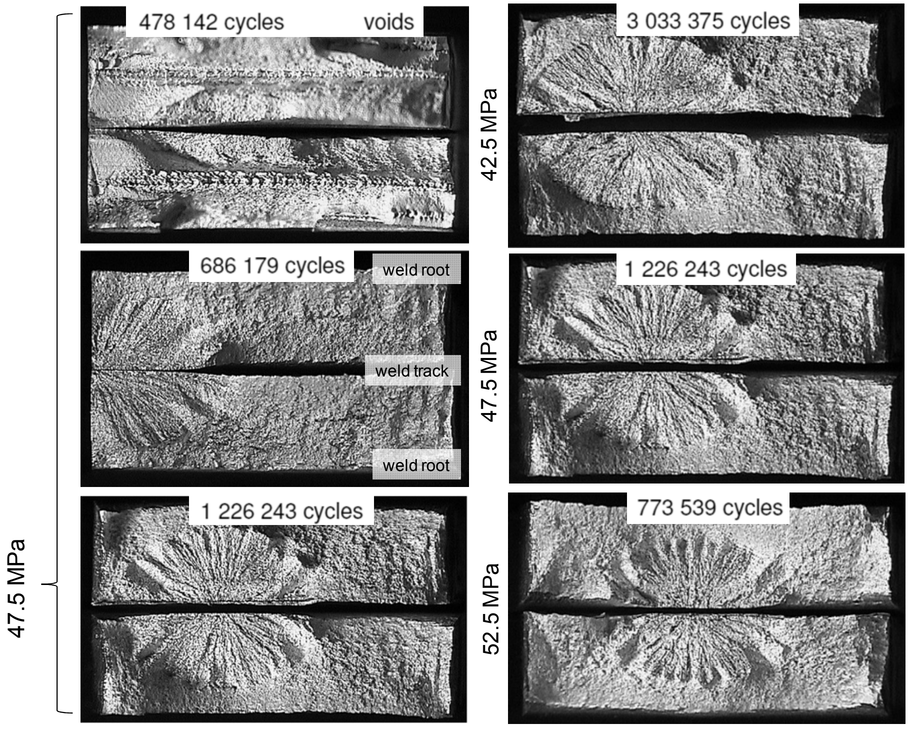

Figure 7: Fracture surfaces of fatigue test specimens with friction stir welds in aluminium alloy AA6061-T6. The images on the left depict different types of fracture that occurred in specimens tested at the same stress amplitude. The images on the right demonstrate that the area of the fatigue fracture surface decreases as the stress amplitude increases.

of the specimens in this fatigue test, as it is common for high-cycle fatigue testing in general.
Parent material specimens were taken out parallel to the profile extrusion direction. All fatigue cracks started close to a corner of the cross section. The parent material specimens tested at 57.5 MPa stress amplitude had lifetimes within the same range as those with good FS welds. The parent material specimen tested at 42.5 MPa stress amplitude had a much longer lifetime (exceeding, in fact, 30 million cycles) than the specimens with FS welds. It is expected that the presence of a weld reduces lifetimes especially at the lower stress levels where the time for crack nucleation dominates the total fatigue life and even small stress raisers may significantly reduce the fatigue life. All fatigue cracks in parent material started in the recrystallized surface layer.

4 Conclusion

Small voids in friction stir welds in AA6061-T6 reduce the tensile strength by approximately 10% as compared to void-free welds. The fatigue strength is reduced by approximately 20% as compared to void-free specimens where the fatigue crack does not include a corner of the specimen cross section. Voids reduce both the time to the nucleation of fatigue crack growth and lead to an earlier start of the unstable crack growth of the final overload fracture.
Fatigue lifetimes of void-free specimens with cracks that initiated close to a corner of the cross-section of friction stir welds in AA6061-T6 were shorter than fatigue lives of void-free specimens where the fatigue cracks did not include a corner.

Acknowledgement
Financial support from the Sapa R&D programme on fabrication and joining technologies as well as stimulating discussions with Peter Benson and Henrik Nyström are gratefully acknowledged. I would also like to thank Wojciech Osikowicz for support with fundamental and practical issues of friction stir welding, and Ove Karlsson, Conny Widlund, and Stefan Nilsson for laboratory work.

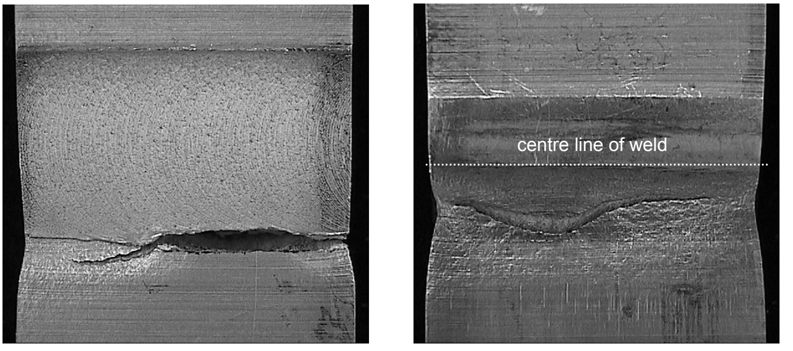

Figure 8: Top and bottom view of the crack of a specimen cycled at a stress amplitude of 47.5 MPa for 1 226 243 cycles until fracture occurred. The crack nucleated at the edge of the weld track on the advancing side of the friction stir weld.

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