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Comparison of fatigue life of 2024 and 7475 friction welded joints with kissing bond defects

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Abstract. The paper analyses and compares the static and fatigue properties of 7475 T7351 and 2024 T3 aluminum alloy plate materials with friction stir welded (FSW) joints in order to determine a critical size of the kissing bond (KB) flaw that will not significantly decrease the weld performance. While the static tensile strength of the FSW decreases with KB increase, the yield strain in not influenced by the KB presence. The flaw affects the material structure locally, which leads to a decrease in the fatigue properties. The crack initiation area (KB or out of KB initiation) provides information about significant decrease of fatigue properties of FSW joint. Comparison of both material sensitivity to KB defects lead to conclusion that 7475 material is more sensitive to KB defect in comparison to the 2024 plate material.

Introduction

Friction stir welding (FSW) is a high-performance joining technique used primarily for aluminium alloys. FSW technology contributes to increased joining speed, higher stress tolerance, better reproducibility and longer service life when compared to common riveting methods. FSW is joining method widely used mainly in aerospace and automotive, where fatigue performance is particularly crucial [1]. As the temperature gradients and heat affected zone of FSW welds are lower in comparison with traditional welding techniques, mechanical properties of FSW joints are higher compared with traditional welded joint. However, wider use of FSW among industrial applications is limited due the ability to detect flaws of a relatively small geometry. This problem limits the adoption of FSW for joining for critical components.

The FSW manufacturing process is influenced by many parameters. All parameter controlling in required tolerances is not so easy. For example, an inappropriate rate of heating can result in the formation defects such as lack of penetration, lack of fusion, tunnels, voids, surface grooves, excessive flash, surface galling, nugget collapse and kissing bonds [2]. The paper is focused on a typical weld defect occurring in joints made with FSW - the kissing bond (KB) defect. A kissing bond is a specific type of solid-state bonding defect where two previously separated regions of the material are in contact with little or no metallic bond present. KB flaws can occur in the root of the weld; in this situation, the materials are in close contact but are not chemically or mechanically bonded [3].

KBs can reduce the fatigue performance of joints and they are currently highly difficult to detect using existing non-destructive technique (NDT) methods. In recent years, several investigations have been conducted on the fatigue properties of friction stir welded joints at VZLU. Comparison of KB flaw geometry on reduction of the fatigue life of two typical aluminium materials used in aerospace – 2024 and 7475 is the main aim of this paper. Individual characterisation of 2024 and 7475 FSW joint is discussed in detail in [4,5].

Material and Test methods

Fatigue and static behaviour of two aluminium alloys (AA) – 2024 T3 and 7474 T7351 with or without KB were investigated. Plates with thickness of 6.35 mm were used. Several plates with different KB flaw sizes and a flaw free FSW joint were produced by TWI. Fatigue test and static tension specimens were machined from the same plates.

The test specimens were machined from the plates to the dimensions shown in Fig. 1a. The specimen design for static tension behaviour evaluation described in the AWS standard [6] was adopted. In the tests, values of yield strength, tensile strength, and elongation were evaluated. The specimen design described in the EN 6072 standard [7] was adopted. Test specimens were manufactured according to the drawing in Fig. 1b. Wöhler curve was obtained for each plate with varying KB sizes.

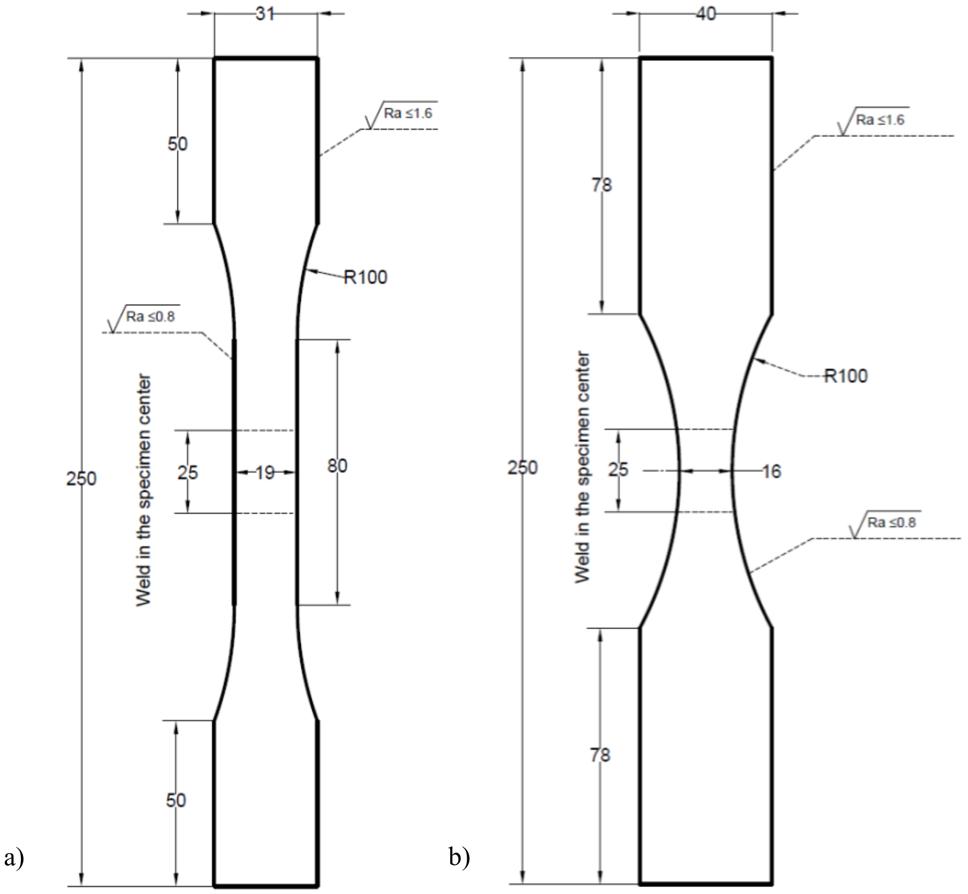


Fig. 1: Actual specimens' geometry based on the a) AWS standard [6] and b) EN standard [7]

Static tensile tests were performed on a mechanical test machine Instron 100 kN (Fig. 2 – left) and fatigue tests were performed on Hydraulic frame IST Hydropuls Sinus 100 kN (Fig. 2 – right). In the fatigue experiments using load control, data were generated using constant amplitude sinus loading with a stress ratio $R = \sigma_{min}/\sigma_{max}$ (max load/peak load) 0.1 and several different maximum stress levels σ_{max}. The test frequency range was between 5 Hz and 15 Hz. A fatigue curve was generated by performing a series of experiments at prescribed maximum stress levels in order to obtain the fatigue lives between 10^4 and 3.10^6 cycles.

Several scraps of each plate were cut in order to evaluate the weld microstructure, grains distribution and internal defects. The samples were prepared using the standard metallographic method. Microstructure of the samples was revealed by electrolytic Barker's etching method with subsequent optical microstructural contrasting in polarized light using Olympus GX51 light optical microscope.

Basic failure modes were identified by a visual examination which can provide a considerable amount of information about the failure process. The microfractographic analyses of the fracture surfaces were carried out using the TESCAN 3SBU Scanning Electron Microscope (SEM).

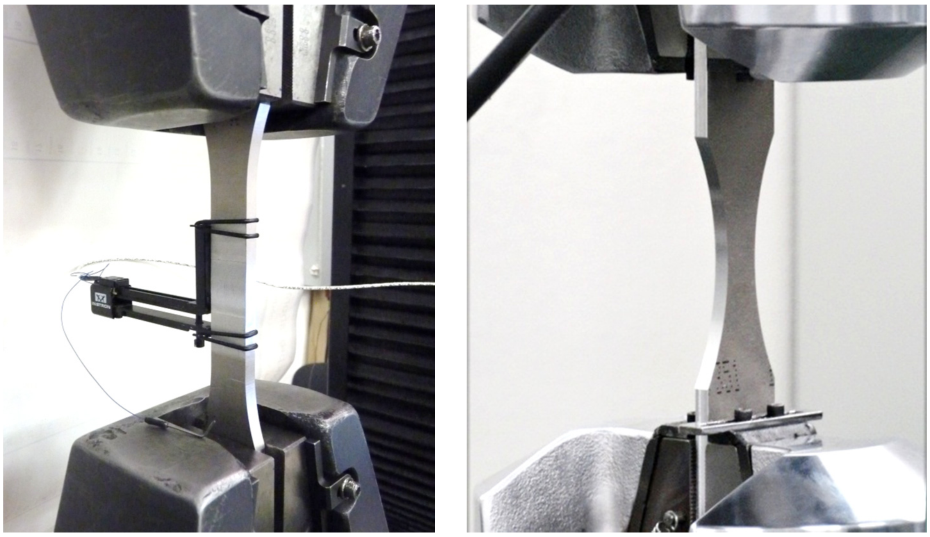


Fig. 2: Static tensile (left) and fatigue (right) test set-up

Static properties

The tensile strength (maximum stress), elongation (maximum achieved strain before fracture) and yield strength (offset stress point at 0.2% of the strain – $R_{p0.2}$) were evaluated for each specimen. Mean values of tensile strength and yield strength and respective sample standard deviations are compared for the both plate materials in the column graphs – Fig. 3 and Fig. 4.

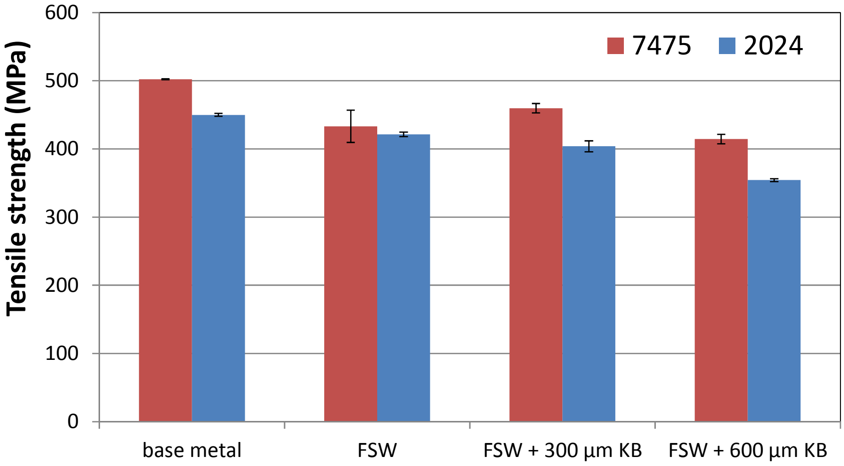


Fig. 3: Tensile static strength comparison of 2024 and 7475 materials

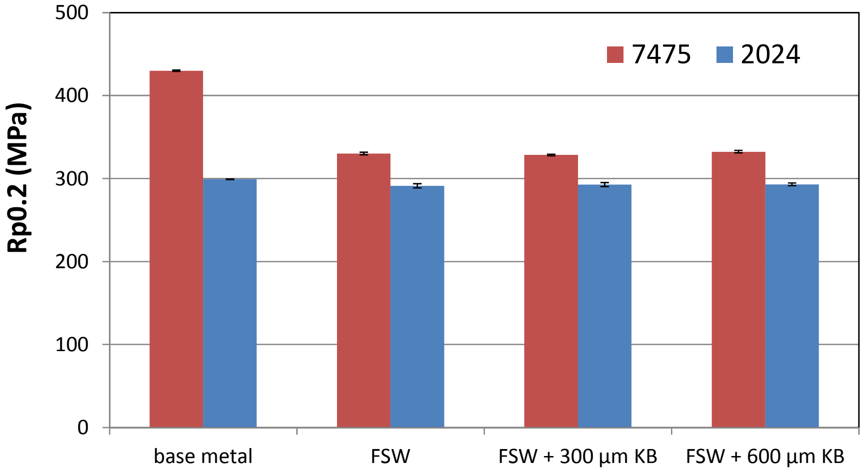


Fig. 4: Yield strength comparison of 2024 and 7475 materials

It can be stated that while the strength of the FSW decreases with KB depth increase, the Yield strain in not influenced by KB presence. Very slight differences of static strengths may be caused due to the fact that different batches of plates were used for the experiment. The batch-to-batch difference shows the sensitivity of properties on the weld performance conditions.

Fatigue properties

The values of fatigue life for individual specimens with selected load levels were obtained. The FSW specimens without and with KB with different sizes were compared. Comparison of evaluated data in a graphical form is shown in Fig.5. The maximal stress values σ_{MAX} presented in the graph are relative to the net cross section in the narrowest part of the specimen.

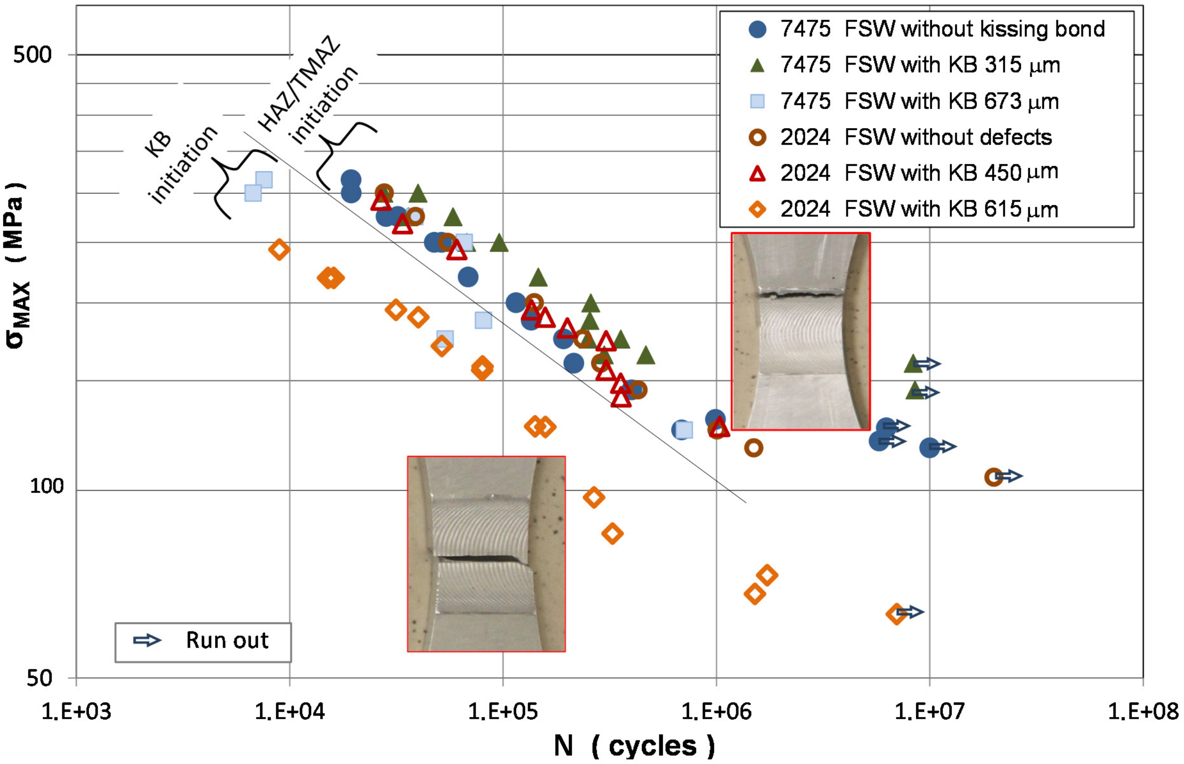


Fig. 5: Fatigue strength comparison of 2024 and 7475 materials

The full and empty circle points in Fig. 5 represent the reference results corresponding to the FSW of 2024 and 7475 material without any flaw, respectively. For all these specimens, the fracture initiation locations were detected in the transition area between the weld zone and parent material or out of weld initiation. Based on the statistical analyses it can be stated no difference between the fatigue behaviour of both materials was found.

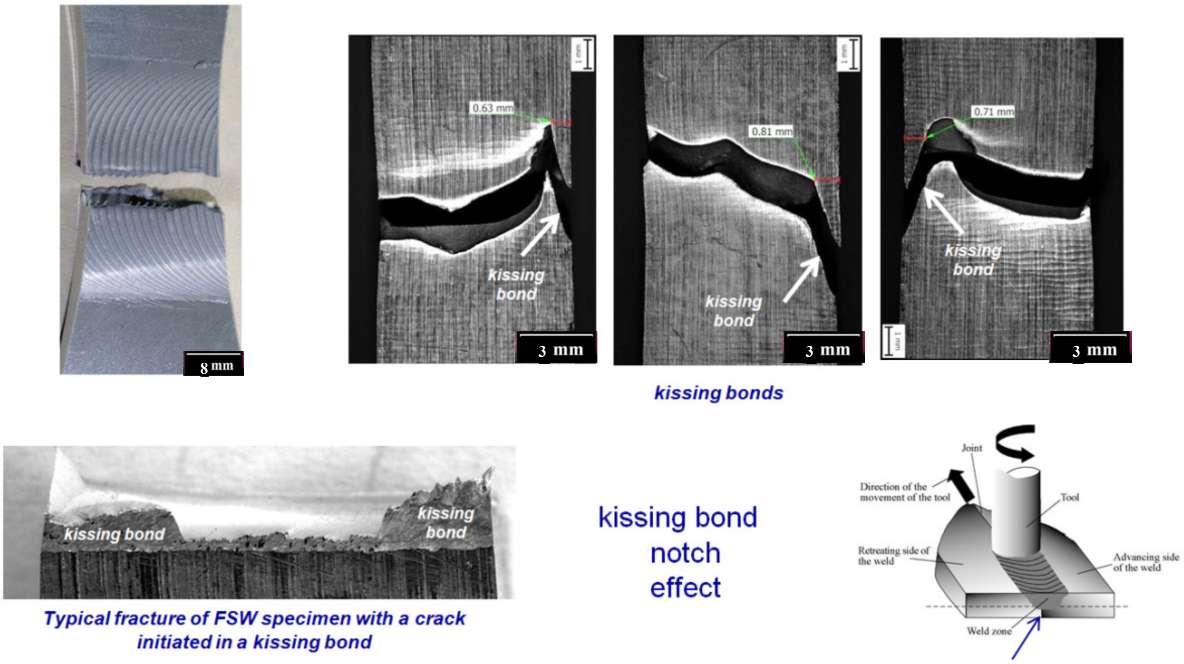
The full and empty triangle points in Fig. 5 represent the FSW with KB flaw of average depth equal to 315 μm for 7475 and average depth equal to 450 μm for 2024 material. Similarly to flaw free welds all the specimens with "small" KB defects (<315 μm resp. <450 μm), no difference between the fatigue behaviour of both materials was found. No decreasing of fatigue properties were detected. By contrast, the fatigue lives of 7475 material with KB flaws of 315 μm were higher both for higher load levels and fatigue limit compared with flaw free FSW specimens. This fact can be caused by the fact that different batches of plates were used for the experiment. The possible reason for this behaviour could be different heat treatment response. All the fracture initiation locations were detected in the transition area between the weld zone and parent material. Based on the statistical analyses it can be stated the fatigue behaviour of specimens with the "small" KB flaws is not affected by presence of the flaw.

The third group of results generated the specimens with "large" size of KB flaws. It represents FSW with the 673 μm KB in case of 7475 material and FSW with the 615 μm KB in case of 2024 material. In case of 7475 material the results with a large data scatter in fatigue lives were obtained. Therefore, fatigue specimens manufactured from the third plate were categorised into the two groups based on the location of initiated fatigue cracks in the specimens. The results with crack initiation in KB are separated in Fig. 5 by the sloping thin black line. The 7475 specimens with cracks initiation in the KB had significantly lower fatigue lives decreased by one order of magnitude in comparison with the 7475 defect-free weld or with specimens with "small" KB flaws. The other group of 7475 "large" KB flaw specimens with initiation in in the transition zone had fatigue lives similar to pure FSW. By contrast the all fatigue cracks of 2024 specimens with "large" KB flaws of 673 μm initiated in KB defect and at the same time the fatigue lives were significantly (by one order of magnitude) shorter in comparison with the defect-free weld or with specimens with "small" KB flaws.

The results and discussion above indicate a higher sensitivity to KB defect of 2024 material as compared with 7475 material.

Metallographic and Fractography analyses

The crack initiation mechanism from the KB flaw notches is very similar for both materials. Fatigue cracks that initiated from a kissing bond are visible in Figure 6. The figure shows a crack initiation from the KB notch which was observed in most samples. The fatigue crack initiation locations were dependent on specimen widths and crack lengths. This was different in every specimen, which have resulted in the large scatter in fatigue lives graph for the large KB series. Fig. 7 shows an example of fatigue crack formation observed by scanning electron microscopy in 2024 FSW joint. A multiple crack initiation was usually observed with typical ratchet marks initiated at the kissing bond. The cracks interconnected into one major crack that propagated by the striation mechanism until a final fracture (typical ductile dimples observed).



kissing bonds

Typical fracture of FSW specimen with a crack initiated in a kissing bond

kissing bond notch effect

Fig. 6: Fatigue cracks initiation from a kissing bond

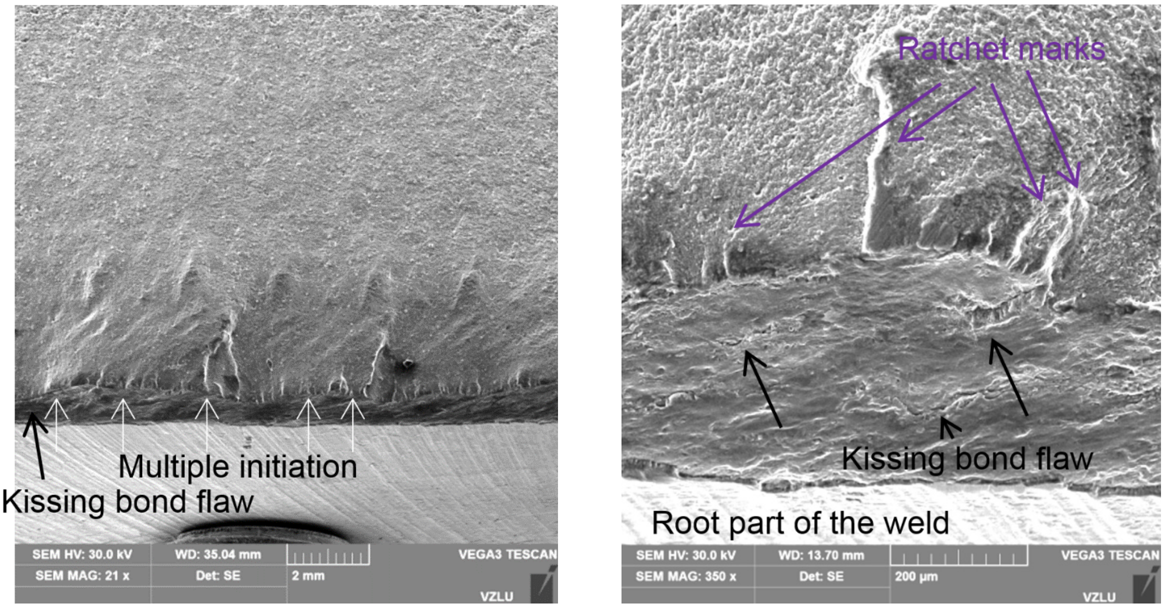


Fig. 7: Fatigue crack initiation from the KB flaw notch observed by electron microscopy: left) multiple crack initiation in KB; right) detail of KB surface.

Conclusions

While the static tensile strength of the FSW decreases with KB increase, the yield strain in not influenced by KB presence. Very slight differences of static strengths may be caused due to the fact that different batches of plates were used for the experiment. The batch-to-batch difference shows the sensitivity of properties on the weld performance conditions.

The experimental program and associated metallography and fractography analyses on a series of FS welded joints of AA 2024 T3 and AA 7475 T7351 materials that included various kissing bond sizes provided the following results:

- The flaw affects the material structure locally, which leads to a decrease in the fatigue properties.

- FSW of 2024 T3 material with 615 µm KB defect caused a significant decrease in the fatigue life and initiation from the KB was observed in all cases. Certain of the FSW specimens with 450 µm KB in depth failed out of the KB, in the HAZ/TMAZ area, and the fatigue behaviour was comparable with flaw-free FSW specimens. This finding means that the criterion and simultaneously the minimum detectable size for AA2024 T3 alloy must be below 400 µm.
- FSW of 7475 T7351 with 315 µm KB defect was demonstrated to be insignificant with respect to the fatigue life.
- Comparison of both material sensitivity to KB defects lead to conclusion that 2024 material is more sensitive to KB defect in contrast to the 7475 plate material.

Acknowledgement

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