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FATIGUE DESIGN OF FRICTION STIR WELDED JOINTS IN ALUMINIUM BRIDGE DECKS

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Abstract: When it comes to vehicular bridges rehabilitation or replacement, designers hardly think of aluminium as a potential structural material. Still, lightweight, corrosion resistance and lower maintenance costs are some assets that aluminium offers compared to steel or concrete. Also, some cases in North America have proven that the retrofit or replacement of an existing bridge deck by one in aluminium is effective, quick and profitable. This factory-built technology is made of extruded aluminium profiles joined by the friction stir welding (FSW) process, a solid-state joining process for different kinds of metals. Even with higher productivity and better-quality joint obtained with FSW compared to fusion welding processes, it is still barely regulated in fatigue and dynamic behaviour design codes for structural applications. In order to overcome the current situation, the main goal of this project is to develop improved, "performance-based" code provisions for the quality control and fatigue design of FSW joints in aluminium bridge decks. This study will contribute to develop fatigue criteria and welding defect tolerances in design codes and regulations for FSW which, hopefully, will be promoting aluminium using in civil engineering. It includes fatigue characterisation of 6061-T651 FSW joints under constant amplitude and simulated in-service loading conditions. So far, ADM Cat. B curve would be a conservative design tool for properly FSW joint, assumed to be submitted to variable amplitude loading. Also, wormhole defect within the joint considerably reduce fatigue life as expected. Furthermore, welding defect will be studied, and tolerances will be established for structural applications.

1 INTRODUCTION

In North America, existing bridges structures require constant investment for maintenance and rehabilitation. In USA for instance, report in Table 1 shows that more and more structures are getting close to or have overpassed their in-service life. Even though there's some improvement in deficiency and obsolescence, there's still a lot of work to do before giving a good grade to the bridge park condition.

Table 1: Bridge park condition in USA (American Society of Civil Engineering 2013, 2017)

Year	Bridge rating in percentage for:		Percentage of bridge with 50 years or older
	Structurally deficient	Functionally obsolete	
2016	9,1%	13,6%	39,0%
2012	11,0%	13,9%	30,0%
2007	12,1%	14,8%	-

An attractive way to upgrade the bridges condition would be to retrofit or to replace existing bridges deck by one in aluminium. Some practical cases have proven that this is an effective, quick and profitable choice. Along with a fast installation, lightweight and good resistance to corrosion are some properties of aluminium, which would increase in-service life as well as respond to the constant growing of traffic. Figure 1 shows steps of this technology, from joining of multiple extrusions using friction stir welding (FSW) to installation.

Figure 1: Aluminium bridge deck a) Extrusions joined by FSW b) Installation c) Final product (Beaulieu and Internoscia 2015)

FSW is being used in multiple applications such as aviation, automotive, aerospace and, more recently, construction. This solid-state joining process is perfectly adapted for aluminium alloys and produces good quality welds, which makes it attractive to use. It has also a higher productivity rate than some manual fusion welding processes because of its automatization and fast travel speed. Some equipment can weld up to 1000 mm/min or over. The nature behind this process is shown in Figure 2 a). A rotating tool penetrates in two pieces. When the tool shoulder is in contact with the working pieces top surface, heat is generated due to friction. Material can then be easily deformed, and tool probe mix the two pieces together. As the tool travels forward, the joint is consolidated. Considering the rotational direction, the weld is asymmetric, so there is an advancing side (AS) and a retreating side (RS).

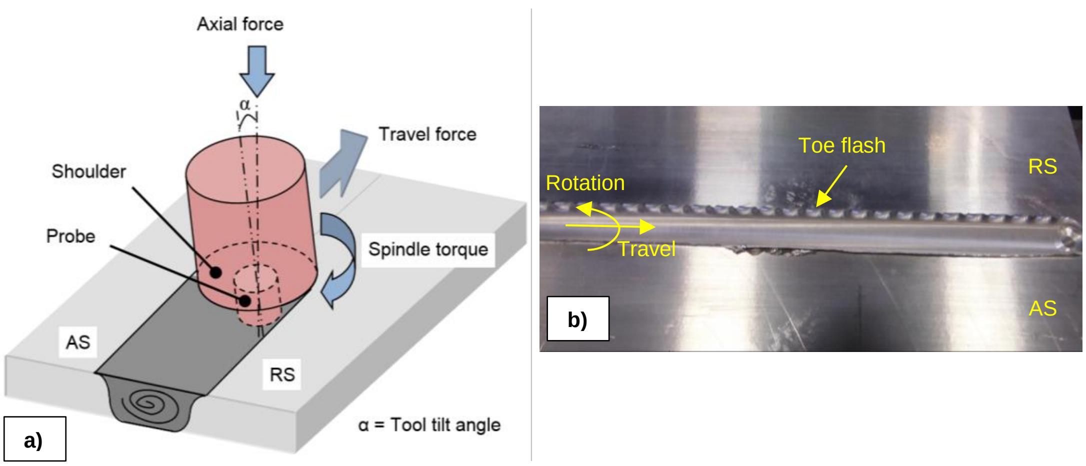

Figure 2: Friction stir welding a) Forging forces b) Typical FSW joint

This process is however not defect proof. Surface and subsurface defect can be part of the joint and can have a negative effect on its fatigue behaviour. Kissing bond due to a lack of penetration and wormhole defects are high stress concentration sites proper to fatigue cracks initiation. In case of a wormhole defect, it even has two sides of fatigue cracks initiation and propagation. Excessive toe flash on Figure 2 b) can also raise the stress concentration on the RS. So far, studies have shown that excessive toe flash and kissing bond under 0,3 µm length have an insignificant impact on fatigue life (Guo et al. 2019, Dickerson and Przydatek 2003, Guo 2018). Exceeding this kissing bond length, failure from crack initiation at the weld root is more likely to happen, which decreases significantly fatigue life. For misalignment defect, few studies have been made on FSW aluminium joints. However, Fowler & al (Fowler, Toumpis, and Galloway 2015) showed, for FSW DH36 steel joints, that misalignment would cause a secondary compressive stress at the bottom of the weld when loaded under direct tension, which increases the fatigue life of the specimen. Ranjan & al (Ranjan et al. 2019) recently found out that a 0,5° angular misalignment defect can result as a ±38 MPa additional stresses. They also pointed out that an additional compressive stress at the weld root increases fatigue life. Since root flaws, particularly kissing bond, are more critical or severe than top surface flaws, assuming a tension at the weld root is a conservative assumption. Guo (Guo et al. 2019) has also observed that a wormhole defect on 5083-H321 has a drastic impact on fatigue life. For instance, for the same stress range, a wormhole fatigue specimen has a fatigue life of 408 156 cycles, while a properly welded joints has a theoretical infinite life (above 5 million cycles). Still, fatigue tests on 6061-T6 FSW joints with a wormhole defect must be done, and fatigue life will certainly decrease in this case.

Some standards and codes, such as ISO 25239 and AWS D1.2, give basic information on quality control and pre-qualification of FSW joints. The Canadian code CAN/CSA W59.2 on welded aluminum construction is trying to adopt similar information. The International Institute of Welding (IIW) (Hobbacher 2016) and the Aluminum Design Manual (ADM) (The Aluminum Association 2015) provide fatigue design curves for aluminium fusion welded joints under multiple configuration. Other codes and standards already exist for fatigue design of steel welded joints. However, fatigue design for aluminium FSW joints in structural welding codes is currently inexistent, so using design curves for fusion welded joints might be a conservative approach considering that FSW has been proven to be a high-quality joining process for aluminium. To provide more adapted design tools, recent work has been made by Guo & al. (Guo et al. 2019). They observed that a properly welded FSW butt joint fatigue life would fall above the ADM Cat. B and FAT62 (m = 7,0) design curves. Also, fatigue life could be estimated using the ADM Cat. D design curve for a lap joint configuration. The main objective of this study is to propose tolerance and severity for wormhole and misalignment defects in AA6061-T651 FSW joints and to provide performance-based criteria for fatigue design in standards for structural application of FSW.

2 EXPERIMENTAL WORKS

Using the CSFM-UQAC gantry equipment on Figure 3, 9,5 mm aluminium flat bar have been welded with a square butt joint configuration. The bars had dimensions of 200 mm width by 480 mm length. A commonly used AA6061-T651 alloy in structural applications has been investigated as base material. It is a medium strength Mg-Si-Cu aluminum alloy with a 310 MPa ultimate tensile strength and a 276 MPa yield tensile strength. Four different joint conditions have been studied, such as a proper weld with optimized parameters (PW), a misalignment defect on advancing side (MAS), a misalignment defect on retreating side (MRS) and a wormhole subsurface defect (WH). An aluminium sheet was placed under one workpiece, either under AS or RS, to create the misalignment, as shown on Figure 3.

Figure 3: FSW setup a) Gantry b) Clamping system c) Aluminium sheet shim under AS d) Aluminium sheet shim under RS details

Welding parameters has been kept constant for PW, MAS and MRS, with a rotational speed of 1120 rpm, a travel speed of 63 mm/min, a tool tilt angle of 2,5° and a depth penetration of 9,0 mm. Some issues have been experienced in multiple attempts to create WH defect. In fact, this defect is complex to recreate when the tool design and the welding parameters are optimised. A lot of test with different approach has been done. Ultimately, to increase the chance of creating a WH defect within the weld, non-optimized parameters were required with a rotational speed of 600 rpm, a travel speed of 120 mm/min and a tool tilt angle of 0,5°. The probe has also been spoiled by grinding off the threads. The tool material is made of H13 steel, quenched and tempered to 46-48 HRC. Its geometry is shown in Table 2. Welds have been performed with a motion control.

Table 2: FSW tool dimensions

Probe	Shoulder
Three flats	Smooth surface
Threaded	Flat
Length = 9,30 mm	Diameter = 15 mm

Fatigue test were performed under tension-only loading condition at University of Waterloo in Ontario. An MTS hydraulic frame with a 100 kN dynamic loading capacity (see Figure 4 a)) at a frequency of 10 and 11 Hz with various stress ranges and a stress ratio of 0,1 was used. For each joint condition, 4 to 6 dog-boned specimens presented on Figure 4 b) were tested under constant amplitude (CA) loading and 4 to 6 of them were tested under variable amplitude (VA) loading. The dog-boned shape was designed by Guo (Guo 2018) using FE analysis in order to always get a higher stress distribution in the reduced section than in the transition region. Scrap material between each fatigue specimen were used for metallurgical analysis. Ultrasonic non-destructive testing (UT) were performed on WH defect welds before machining.

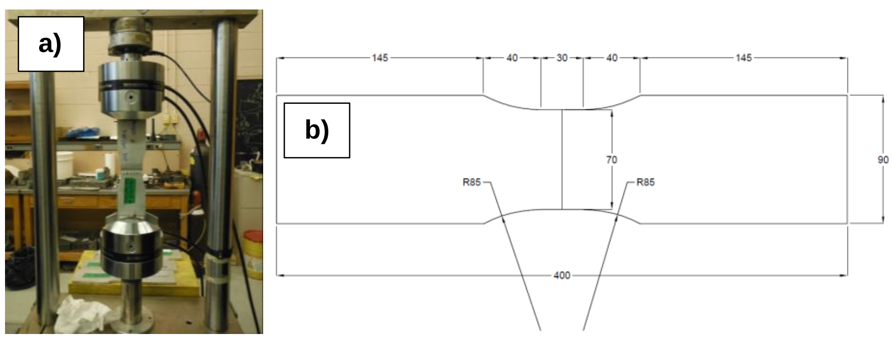

Figure 4: Fatigue test details a) Test frame b) Dog-boned specimen details

3 RESULTS AND DISCUSSION

3.1 Ultrasonic testing to detect wormhole defect

Preliminary metallography on a 100 mm test weld labeled WH03T4 showed that the conditions previously explained in experimental work created a steady WH, as shown in Figure 5 a). To figure if that happened in full length welds, some of them were submitted to UT before machining. In total, 3 welds of 450 mm length (labeled WH04, WH05 and WH06) were fabricated and expected to have a WH defect within the weld nugget. For welds WH04 and WH05, inspection detected a high signal amplitude from the beginning to 300 mm of the travel length. Then, there might be a discontinuity within the weld nugget. For the weld WH06, a high amplitude was observed only on the first 50 mm. There might be no discontinuity thereafter. However, for a given amplitude, one couldn’t estimate the size of the WH defect, nor can one could tell if the defect would be tolerated, since there are no standards in UT for aluminium. Such UT signal tolerance exists in CAN/CSA W59 for welded steel, but not in CAN/CSA W59.2 for welded aluminium.

Subsequent metallographic analysis was made to support those UT results. It was observed that in 2 out of 3 welds, an unsteady WH was introduced at mid-thickness in the AS of the nugget, as shown in Figure 5 b) and c). The WH seems to be bigger at the beginning of the weld, then gradually decreases until it disappears. This could be explained by a stabilisation time in the process until a steady state is reached in terms of workpiece and equipment temperature and material flow. No WH defect was detected on cross-section macrography, but fractured WH06A specimen shows a WH on the left side of the specimen, which is at the beginning of the weld, where UT detected a high signal amplitude. Then, UT inspection results seem to show consistency with reality.

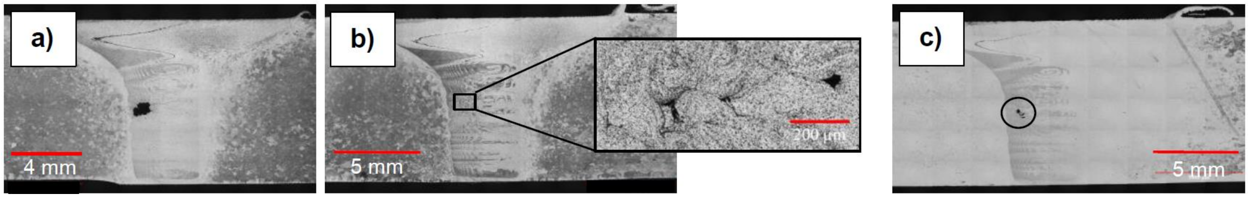

Figure 5: Metallography a) WH03T4 b) WH04 c) WH05

3.2 Fatigue test results

So far results for the constant amplitude fatigue tests are presented in Table *3*. Failure mode is also indicated, where RS stands for retreating side, AS for advancing side, SZ for stirred zone (or nugget), WH for wormhole and BM for base material. For constant amplitude, nominal stress range is simply the difference between the maximal and the minimal stress occurring during the test. For PW joints, lower stress ranges haven't been done yet, but it is expected to reach a runout, which means that the test will be stopped before failure when the fatigue life reaches over at least 2 million of cycle.

Table 3: Fatigue test results

ID	Loading type	Maximal stress (MPa)	Nominal stress range (MPa)	Fatigue life (cycles)	Failure	Notes
Properly welded joints						
PW04C	CA	105,26	94,74	-	-	Runout expected
PWT2A	CA	112,78	101,50	-	-	Runout expected
PWT1A	CA	119,55	107,59	1 712 903	RS	
PW03C	CA	128,36	115,52	1 264 823	RS	
PW04A	CA	132,78	119,50	455 056	RS	
Wormhole defect joints						
WH04C	CA	89,85	80,86	1 260 124	SZ / WH	
WH06C	CA	97,23	87,51	1 968 488	-	Runout
WH06A	CA	104,63	94,17	770 194	BM under AS	Visible WH
WH05A	CA	112,22	101,00	98 290	SZ / WH	

Cracks initiation zone can be observed on Figure 6. In WH defect fracture, initial crack started inside the nugget in the vicinity of the wormhole defect, as expected. Specimen labeled WH05-A has been selected from at the beginning of the weld. UT inspection and macrography showed that a WH was within the weld in this region, and the fractography can confirm that.

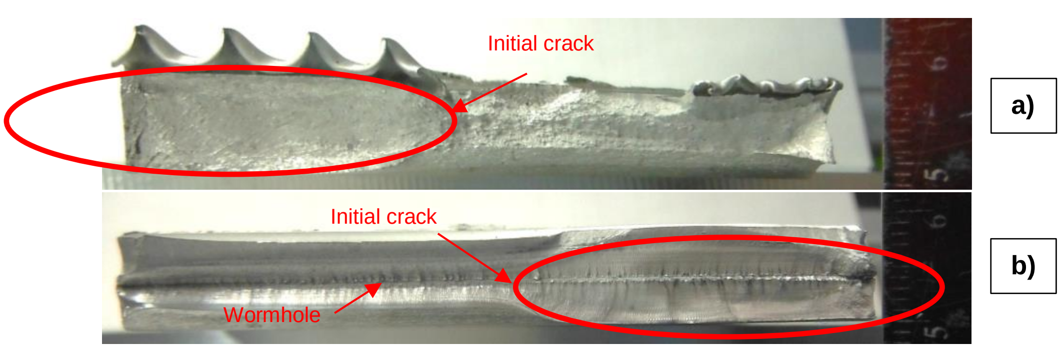

Figure 6: Fracture of a) PWT1-A b) WH05-A

Data extracted from Guo's test (Guo 2018) as well as data from this study shows considerable scatter for PW joints, as seen on Figure 7 a). PW tested specimens in this current study get overly above ADM Cat. B design curve and show no sign of possible kissing bond. Mean and design curve can then be drawn from those results using the statistical analysis method proposed by IIW (Hobbacher 2016) with a survival probability of 95%. When the weld is optimal without any possibility of kissing bond, PW design curve with a -3,23 slope shows that ADM Cat. B is conservative. However, Shi demonstrated that several tested specimens with a kissing bond defect, even in PW joints, fall close or even under ADM Cat. B curve. She then proposed the use of ADM Cat. B and FAT62 (m = 7,0) as design curves for PW joints.

For WH defect type in Figure *7* b), fatigue life is lower than PW joints as expected, and more scatter can be observed. Results achieve ADM Cat. B fatigue life, but when it comes to statistical analysis, a proposed design curve with a -10,11 slope seems to fall under it. Further investigation and test must be performed on this type of defect.

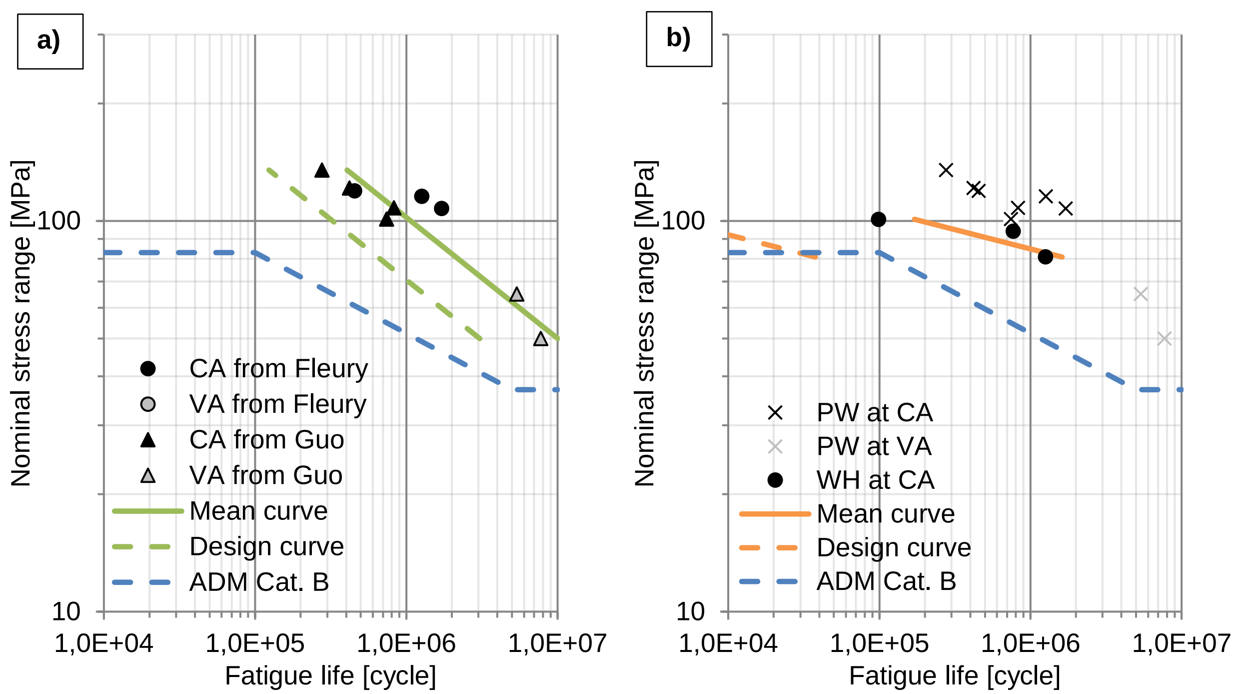

Figure 7: Proposed design curve compared with ADM Cat. B for a) PW (Guo 2018) b) WH

Even though tests on misalignment defect have not been done yet, both on AS and RS, some suppositions can be expected. To provide conservative results, specimen will be placed inside the grips so that the additional tension would be distributed at the weld root. Fatigue life is expected to decrease compared to a PW joint or to a joint with a compressive stress at the root. To evaluate the stress distribution through the thickness of the specimen, strain gages will be placed on top and bottom surface of some specimens.

4 CONCLUSIONS

In this investigation, an attempt has been made to study the effect on fatigue life of possible flaws in friction stir welded aluminium joints. For the 6061-T6 alloy, the following observations can be made:

(i) Properly welded joint achieves in most cases fatigue life of ADM Cat. B and FAT62 (m = 7,0). A design curve with a slope of -3,23 has been proposed, but may be non-conservative if a kissing bond occurs and if variable amplitude loading is applied.

(ii) Wormhole defect within the nugget decrease considerably the fatigue life compared with PW joint. So far, fatigue life from 3 data gets above ADM Cat. B curve, but further test must be performed to propose a proper design curve.

(iii) Ultrasonic inspection is a good way to detect volumetric defect within the weld nugget in FSW, such as wormhole.

In the future, variable amplitude loading will be performed as well as more data from PW, WH joints. Test on misalignment defect type will also be performed along with an evaluation of the stress distribution along the weld cross-section. Further metallurgical and fracture mechanics analysis will also be performed.

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