Ultrasonic evaluation of friction stir welds and dissimilar intermixing using synthetic aperture focusing technique

Lévesque, D.; Toubal, L.; Cao, X.; Dubourg, L.

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Friction stir welding (FSW) is a recently developed solid-state joining process that uses a specially shaped rotating tool to produce lap or butt joints. At the National Research Council, an inter-institute collaboration was started in 2007 with the goal of exploiting the NDE expertise and applying it for the characterization of friction stir welds for various industrial applications. In particular, very good performance was obtained using ultrasonic immersion or laser-ultrasonics combined with the synthetic aperture focusing technique (SAFT) for detecting lack of penetration in butt joints, discontinuities such as wormholes and hooking in lap joints. Dissimilar metal welds of aluminum and magnesium by FSW are also considered for automotive and aerospace applications. Complex vortex flows are produced during the FSW process that may create intercalated lamellar structures with the possible formation of intermetallic compounds, causing variable hardness and degradation in mechanical properties. A modified version of SAFT that takes into account the difference of ultrasonic velocity in the joint between that of Al and Mg has been developed to study the dissimilar intermixing. Welded samples in the butt configuration with different welding speeds and seam offsets are tested using the immersion technique with the modified SAFT. Results will be presented for both defect detection and weld characterization, and the capabilities and limitations will be discussed.

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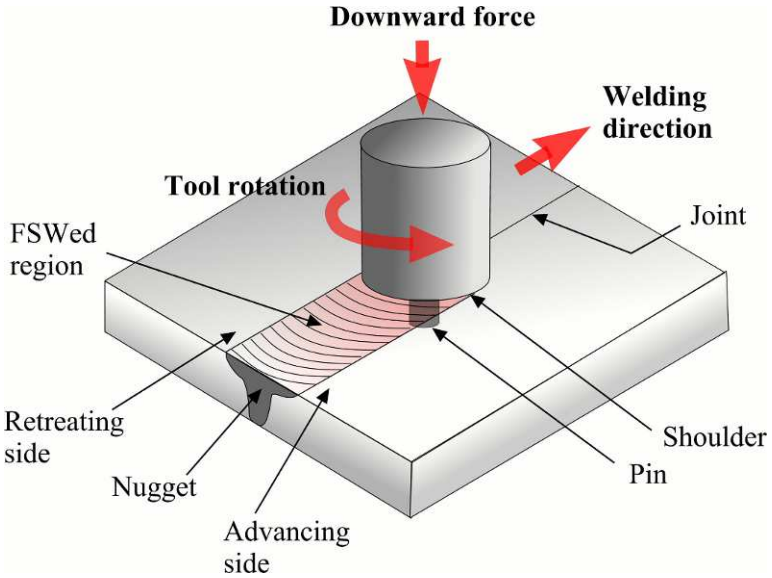
National Research Council Canada

Agenda

- Friction stir welding (FSW)
- SAFT imaging
  - principles
  - improvements
- Results
  - Lap joints, butt joints
  - Dissimilar metal welds
- Comparison with destructive methods

Friction stir welding

- Manufacturing of aircraft panels
- Rivet replacement: saving of weight, productivity and aerodynamics
- Some challenges: hooking, lack of penetration, wormholes, kissing bond

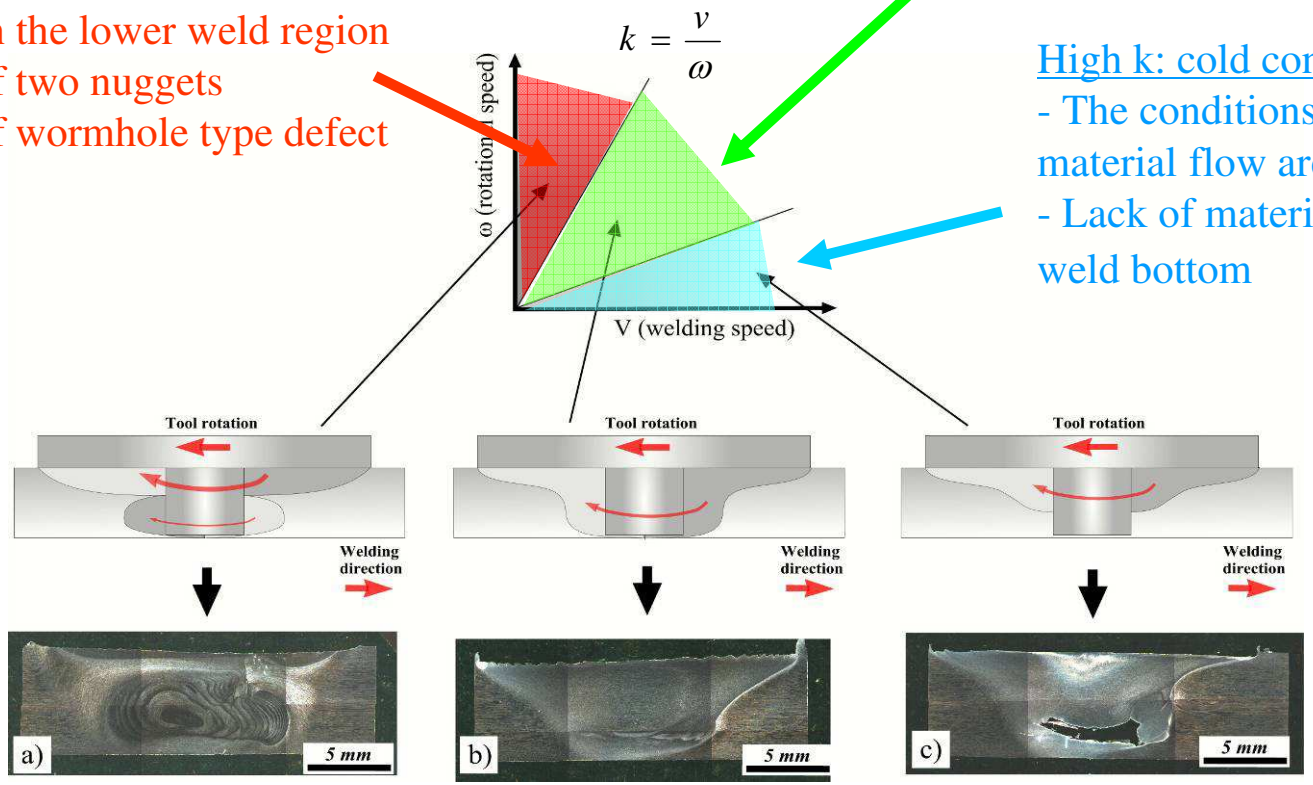


Material flow

Low k: hot condition (overstirring)
- High heat generation and stirring under the shoulder
- The material rotates more under the shoulder than in the lower weld region
- Appearance of two nuggets
- Appearance of wormhole type defect

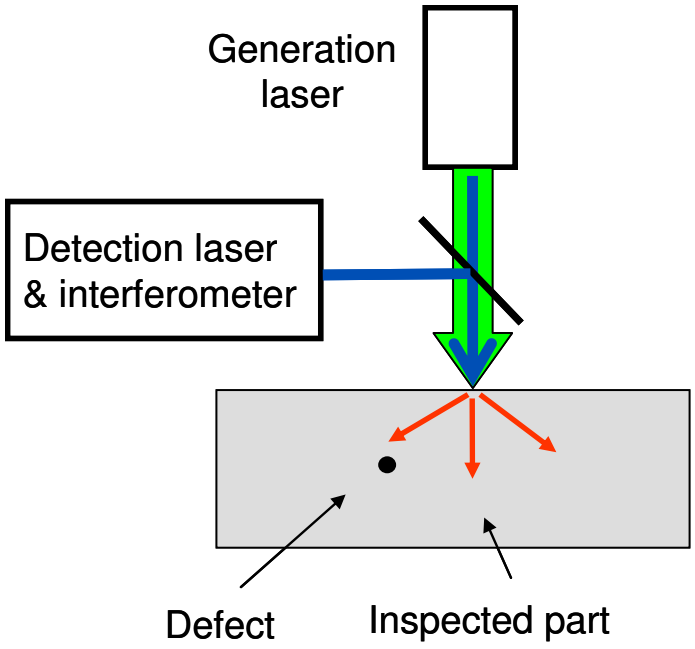
Intermediate k: stable condition
- The flow of the boundary layer is stable
- Sound and defect-free weld

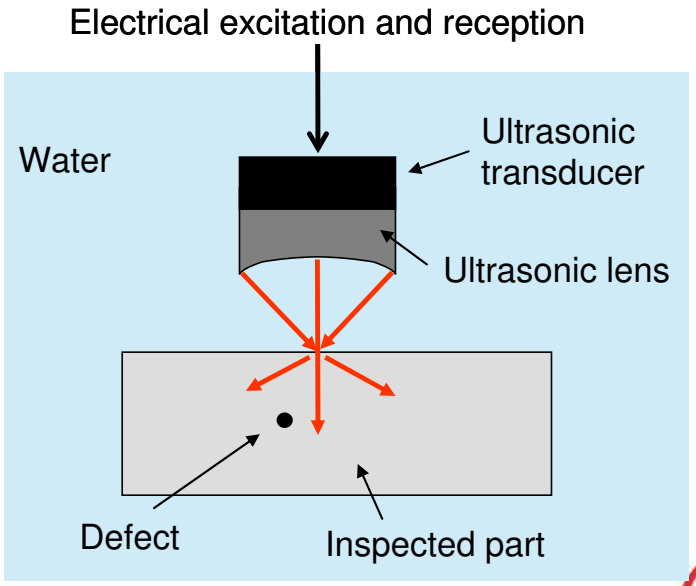
High k: cold condition
- The conditions for stable material flow are not reached
- Lack of material feeding in the weld bottom



Synthetic aperture focusing technique (SAFT)

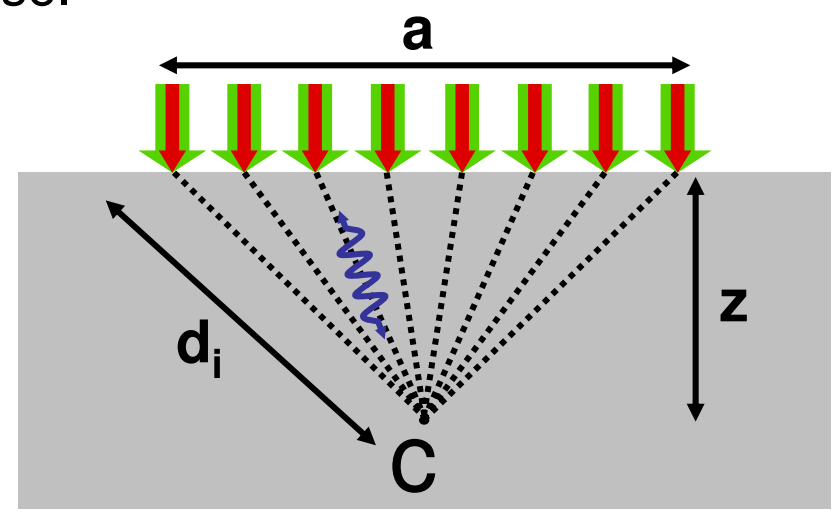
- Source of ultrasound and detection zone overlap at the surface of the part
- Laser-ultrasonics or conventional piezoelectric transducer focused on the surface
- Mechanical scanning along two axis (can also use a transducer array for one or two-axis scan)
- Numerical acquisition of all the A-scans





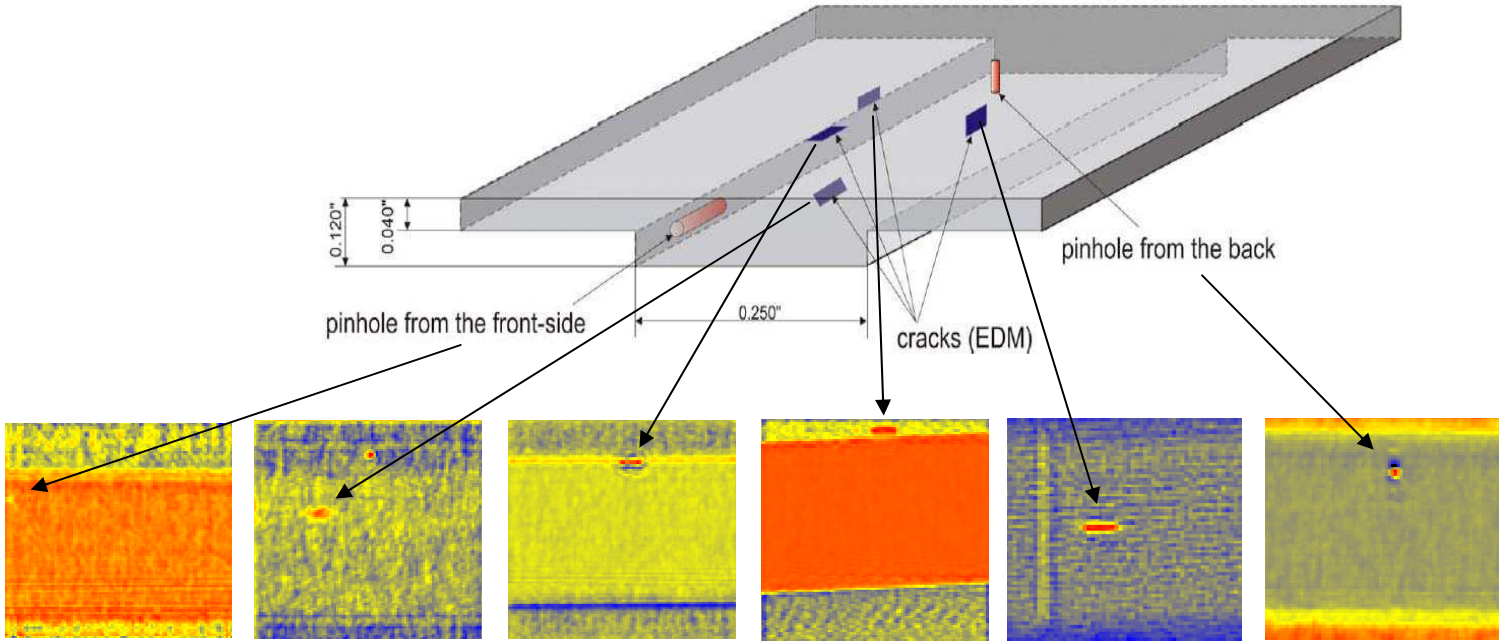
Time domain SAFT

- For any point C in the volume:
  1- Locate the amplitude of each signal at time $2d_i/v$
  2- Sum the contributions in the aperture a
- Large amplitude obtained if a flaw is located at C; otherwise, a reduction of noise.



- In practice, computation in the Fourier domain: F-SAFT

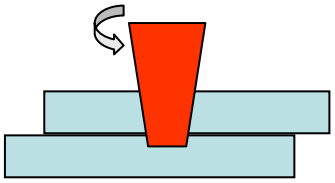
Sample with artificial defects

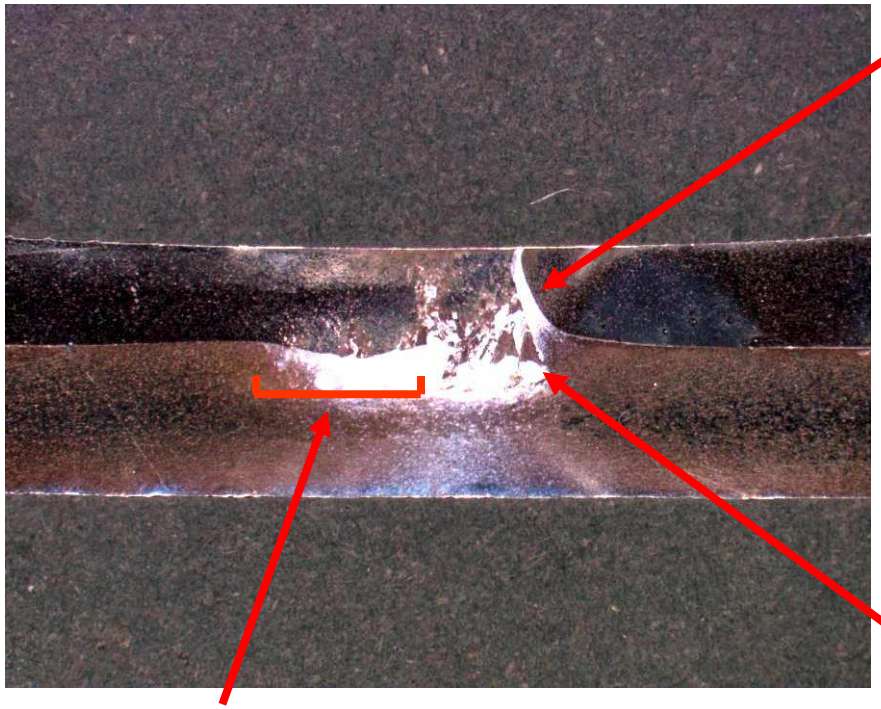


Thickness: 3 mm
Pin holes: 0.5 mm dia; EDM slots: 0.175 mm width

FSW lap joint

- Al sample, 4 mm thick

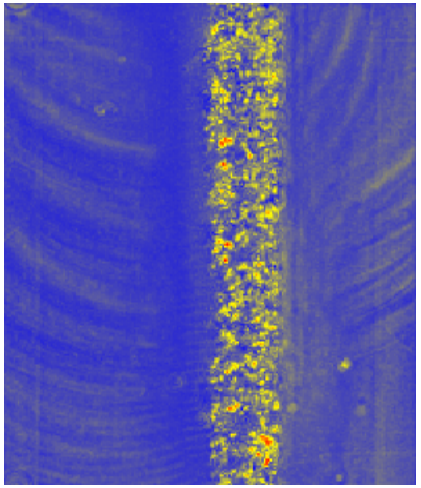




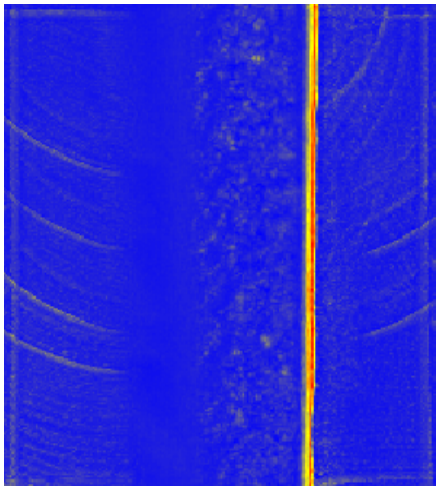
RS: retreating side
AS: advancing side

SAFT results: tool side

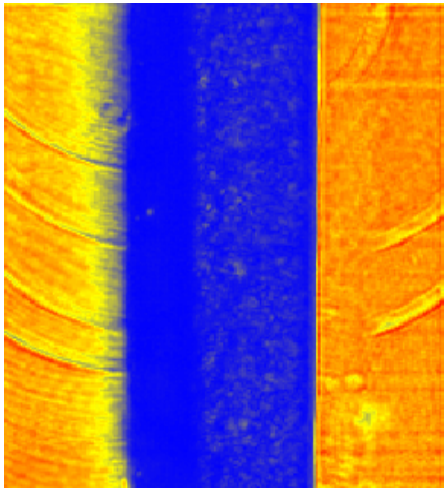
C-scan 0.8 mm *above* interface



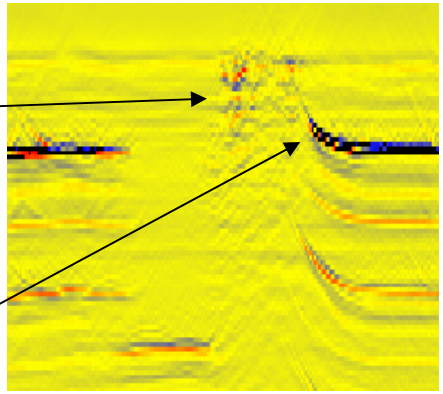
C-scan 0.25 mm *above* interface



C-scan (slice) at interface



B-scan across the weld



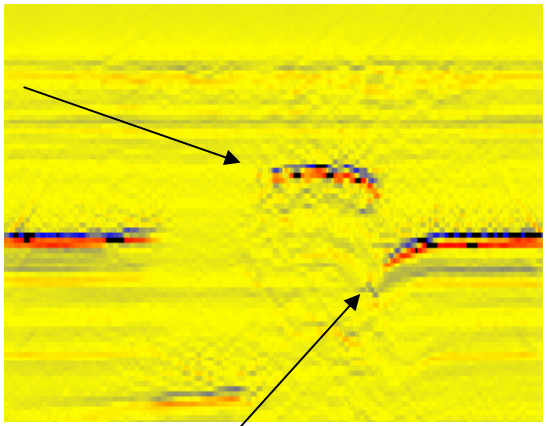
SAFT results: opposite side

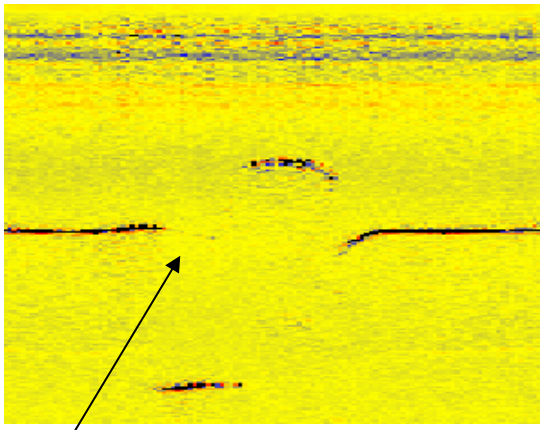
Immersion
Frequency up to 50 MHz

Laser-ultrasonics
Frequency up to 220 MHz

wormhole

B-scan across the weld



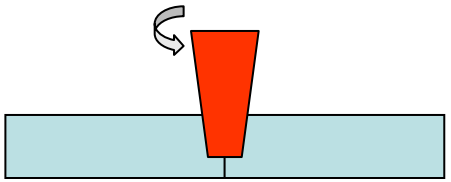


hooking

kissing bond

FSW butt joint

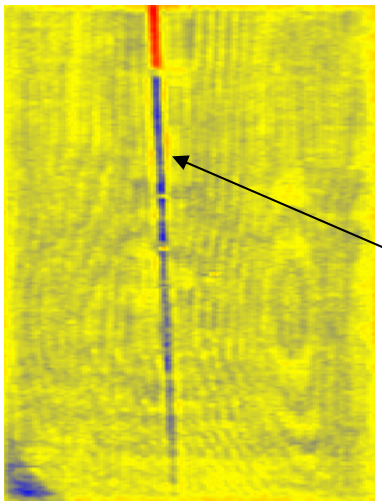
- Al sample, 2 mm thick



LOP height: 600 μm
LOP width: 10 μm

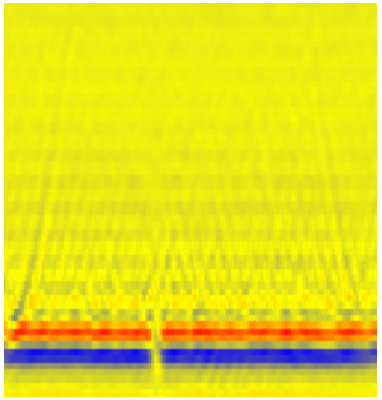
SAFT results: tool side

C-scan (slice)
near bottom face



Lack of
penetration

B-scan across
the weld



Backwall

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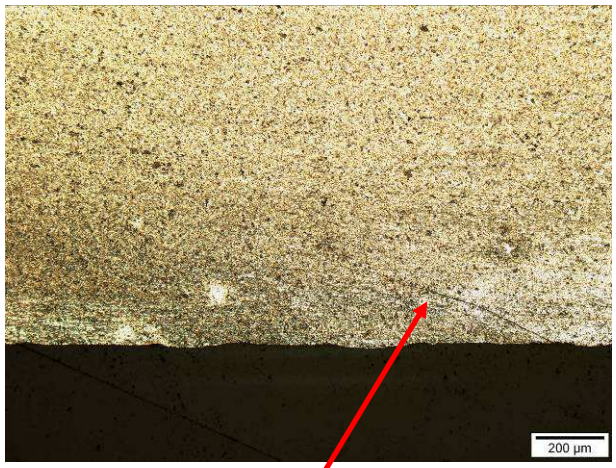
Sample with variable pin length

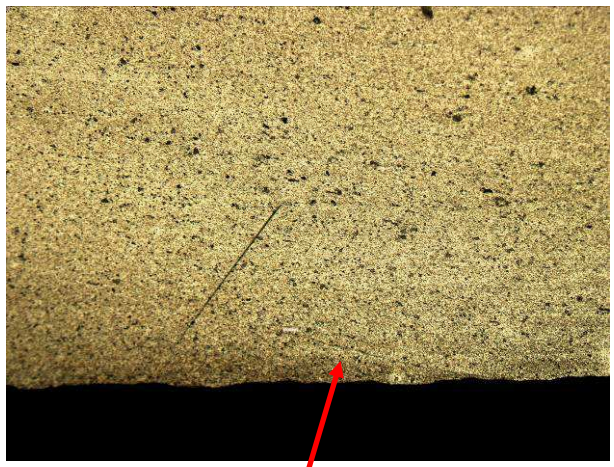
Al sample
2.56 mm thick (0.1 inch)

Pin penetration= 1.9 mm



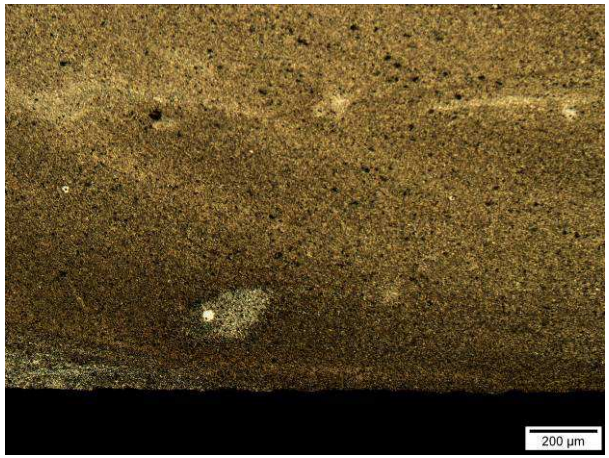
Lack of penetration

Pin penetration= 2.1 mm



Small lack of penetration

Pin penetration= 2.2 mm

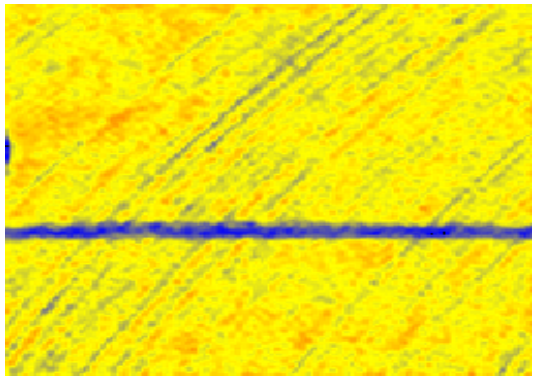


Full penetration

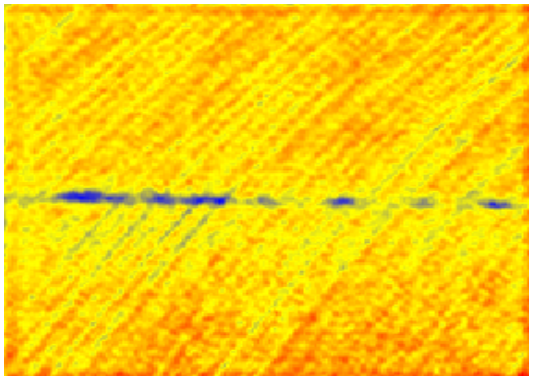
- No visible defect for a pin penetration ≥ 2.2 mm

SAFT results: tool side

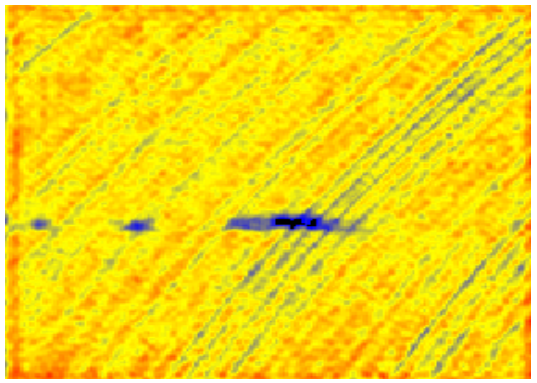
1.4 mm

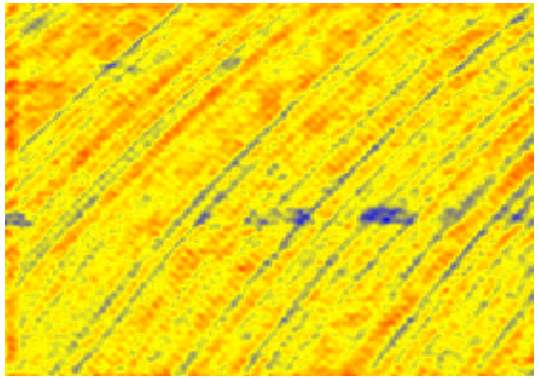


1.6 mm

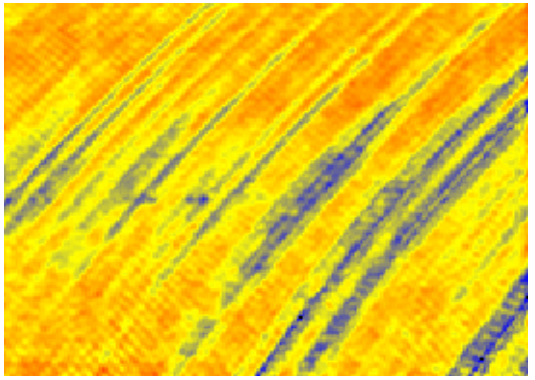


1.8 mm

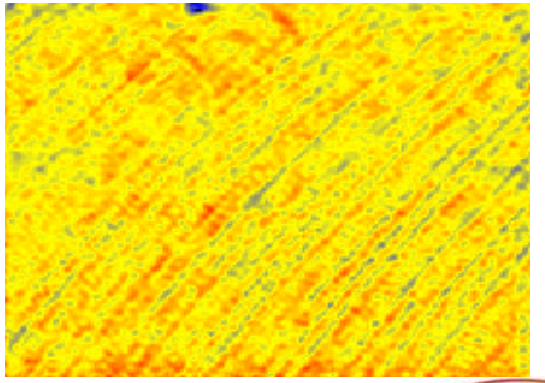




2.0 mm



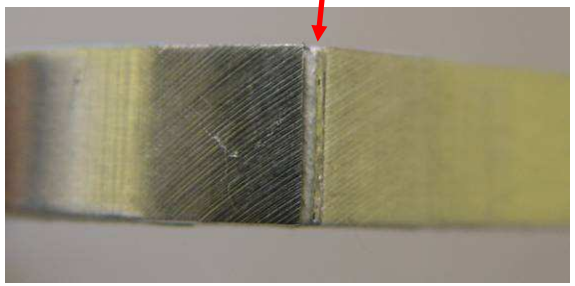
2.1 mm



2.2 mm

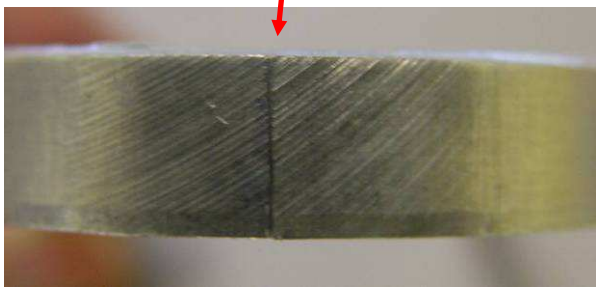
Bend test results

Failure



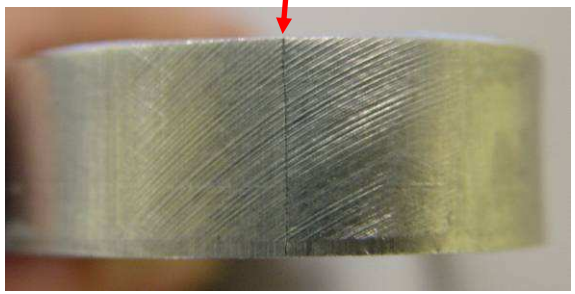
1.25 to 1.3 mm

Failure



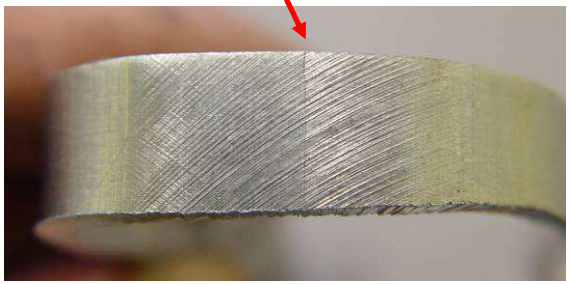
1.45 to 1.5 mm

Failure



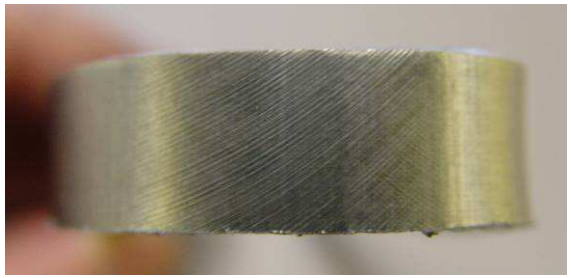
1.65 to 1.7 mm

Failure



1.85 to 1.9 mm

Small failures observed by microscopy



1.95 to 2.0 mm

Very small and irregular failures observed by microscopy

2.05 to 2.1 mm

- No failure for a pin penetration ≥ 2.14 mm

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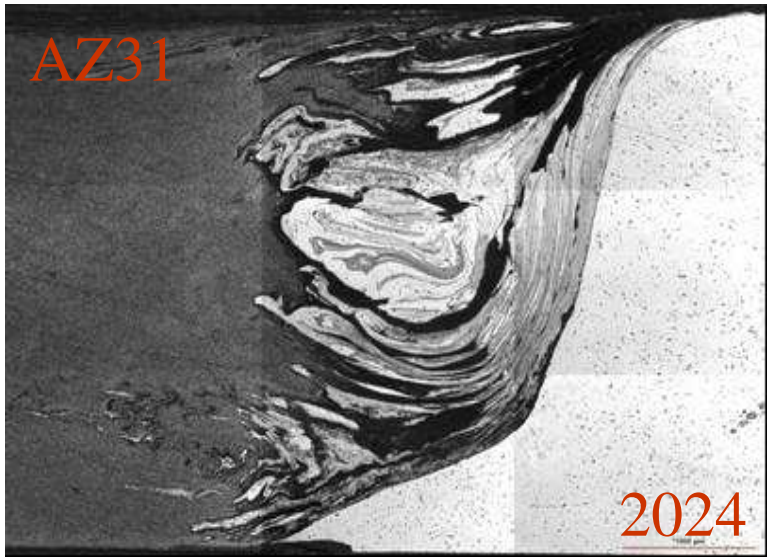
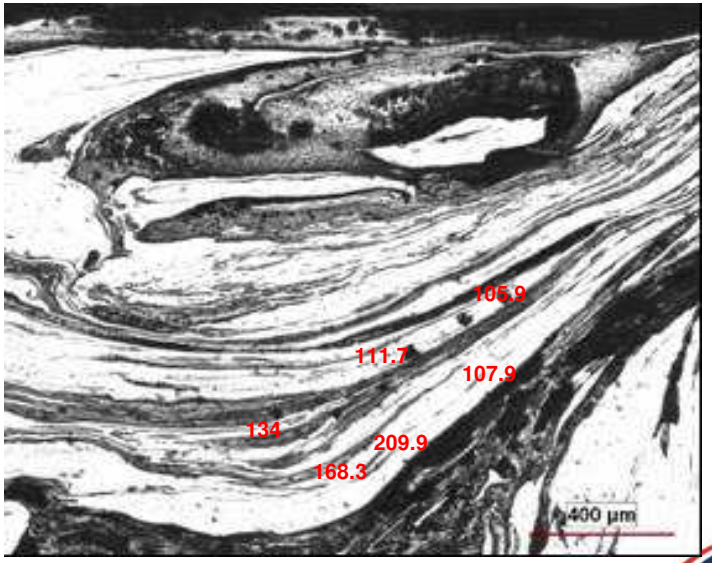
Dissimilar FSW welds

- Determination of process parameters for FSW of butt joints Mg AZ31 and Al 2024.
- Complex vortex flow characterized by intercalated lamellar structure.
- High hardness probably due to the formation of $Al_{12}Mg_{17}$.
- Low hardness probably due to loose structure.





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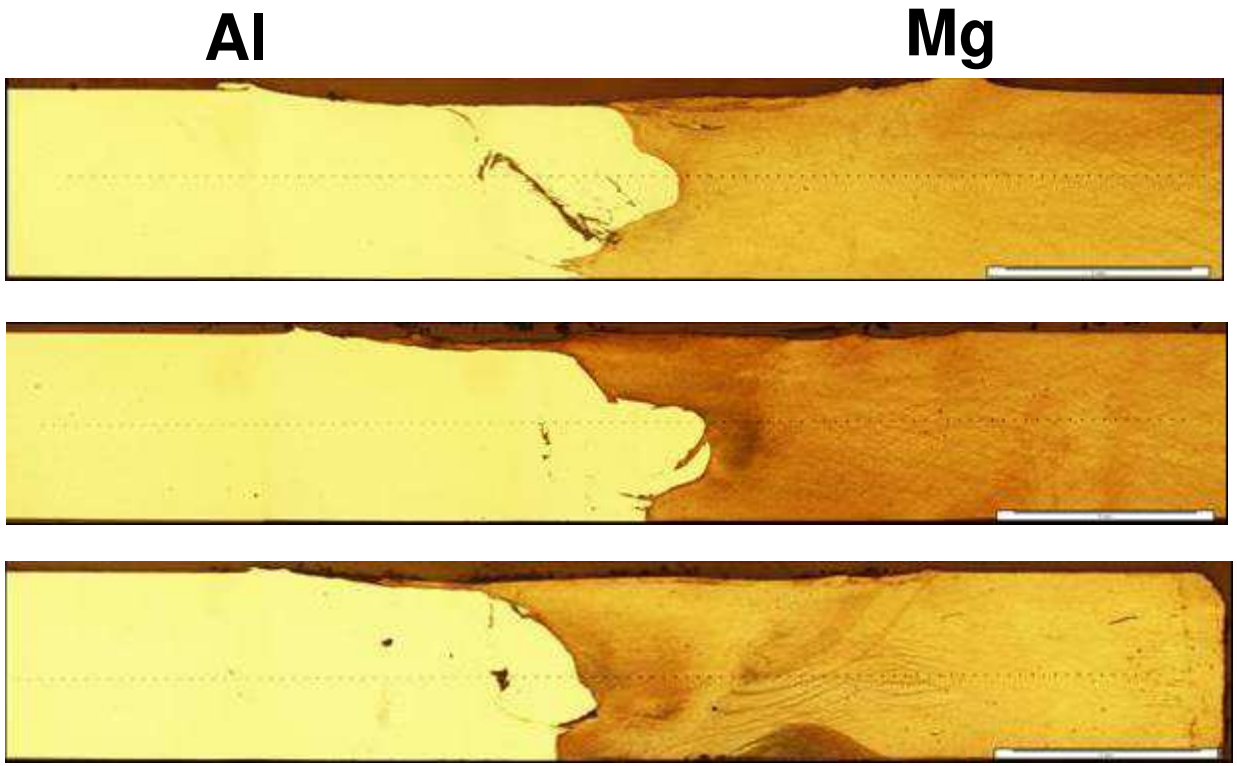
Effect of welding speed



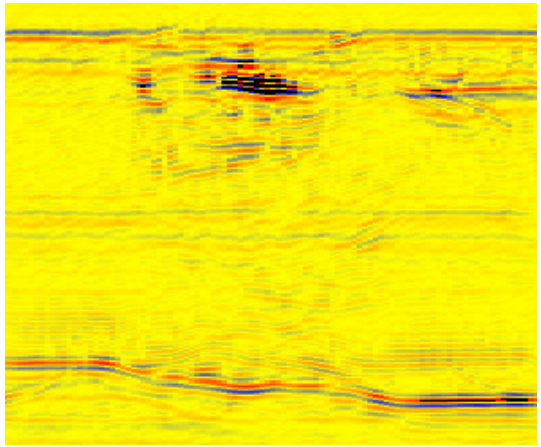
Rotational speed: 250 RPM
Thickness: 5 mm

V ↓ , T ↑, intermetallic ↑

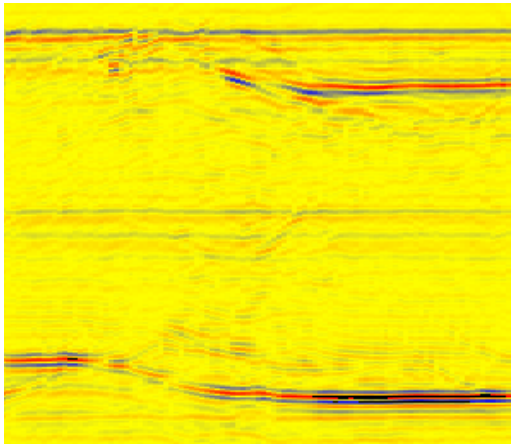
Measurement: tool side

- B-scan

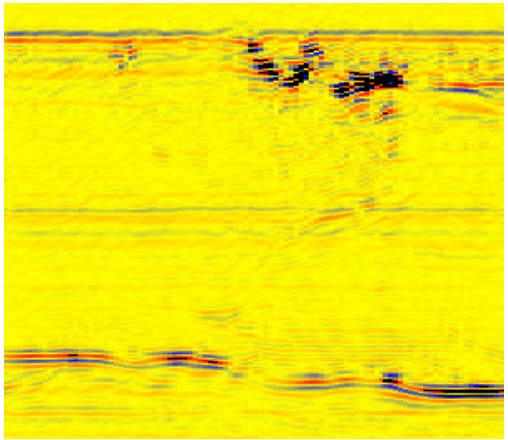
Line 20



Line 85



Line 110

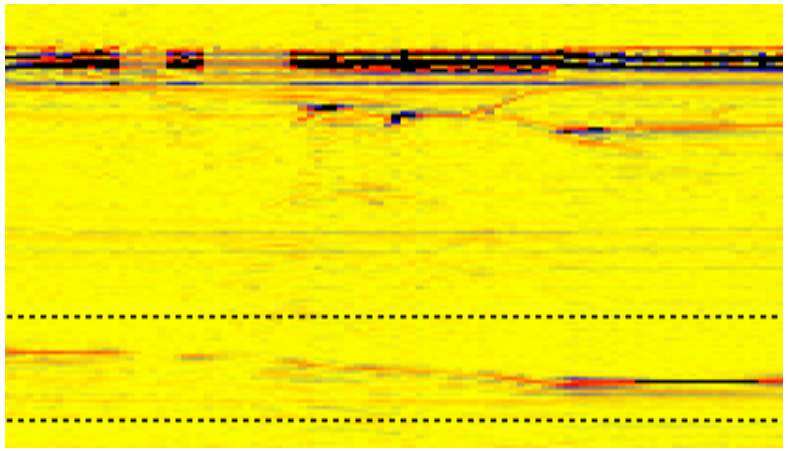


Al (left) - Mg (right)

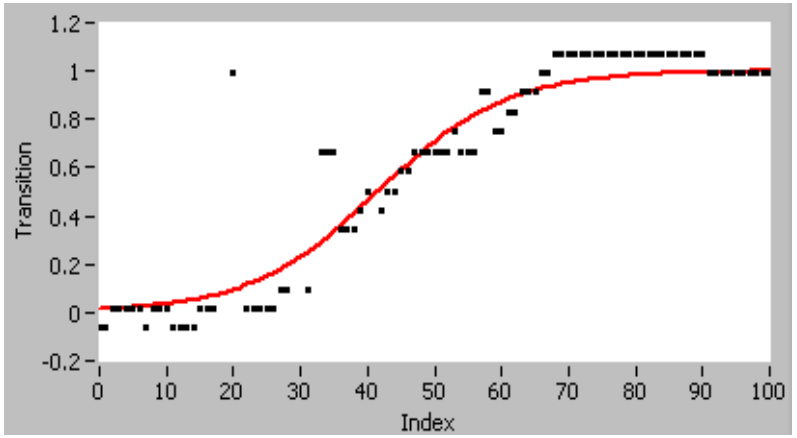
Scan: 10 mm wide, 20 mm along weld axis

SAFT: improvements

B-scan:
Butt joint, 5 mm thick



Transition:
Fit of the bottom echo



Al (left)
6.4 mm/us

Mg (right)
5.8 mm/us

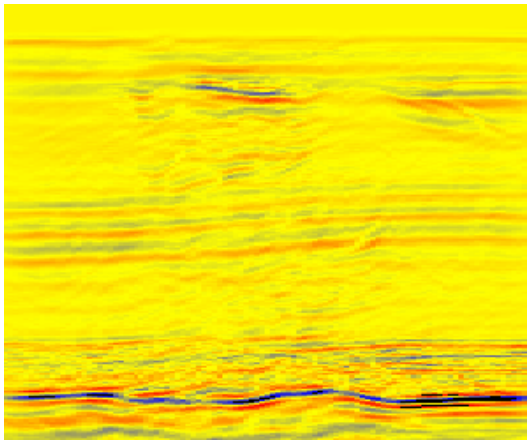
This information from the backwall echo is used in the SAFT reconstruction

NRC·CNRC
From Discovery to Innovation...

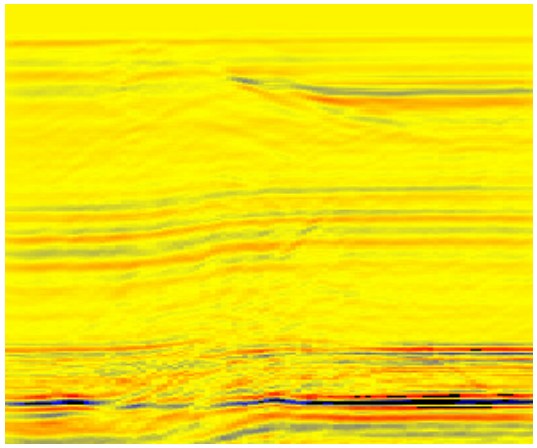
SAFT results

- B-scan

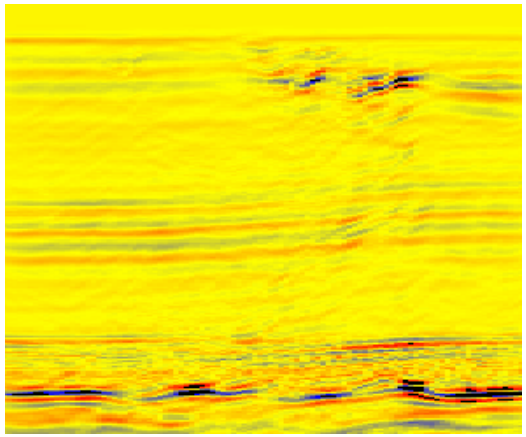
Line 20



Line 85



Line 110

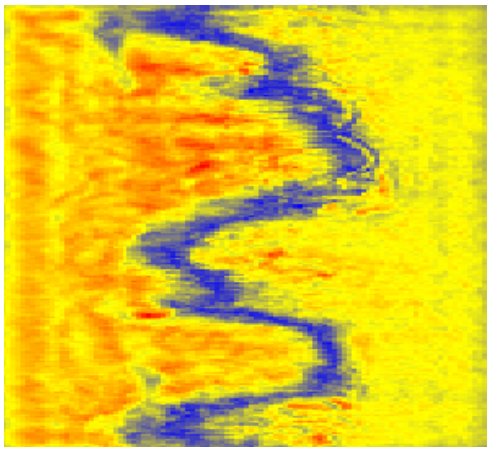


Al (left) - Mg (right)

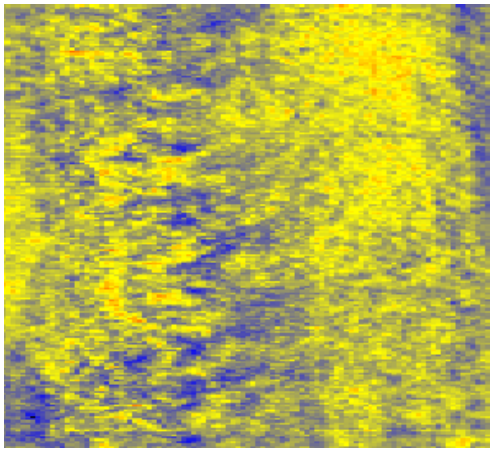
SAFT results: mid-plane

- C-scan

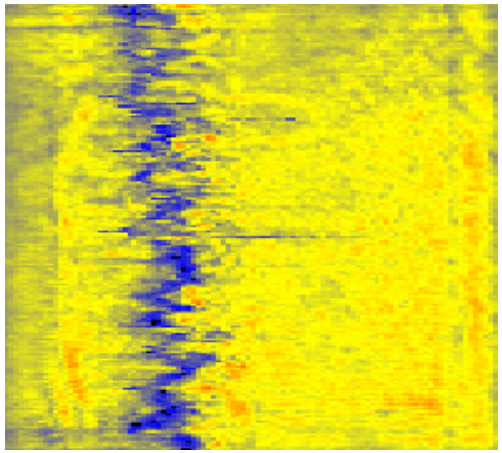
0.75 mm/s



9.0 mm/s



15.0 mm/s

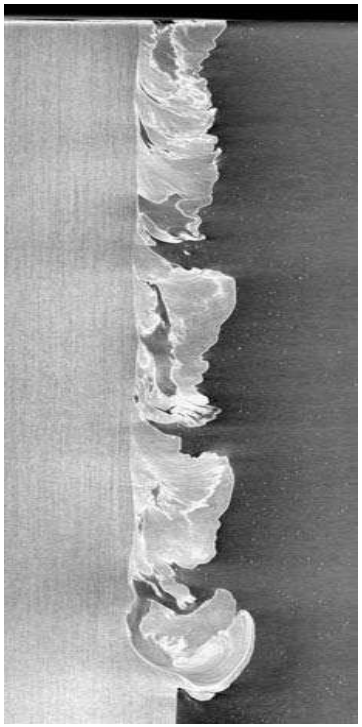


Al (left) - Mg (right)

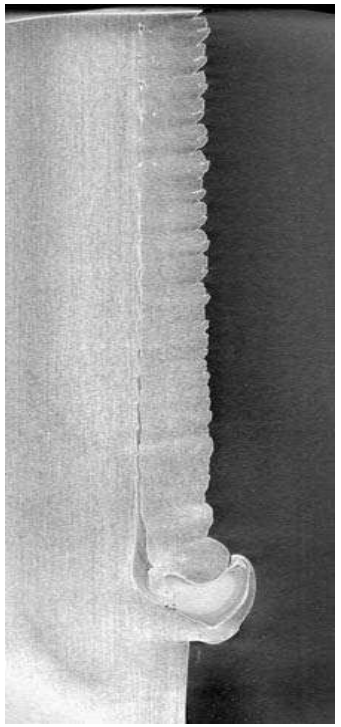
Testing by Micro-CT

- **Front views, mid-plane**

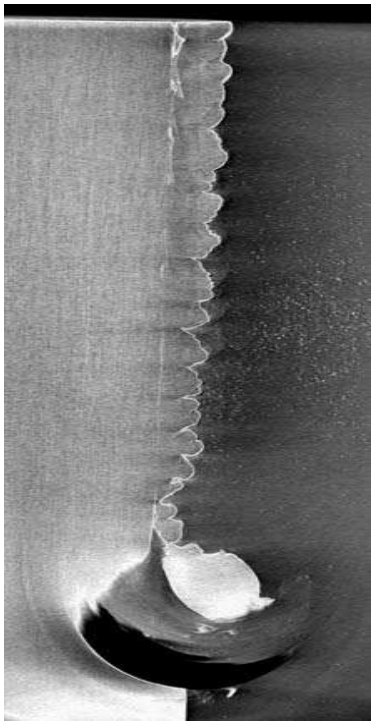
0.75 mm/s



9.0 mm/s



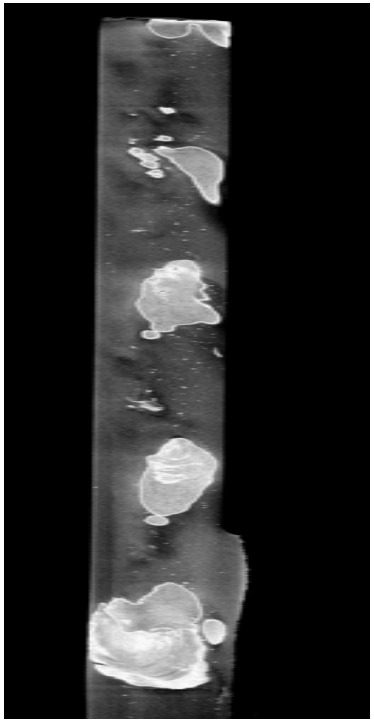
15.0 mm/s



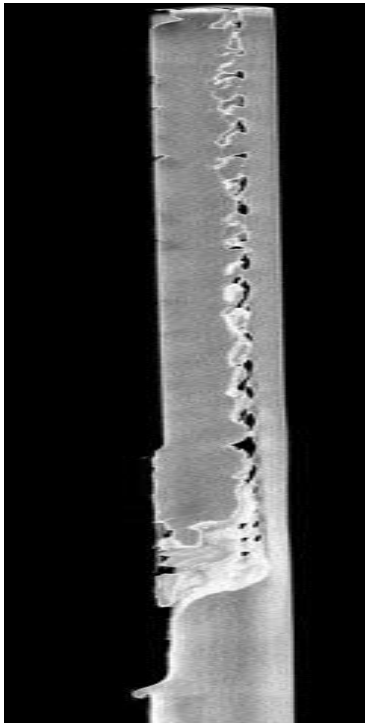
Testing by Micro-CT

- **Side views**

0.75 mm/s



9.0 mm/s



15.0 mm/s

Conclusion

- Performance of SAFT demonstrated in different configurations of FSW. Ability to detect wormhole, hooking and lack of penetration.
- High frequency laser-ultrasonics seems to be able to detect kissing bond in FSW.
- Defect can be irregular: without NDE, many cross-sectional views required.
- SAFT can be modified to visualize material intermixing in dissimilar metal welds.

References

1. D. Kleiner and C.R. Bird, “Signal processing for quality assurance in friction stir welds”, Insight, Vol. 46, pp. 85-87, 2004.
2. S. Iwaki et al., Imperfections in friction stir welded zones and their precision non-destructive testing. Studies on characteristics of friction stir welded joints in structural thin aluminium alloys, Welding Intern. 20, pp. 197-205, 2006.
3. D. Lévesque, A. Blouin, C. Néron and J.-P. Monchalin, Performance of laser-ultrasonic F-SAFT imaging, Ultrasonics 40, pp. 1057-1063, 2002.
4. D. Lévesque et al., “Synthetic aperture focusing technique for the ultrasonic evaluation of friction stir welds”, Review of Progress in Quantitative NDE Vol. 27, ed. by D.O. Thompson and D.E. Chimenti, AIP, New York, pp. 263-270, 2008.

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Thank You!