Effect of defects on fatigue lifetime of friction stir welded Al-Cu-Li alloy

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Industrial context

- Alloy studied: Al-Cu-Li (2198-T8), 3.1 mm

<table>
<thead>
<tr>
<th>Cu</th>
<th>Li</th>
<th>Mg</th>
<th>Ag</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.20</td>
<td>0.98</td>
<td>0.31</td>
<td>0.31</td>
<td>0.04</td>
</tr>
</tbody>
</table>

(%) weight

Lithium allows:
- to increase Young modulus
- to decrease density

This alloy is aimed for parts under tension ($10^5$ cycles)
Industrial context

MASAE Project

**Aim:** to certify the friction stir welds (FSW) for aerospace parts

**Financial support:** FRAE

**Partners:** ONERA, CEA-LIST, EADS

Advantages of FSW process:
- solid state process
- allows to weld age hardening alloys
- produces low residual stresses
- produces few defects (no porosities, cracks)

FSW could be the best welding process to replace riveting for aerospace industry

Fatigue resistance needs to be checked
Outline

- Microstructural defect characterization
- Tensile behaviour/plasticity
- Fatigue behaviour of welds
  - S-N curves
  - Fractography
  - Fracture mechanics
- Final fracture
- Conclusions and Outlook
Controlled weld defect generation

Sound welds

Join Line Remnant

Kissing Bond

GAP 0.3 mm

GAP 0.7 mm

Specimens cut and tested along the T direction

Left at room temperature after welding

Welds produced by ONERA

(A. Denquin, C. Rouaud)
Welds characterization

- Microstructural characterization

**Retreating Side**
- HAZ
- TMAZ
- WN

**Advancing Side**
- HAZ
- TMAZ

**Weld Nugget (WN)**
- Equiaxed recrystallised grains

**TMAZ** (Thermo-Mechanically Affected Zone)
- Highly deformed grains

![Graph showing hardness variation](image-url)
Welds containing a Kissing Bond (KB)

- Contains a joint line remnant
- Contains a Kissing Bond (KB)
- KB opened in bending

EBSD observations show that the KB is an intergranular feature
GAP-welds

- Produced with and initial gap between sheets of:
  - 0,3 mm (GAP-0.3)
  - 10% of the sheet thickness
  - Aimed tolerance for welding
- 0,7 mm (GAP-0.7)

TEM reveals oxide particles on grain boundaries
Tensile testing

- Optical marker tracking technique
- \( L_0 = 14 \text{ mm} \)
- -40% in yield strength
- -20% in UTS
- No significant effect of JLR
- No significant effect of KB
- Weak effect for GAP defect
- DIC: Strain localisation in the TMAZ on the retreating side (except for GAP-0,7)
Simulation of the different weld zone behavior

- 6 zones with different plastic behavior

Identification of 6 different stress-strain curves

- Via displacement field analysis obtained by digital image correlation
- Macroscopic stress (iso-stress hypothesis)
- Nominal stress and strain (parallel to the loading direction)
Simulation of the different weld zone behavior

- 3D mesh

Hardening law (Voce)

\[ R_p = R_0 + Q\left(1 - e^{-bp}\right) \]

- Isotropic
- Non-linear
- von Mises

- Good agreement up to 10% strain

- The weld nugget is in uniaxial tension

*Inspired by Nielsen et al 2010*
Simulation of the different weld zone behavior

- Strain distribution along the weld

- Good agreement up to 360 MPa

- Overprediction of strain localisation in TMAZ
Tensile testing: crack location

Sound welds + Welds bearing
JLR+ GAP 0.3

Welds bearing KB+
GAP 0.7

Fracture occurs on the TMAZ in the Retreating Side

Fracture occurs in the Weld Nugget from
- the Kissing Bond
- Grains for GAP 0.7
KB crack initiation

- Critical stress for KB opening?
  - In-situ SEM observation of KB on the lower surface

Opening of KB from $\sigma=280$ MPa
KB-tensile opening studied by US and tomography

- ~30 mm wide Material ‘stip’ KB loaded to 380 MPa

**Ultrasound non destructive testing by CEA List**

**Tomographie (ESRF ID19, 0.7 µm voxel size)**

- The KB is not opened over the entire length
- Consistent with in situ SEM test
- The opened KB can be detected by US
Fatigue behaviour of welds

Aim: to obtain the S-N curves of the different materials and to understand the initiation mechanisms of fatigue cracks

- Testing conditions:
  - Stress ratio R=0.1
  - Frequency 20 Hz

Milling → Edges ground off → Grinding of surfaces → Measures of roughness (0.15 < Ra < 0.25)

Cross-weld specimen geometry

Base material geometry
First 20 fatigue cycles

- Plasticity of welds measured by optical marker technique

The entire joint deforms plastically during 1st cycle for loads corresponding to the aimed lifetime

Redistribution of residual stresses (not assessed in this study)
Fatigue behaviour of welds

- S-N curves of base material

- The fatigue behaviour of the base material along both L and T directions is similar
Fatigue behaviour of welds

- S-N curve of sound welds

- Reduction of 10% on the fatigue strength at $10^5$ cycles for sound welds compared to the base material (T)

- At $10^5$ cycles the fatigue strength is higher than the yield strength of welds
Fatigue behaviour of welds

- S-N curve of welds bearing JLR

![Graph showing S-N curve with data points for base material (L), base material (T), welds with JLR, and sound welds.]

- Reduction of 15% on the fatigue strength at $10^5$ cycles for sound welds compared to the base material (T)

*Le Jolu et al., Science and Technology of Welding and Joining, 2010*
KB-weld with surface grinding

- Reduction of 18% in stress at $10^5$ cycles
- Significant effect of KB on fatigue lifetime
- Crack starts from KB for $\sigma > 280$ MPa (consistent with SEM in situ tensile test)

- KB reduces fatigue crack initiation cycles
- The KB is supposed to be opened from the first cycle onwards $\sigma > 280$MPa
KB-weld with surface grinding

- $\Delta \sigma = 306$ MPa
- $N_R = 13\,000$ cycles

In the case of crack initiation on KB: ductile KB opening fracture surface
KB-weld without surface grinding

- Reduction of 8% of stress at $10^5$ compared to sound welds
- Smaller effect of KB welds without surface treatment

- No stress effect on initiation location
- Initiation on rough features on the as-weld surface
- Effect of KB inclination

![Graph showing stress and cycles to rupture](image-url)
KB-weld without surface grinding

- $\Delta \sigma = 279$ MPa
- $N_R = 70,000$ cycles

- Little KB opening during first cycle
- The fatigue crack ‘leaves’ the KB after a few $\mu$m.
• Reduction of 26% in stress at $10^5$ cycles
• For GAP-0.3 welds: critical stress for initiation on defect $\Delta \sigma = 240$ MPa
• Significant reduction for fatigue crack initiation also for initiation outside the nugget
GAP-welds

- GAP-0.3
- $\Delta \sigma = 256$ MPa
- $N_R = 26\,500$ cycles

Intergranular crack formation during first load cycle
Fatigue crack starts from the intergranular crack
Similar fracture surface for GAP-0.3 et GAP-0.7 welds
Fracture mechanics: KB-welds

- The KB may act as crack after the 1st load cycle
  - Calculation of the stress intensity factor after the first load cycles for the case of an opened Kissing Bond ($\Delta\sigma=240$ MPa)

\[ K_I = \sigma \times \sqrt{\pi \times a \times F_1(\alpha)} \]

\[ F_1(\alpha) = 1,12 - 0,231 \times \alpha + 10,55 \times \alpha^2 - 21,72 \times \alpha^3 + 30,39 \times \alpha^4 \]

* Tada et coll., 1973

\[ \Delta K_{280} = 3,5 \text{MPa}\sqrt{m} \]

\[ \alpha = a/W \]

Also possible:

\[ K_I^* = K_I \times \cos^3\left(\frac{\theta}{2}\right) \]

\[ \begin{align*}
    a &= 50 \mu\text{m} \\
    W &= 3 \text{ mm}
\end{align*} \]
Fracture mechanics: KB-welds

- Calculation of K for stopped fatigue tests

Based on 2 stopped test we can calculate:

- $\Delta K$ after (ductile) opening of the KB at test start ($\Delta K_1$)
- $\Delta K$ at the stop of the test ($\Delta K_2$)
- The mean crack propagation speed

<table>
<thead>
<tr>
<th></th>
<th>20% de la durée de vie (7 000 cycles)</th>
<th>40% de la durée de vie (15 000 cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta K_1$ (MPa $\sqrt{m}$)</td>
<td>4,3</td>
<td>4,3</td>
</tr>
<tr>
<td>$\Delta K_2$ (MPa $\sqrt{m}$)</td>
<td>5,2 – 5,8</td>
<td>5,5 – 6,1</td>
</tr>
<tr>
<td>$\frac{da}{dN}$ moyenne ($10^{-9}$ m/cycle)</td>
<td>4,3 – 7,1</td>
<td>2,6 – 4,0</td>
</tr>
</tbody>
</table>

Results consistent with results obtained by others 2198-T8 (long cracks)
Fracture mechanics: KB-welds

- Propagation threshold?

For every fatigue test:
  - Measurement of the KB opening depth
  - Associated $\Delta K_{\text{initial}}$ is calculated

- $\Delta K_{\text{threshold}} \approx 1 \text{ MPa}\sqrt{\text{m}}$

- $\Delta K_{\text{threshold}}$ close to or smaller than for long cracks determined by others

- Behaviour of (physically) short cracks?
Final fracture

- **Aim**: Assess the tearing resistance of the different welds
  - (these may impact the Wöhler curves)

- **Approach**
  - Kahn tearing tests for different defects
  - Calculation of the unit initiation energy (UIE)
  - Notch in weld centre parallel to weld (representativity?)

![Diagram of force vs. displacement with UIE highlighted]
Final fracture

- The evolution of UIE is similar to lifetime
- JLR seen on fracture surface
- Defects affect resistance

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<tr>
<th>MB-TL</th>
<th>Sound welds</th>
<th>KB</th>
</tr>
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<tbody>
<tr>
<td>166-171</td>
<td>138</td>
<td>87-92</td>
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</table>

UIE (MPa.m)
Summary and discussion

- Reduction of fatigue crack initiation when initiation on defect
- For $\Delta\sigma<250\text{MPa}$: residual stresses may play a major role
- The defect generation is accompanied by a change of the entire weld:
  - The entire weld process needs to be considered!
General conclusions

- The **tensile properties** are hardly affected by the weld defects.
- The **JLR** is an acceptable defect.
- The **surface treated KB** is detrimental for fatigue if loaded above a critical stress (reduces the crack initiation cycles).
- The **non-surface treated KB** is less detrimental.
- The GAP 0.3 mm defect can neither be detected by weld control parameter nor by tensile testing but leads to a substantial reduction in fatigue lifetime (intergranular crack during first load cycle).
- The influence of the weld defects cannot be decorrelated due to the impact of the process change on the entire weld.
Thank you for your attention

Jolu, T. Le1; Morgeneyer, T. F.2; Gourgues-Lorenzon, A. F.
Effect of joint line remnant on fatigue lifetime of friction stir welded Al–Cu–Li alloy
Science and Technology of Welding and Joining, Volume 15, Number 8, 2010
2198 T8 5mm

Cavaliere et al 2009
(b) Residual stress perpendicular to weld direction in 3 sizes of ESET samples
Fig. 6 Residual stress profiles in ESE(T) samples

Ma et al. 2011
2024 T351

Fratini et al. 2009
Fracture surface

$\Delta \sigma = 306 \text{ MPa} \sim (\sim 13\,000 \text{ cycles})$
Opening of KB during the first half cycle

→ The fatigue crack propagation occurs from the second cycle?
Stopped fatigue tests

- Tested during 40% of the fatigue lifetime (15,000 cycles)
- $\Delta\sigma = 279 \text{ MPa}$

- Tested during 20% of the fatigue lifetime (7,000 cycles)
- $\Delta\sigma = 279 \text{ MPa}$

A fatigue crack propagated from the crack due to the KB on 40-55 $\mu$m

The KB seems to be opened during the first half cycle and then a fatigue crack propagate from the second cycle
Fracture surface of welds bearing KB

Fracture due to KB

Fracture surface due to JLR

Initiation triangular zone

Recuction of toughness responsible for lower S-N curves?
Conclusions

- Effect of Kissing bond on mechanical behaviour of welds:
  - Small effect on tensile properties but KB is responsible for fracture
  - 18% on the stress level \((10^5 \text{ cycles})\) compared to sound welds (KB ground)
  - 8% on the stress level \((10^5 \text{ cycles})\) compared to sound welds (KB with no grinding)
  - KB leads to a fatigue crack propagation from the second cycle
  - Toughness of welds bearing KB is lower than sound welds (because of JLR and KB)