7th International EWI/TWI Seminar on Joining Aerospace Materials

A Review on Microstructure and Properties of Friction Stir Spot Welds (Refill) in Aircraft Aluminium Alloys

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Light-weight Materials Assessment, Computing and Engineering Centre

Boeing Longacres Customer Centre
Renton, WA, 17 – 19 September, 2014

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Outline

- History and Principles of the Refill FSSW
- Motivation and Objectives
- Results
  - 2024-T351 and 2024-T3 ALCLAD
  - AA 7574-T761
  - AA 2198-T8
  - AA5754 / Ti64 Dissimilar Joints
  - AA2024-T351 / CF-PPS
- Final Remarks

History of the process at HZG

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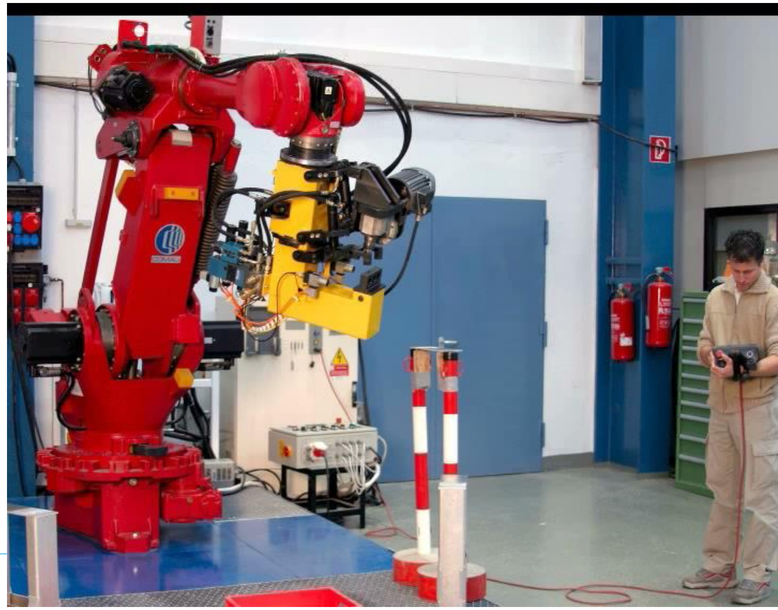
Stitch Friction Stir Spot Welding (Stitch FSSW)

HZG Patent (199 56 963.0)
Priority date: 18.11.99

Presented at the 2. International FSW Symposium in 1999[1] – First mention ever to “Friction Stir Spot Welding” in the literature.



[1] Schilling C, von Strombeck A, dos Santos JF, von Heesen N. A Preliminary Investigation on the Static Properties of Friction Stir Spot Welds. 2nd International Symposium on Friction Stir Welding (2ISFSW) [Internet]. Gothenburg, Sweden: The Welding Institute (TWI), Cambridge, UK; 2000. Available from: http://www.fswsymposium.co.uk/EasySiteWeb/GatewayLink.aspx?alId=1238963

Refill Friction Stir Spot Welding: Process[1]

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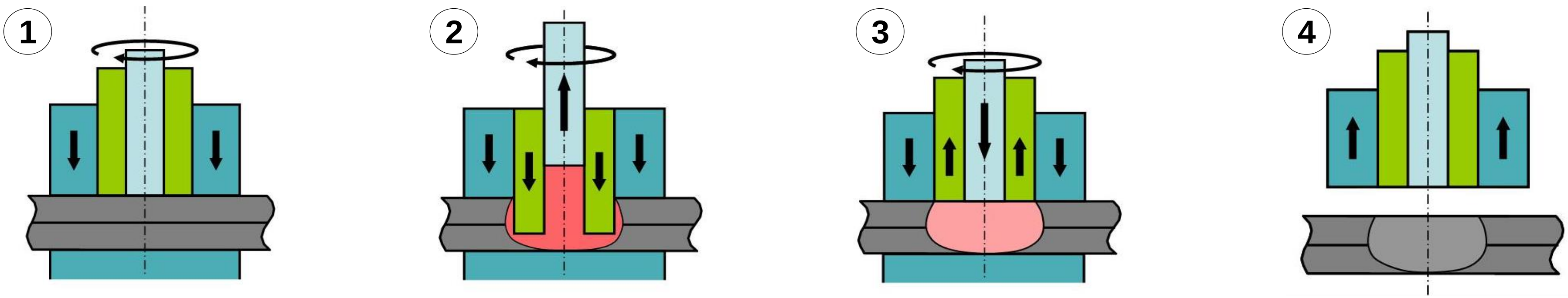
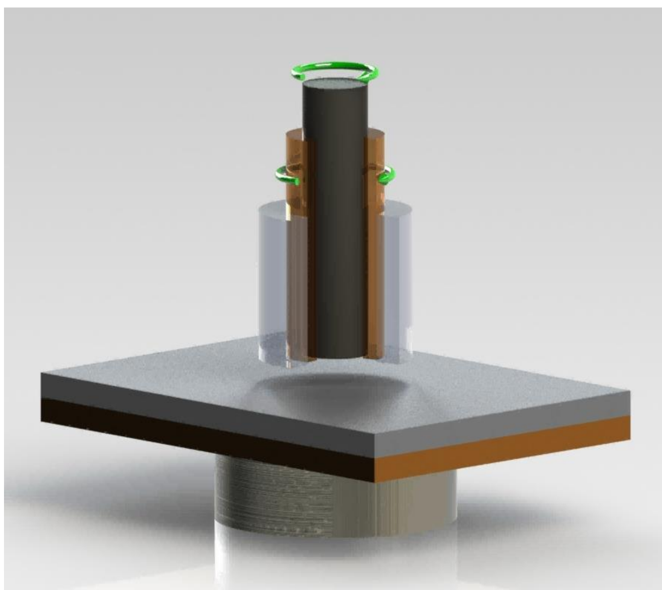


Clamping and tool rotation	Pin retraction and sleeve plunging	Pin plunging and sleeve retraction	Tool retrieval



Friction Spot Welding

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[1] C. Schilling and J. F. dos Santos: *Method and device for joining at least two adjoining work pieces by friction welding.* US Patent US00000006722556B2, April 2004.

History of the process at HZG

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Friction Spot Welding (FSpW)

HZG Patent (199 55 737.3)
Priority Date: 18.11.99
US Patent[1]: US00000006722556B2, April 2004

The process was employed for the first time in the EU Project WAFS.

[1] C. Schilling and J. F. dos Santos: *Method and device for joining at least two adjoining work pieces by friction welding.* US Patent US00000006722556B2, April 2004.

Refill Friction Stir Spot Welding: Machines

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Friction Spot Welding Machine

- Developed in a technology transfer project with the participation of HZG, Harms&Wende and RIFTEC
- Max. 20kN and 3000 rpm
- Independent drives for sleeve and pin
- Tool cooling
- Pneumatic clamping
- Commercially available

Tool assembly

Refill Friction Stir Spot Welding Tool

Refill Friction Stir Spot Welding: Machines

- Tool stroke: 10mm (max. penetration depth
- Max. axial force (pin and sleeve): 10kN
- Max. Torque (pin adn sleeve: 60Nm
- x,y specimen table 1,5m x 1,5m
- Water cooled

Motivation and Objectives

- Reduce non-recurring assembly costs (tooling) and number of activities in the assembly lines:

  hole-to-hole assembly

- Avoid as much as possible conventional assembly methods where parts have to be taken apart after drilling for deburring activities:

  single step assembly

- Reduce assembly time and improve quality by as much automation of the remaining activities in assembly as possible:

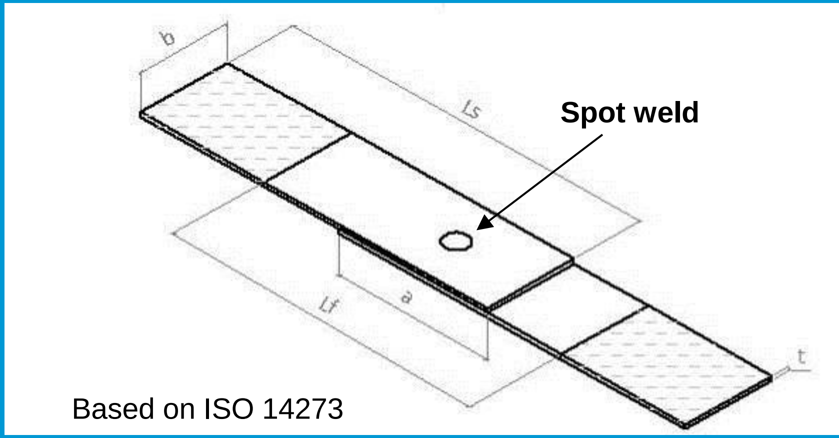
  automated assembly

- Results: reduction of production cost

AA2024-T351 and AA2024-T3 ALCLAD

Process

- No dwell time
- Clamping ring pressure 2,8 bar
- Spot weld diameter = 9mm (sleeve diameter)
- Clamping force constant = 14.5kN



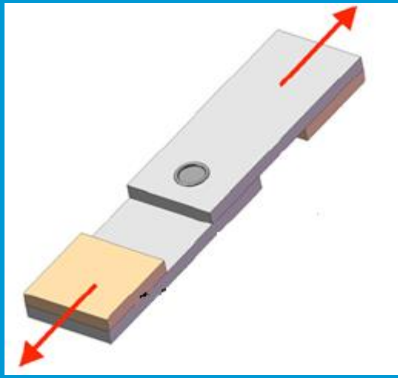
t	2,0mm
a [mm]	60
b [mm]	35
Ls [mm]	150
Lf [mm]	120

Base Material

- Sheet thickness: 2,0mm
- Material in the as-delivered condition (no surface treatment)

Mechanical performance assessment

- Lap shear tests
- All tests performed in triplicate



Design of Experiments

- Full Factorial Design for 3-Level Factors (3^k)*

3^2 = 2 factors in 3 levels

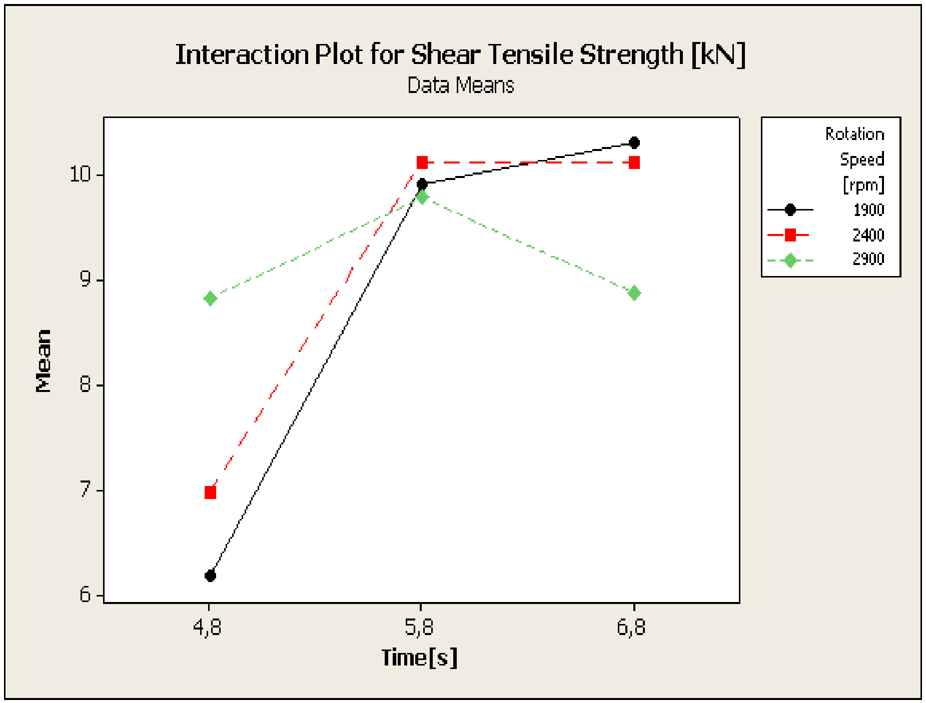
2024-T351 and 2024-T3 ALCLAD		
Condition	Rotation Speed (rpm)	Time (s)
1	1900	4.8
2	1900	5.8
3	1900	6.8
4	2400	4.8
5	2400	5.8
6	2400	6.8
7	2900	4.8
8	2900	5.8
9	2900	6.8

+ Analysis of Variance (ANOVA)

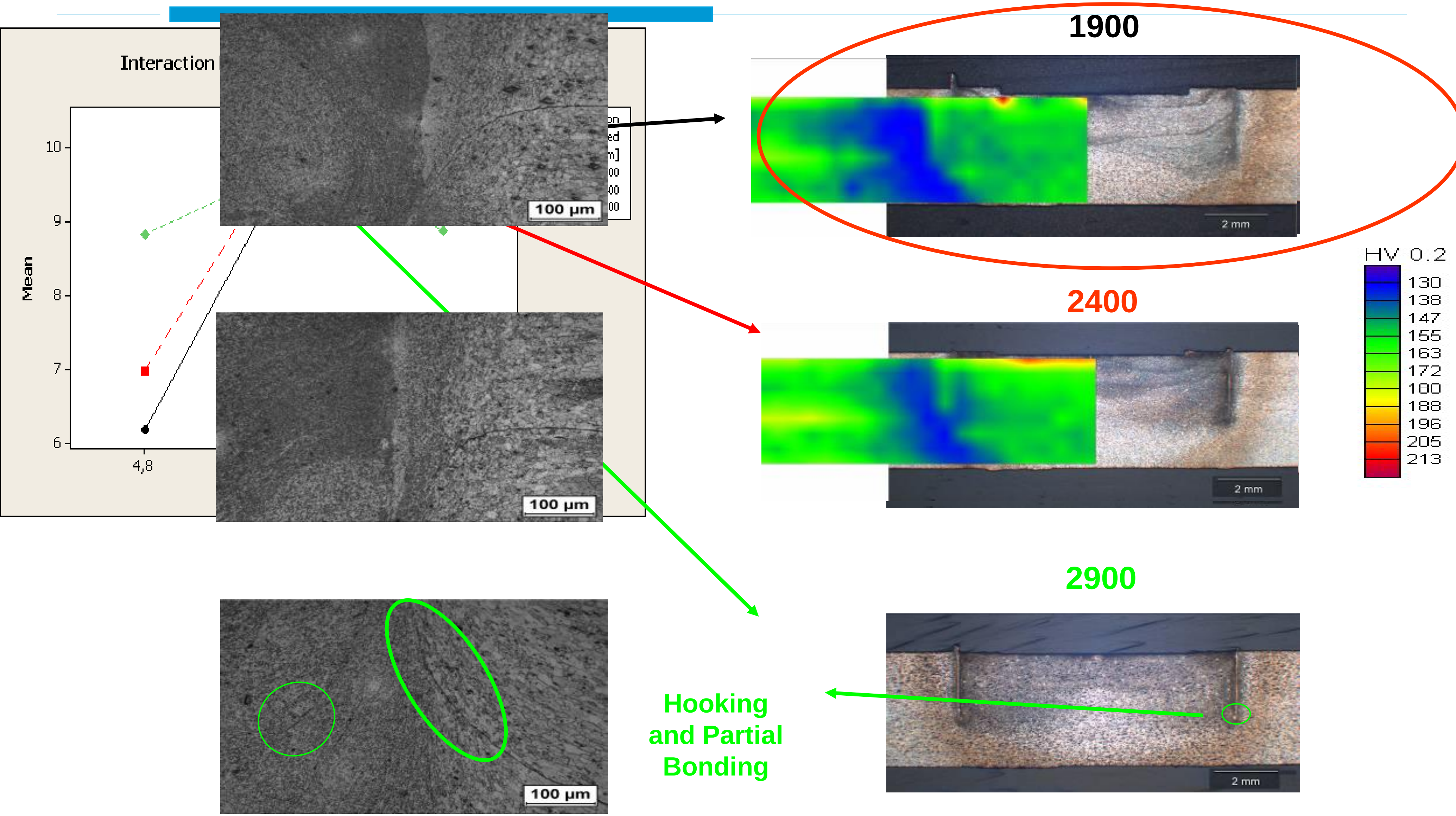
*S.T. Amancio, A.P.C. Camillo, L. Bergmann, J.F. dos Santos, S.E. Kury, N.G.A. Machado, „**Evaluation of the Process-Properties Relationship of Al 2024 Friction Spot Welds**", Proceedings of 12th International Conference on Aluminium Alloys (ICCA-12), Yokohama, Japan, 8th September 2010

AA 2024 – T3

Selected Time: 5,8 s

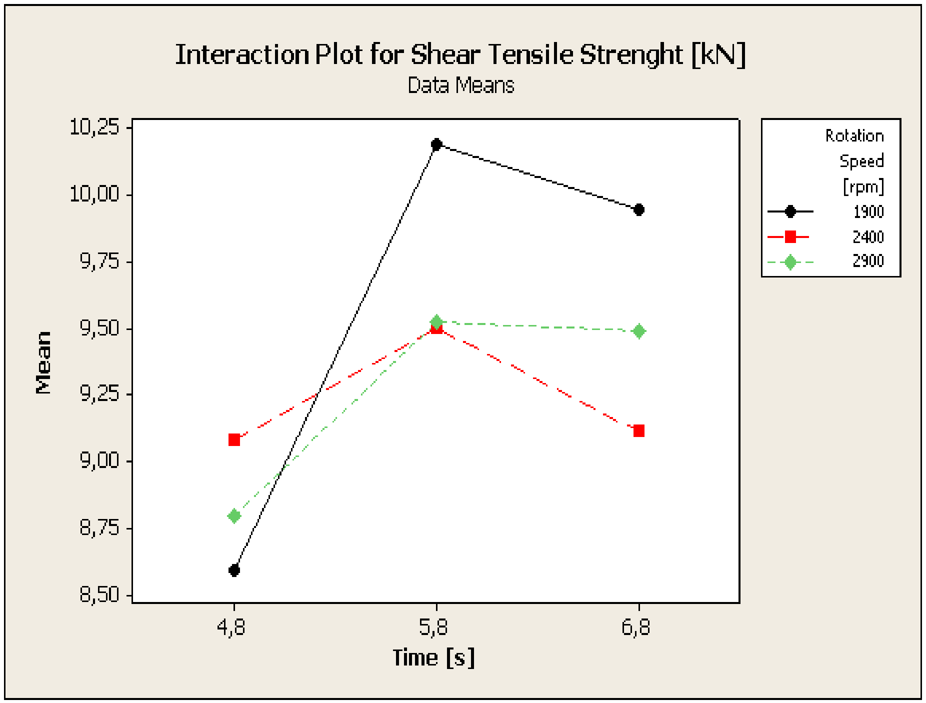


Results AA2024-T3



Alclad 2024-T3

Selected Time: 5,8 s



Results AA2024-T3

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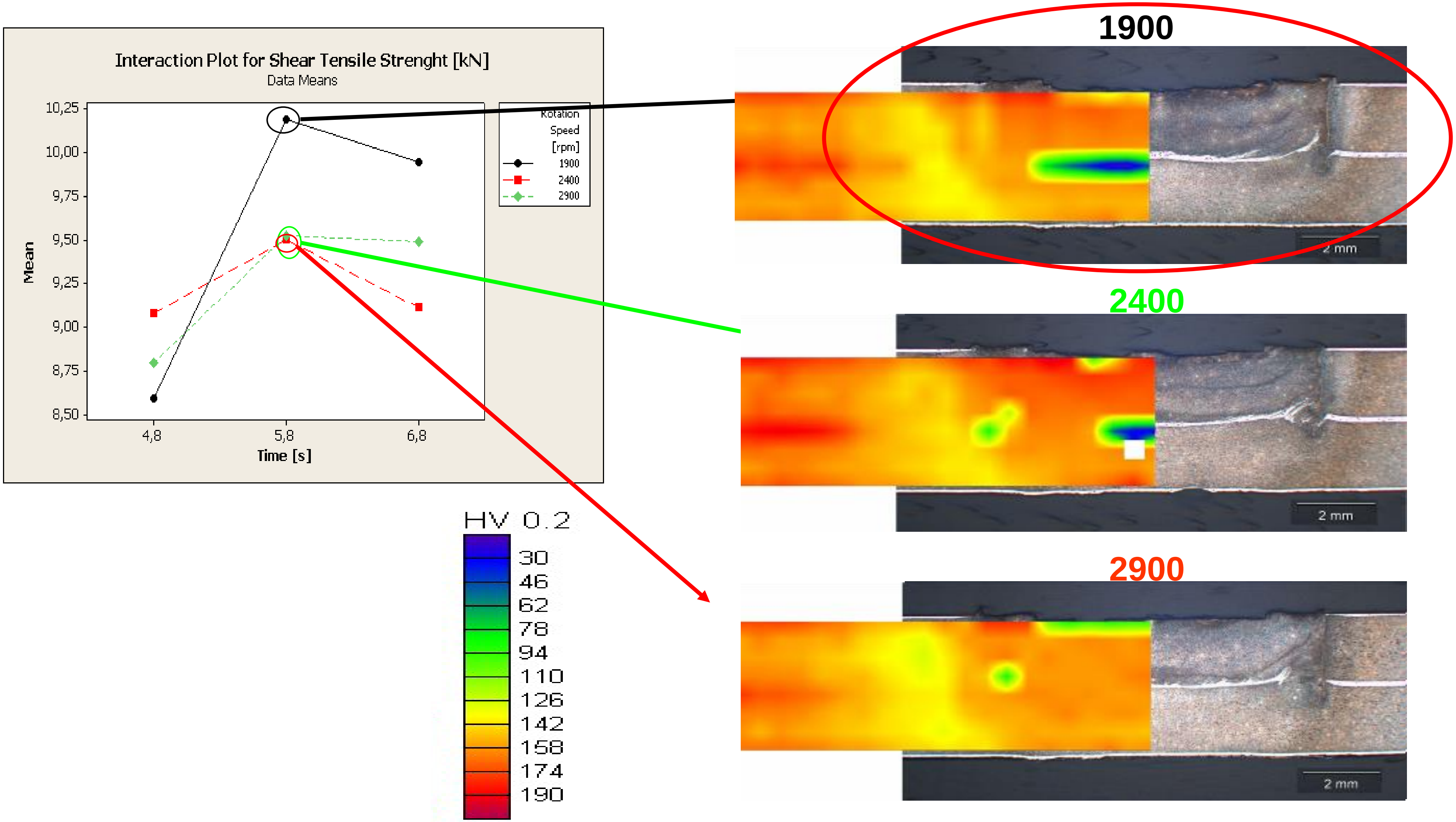
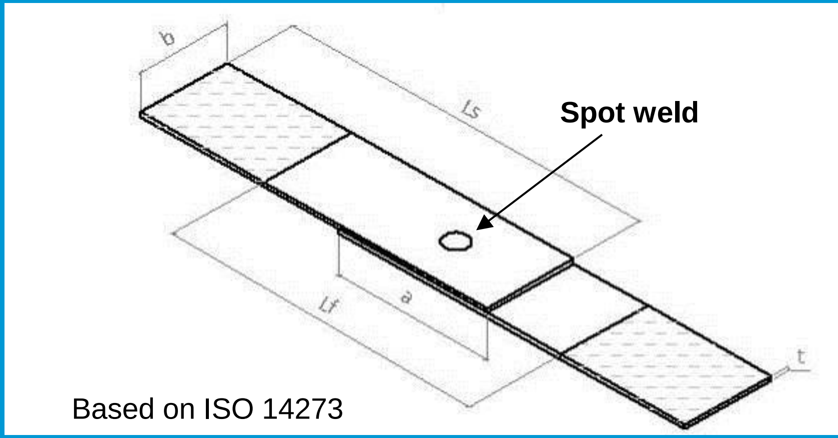


AA7475-T761

Process

- No dwell time
- Clamping ring pressure 2,8 bar
- Spot weld diameter = 9mm (sleeve diameter)
- Clamping force constant = 14.5kN



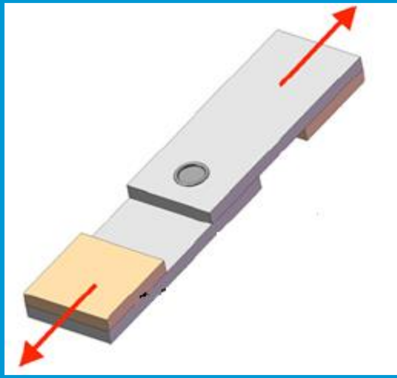
t	2,0mm
a [mm]	60
b [mm]	35
Ls [mm]	150
Lf [mm]	120

Base Material

- Sheet thickness: 2,0mm
- Material in the as-delivered condition (no surface treatment)

Mechanical performance assessment

- Lap shear tests
- All tests performed in triplicate



Design of Experiments

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- Full Factorial Design for 3-Level Factors (3^k)

3^2 = 2 factors in 3 levels

7475-T761		
Condition	Rotation Speed (rpm)	Time (s)
1	1000	7.4
2	1000	9.4
3	1000	11.4
4	1400	7.4
5	1400	9.4
6	1400	11.4
7	1800	7.4
8	1800	9.4
9	1800	11.4

+ Analysis of Variance (ANOVA)

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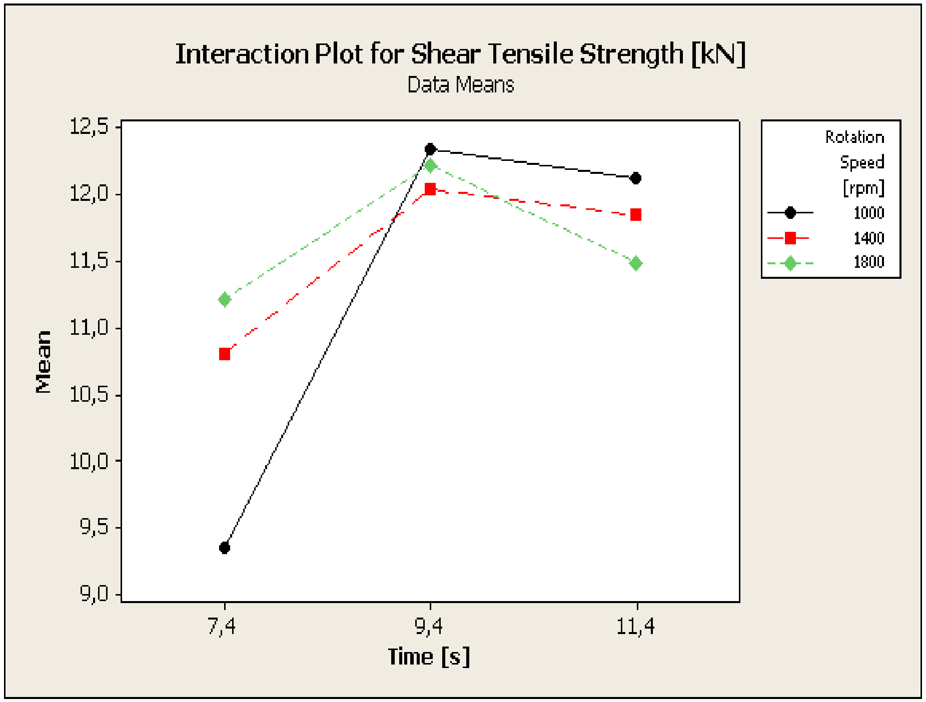
AA 7475 – T761

Selected Time: 9,4 s



Results AA7475-T761

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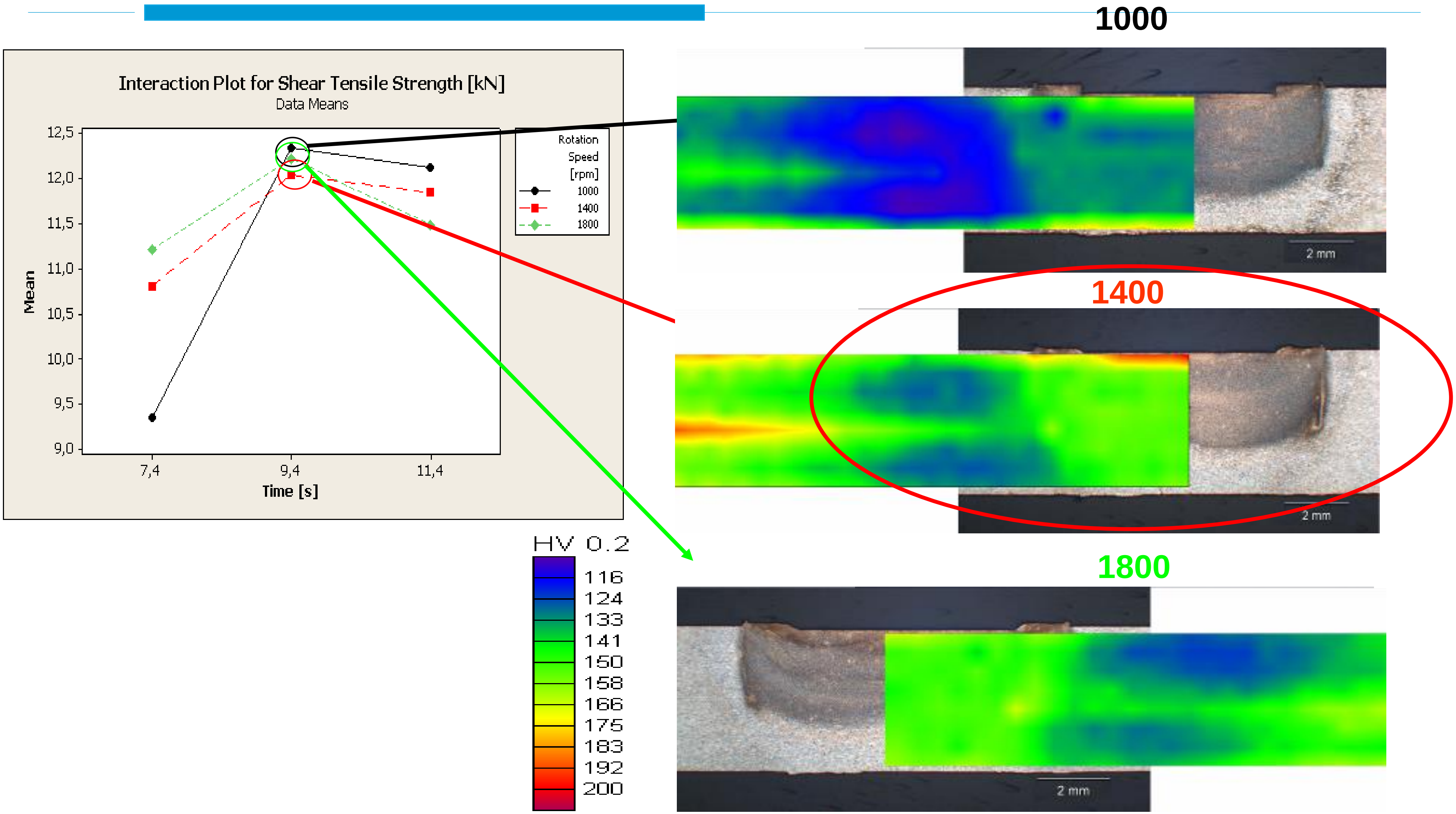
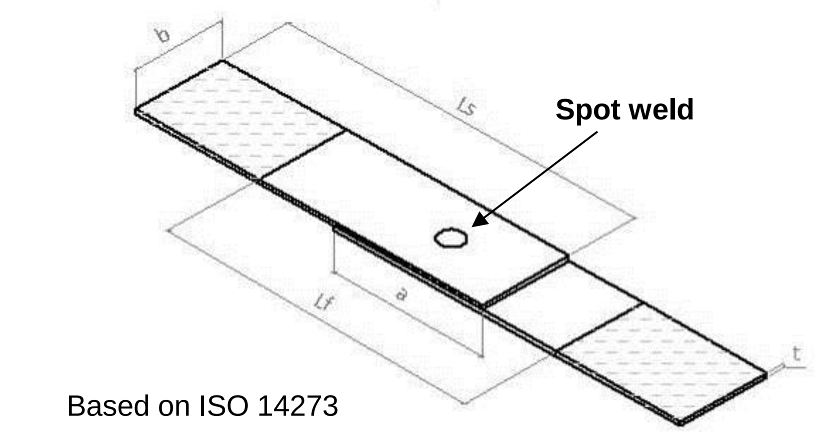


AA2198-T8

Process

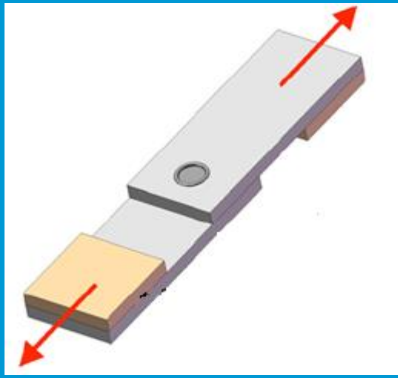
- No dwell time
- Clamping ring pressure 2,8 bar
- Spot weld diameter = 9mm (sleeve diameter)
- Clamping force constant = 14.5kN



t	3.2mm	1.6mm
a [mm]	60	46
b [mm]	35	35
Ls [mm]	150	126
Lf [mm]	120	105

Base Material

- Sheet thickness: 3,2mm and 1,6mm
- Material in the as-delivered condition (no surface treatment)



Mechanical performance assessment

- Lap shear tests
- All tests performed in triplicate

Design of Experiments

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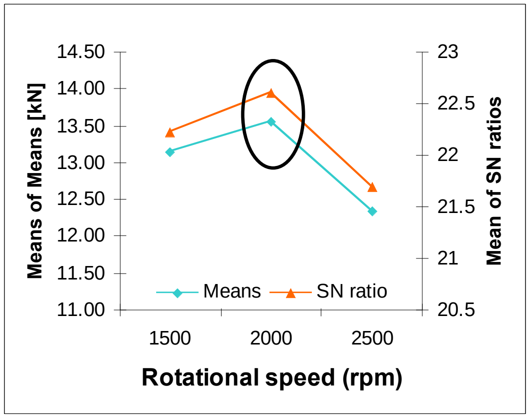
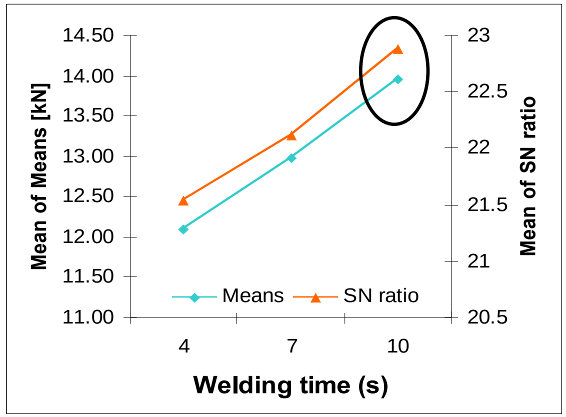
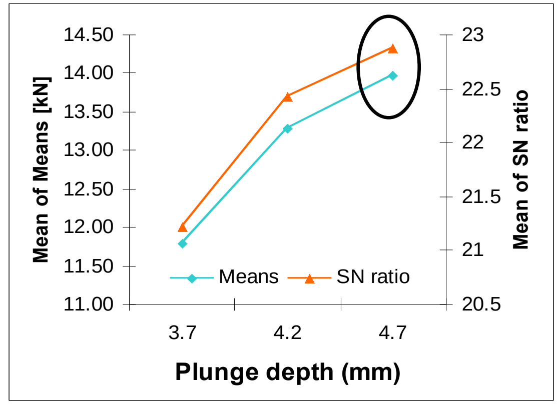
AA2198-T8 Thickness: 3.2mm

- Results evaluated for Means and Signal-to-Noise (S/N) ratio values
- "Higher-the-better" criterion for response
  (maximize the response and reduce the variability)







Parameters combination suggested by Taguchi results – **Welding condition 10**

Factor	Level	Note
Rotational Speed	**2000rpm**	Higher Mean and S/N ratio values
Welding Time	**10s**	
Plunge Depth	**4.7mm**	

Average Lap Shear Strength:

14.73 kN

Optimised welding condition!!

Results: Microstructure and Microhardness

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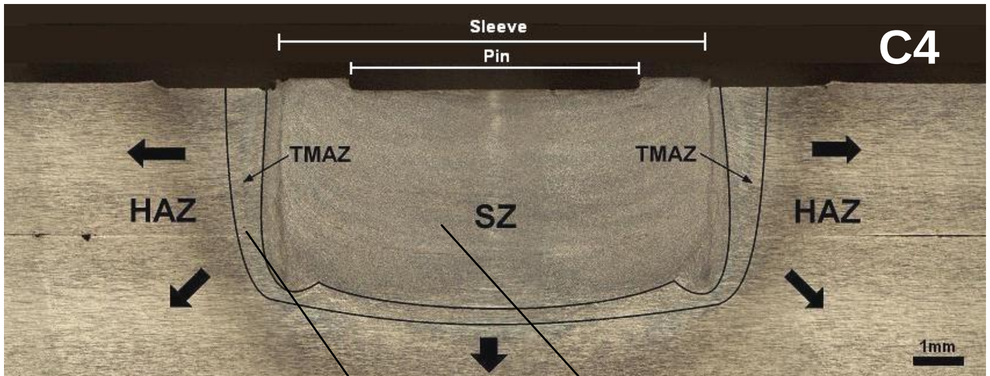
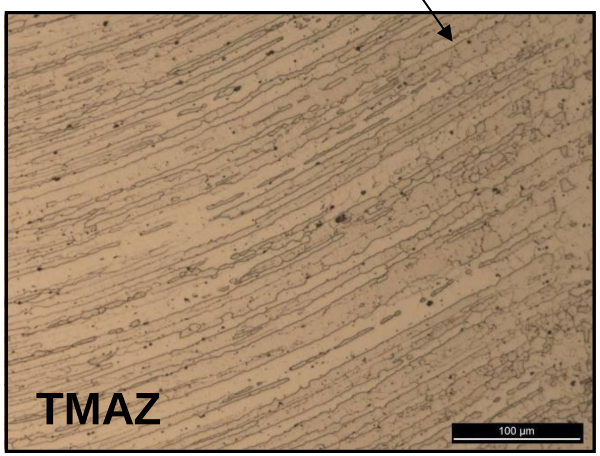
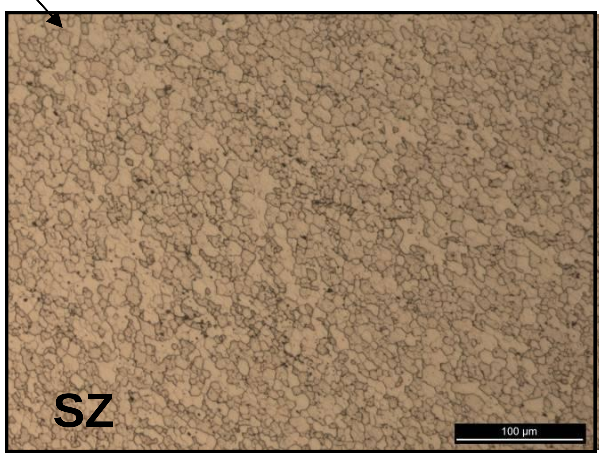
AA2198-T8 Thickness: 3.2mm

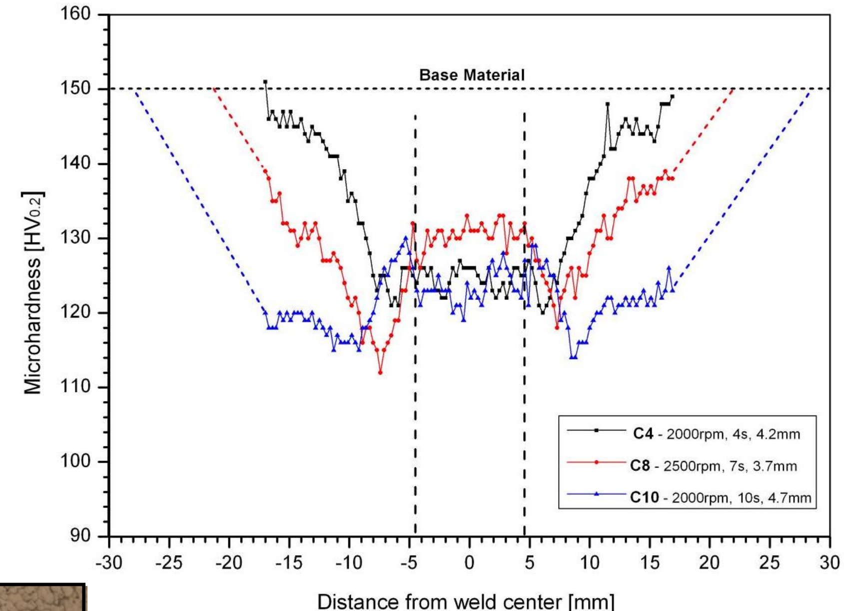




Deformed grains and initial recrystallization



Recrystallized grain structure – Grains in the direction of 90° in relation to TMAZ

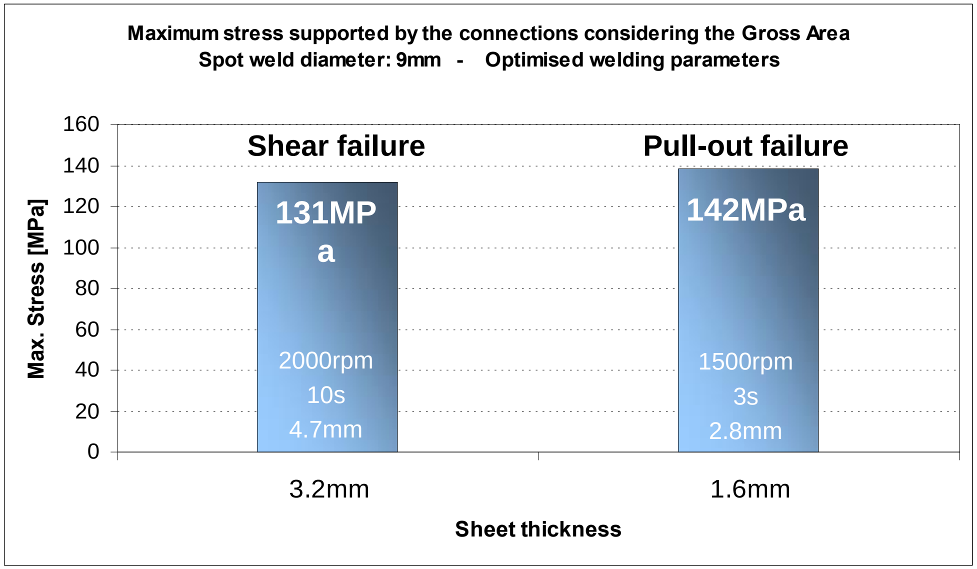


C10: Highest joint strength (14.73kN)

C4: Intermediary joint strength (12.56kN)

C8: Lowest joint strength (10.97kN)

Results: Summary



- Using the optimised welding parameters, the maximum stresses supported by the joints are in a comparable level for both sheet thickness

- High and Low Load Transfer (HLT and LHT) Configurations
- Monotonic Shear Tests
- Mechanical Testing supported by Digital Image Correlation
- Specimen Identification

Results: Structural Assessment

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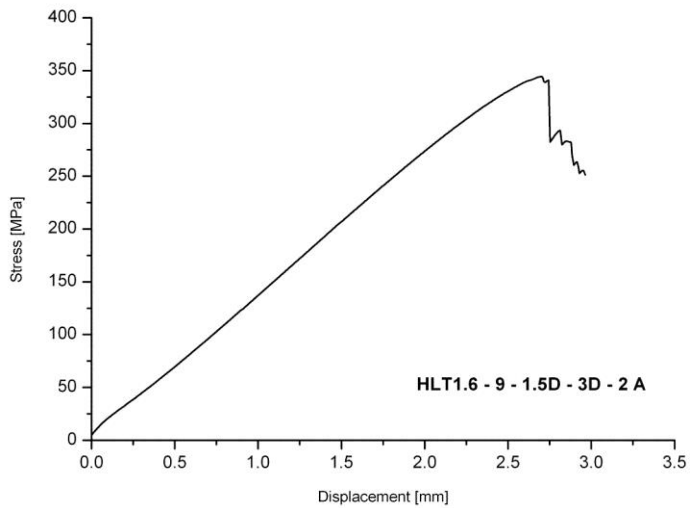
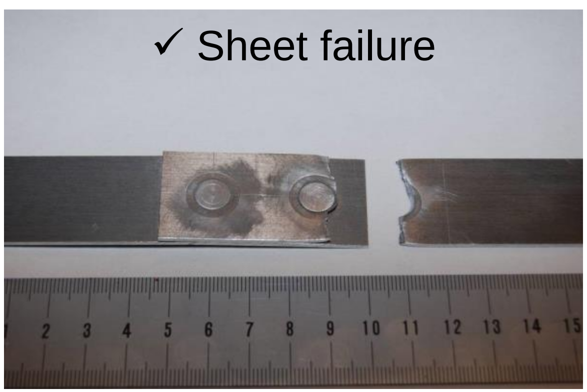
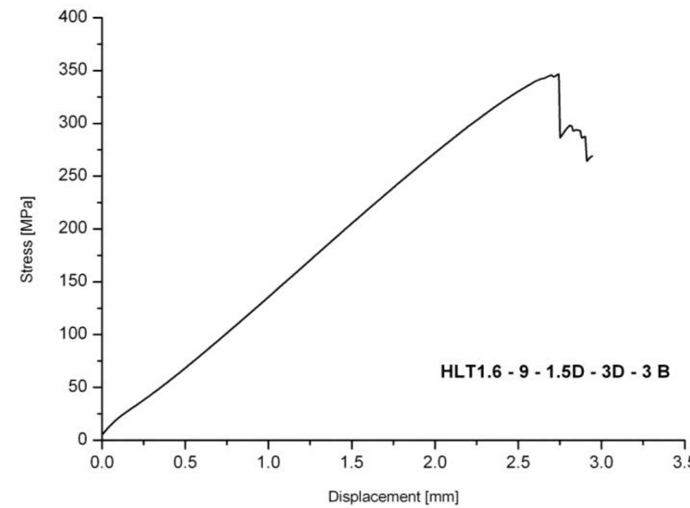
HLT1.6 - 9 - 1.5D - 3D - 2



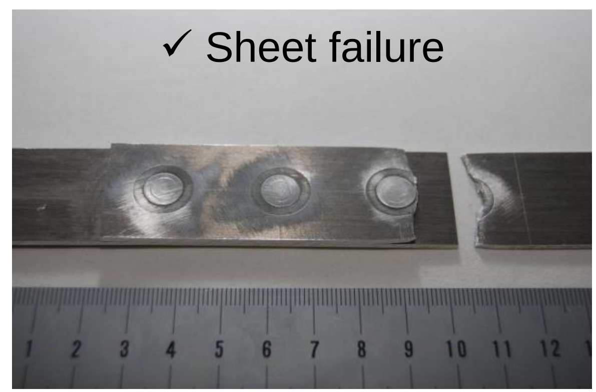
Mean Max. Stress: 344 MPa



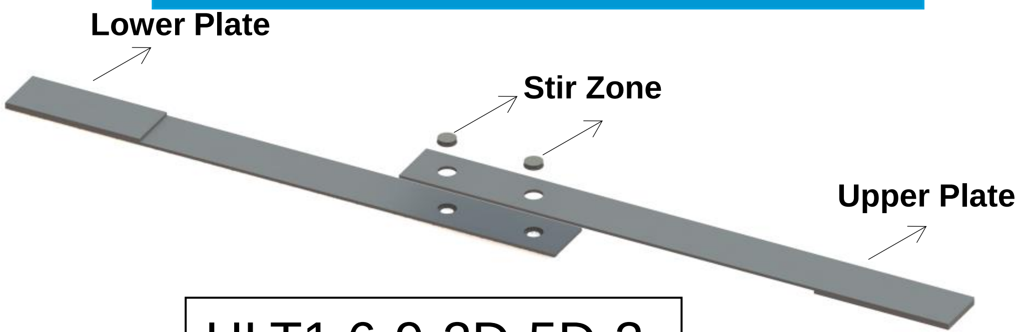
HLT1.6 - 9 - 1.5D - 3D - 3



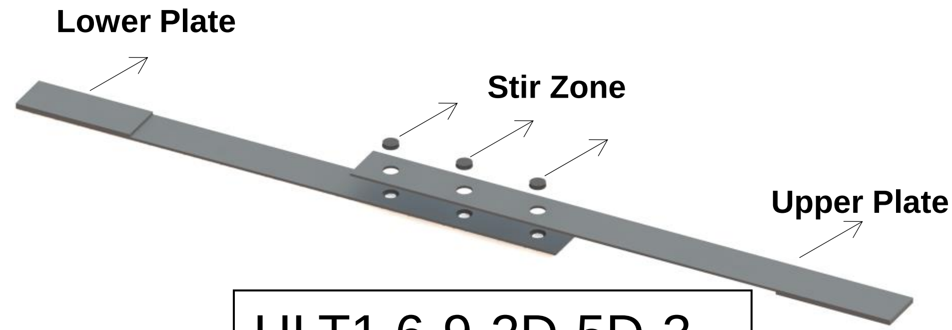
Mean Max. Stress: 354 MPa



Numerical Analysis: Geometry

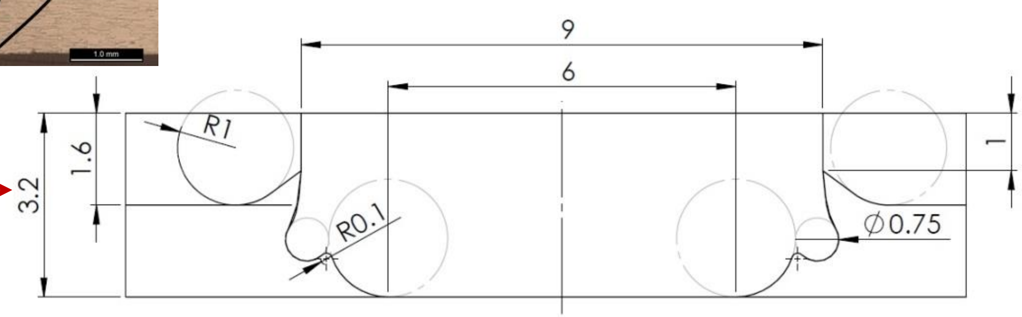


HLT1.6-9-2D-5D-2



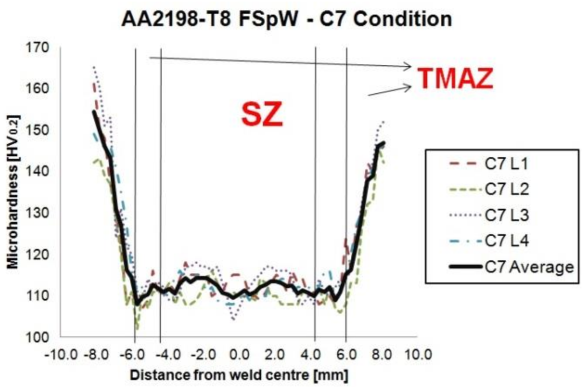
HLT1.6-9-2D-5D-3

Weld Parameters		
Plunge Depth	Welding Time	Tool Rotation Speed
2.8 mm	3 s	1500 rpm



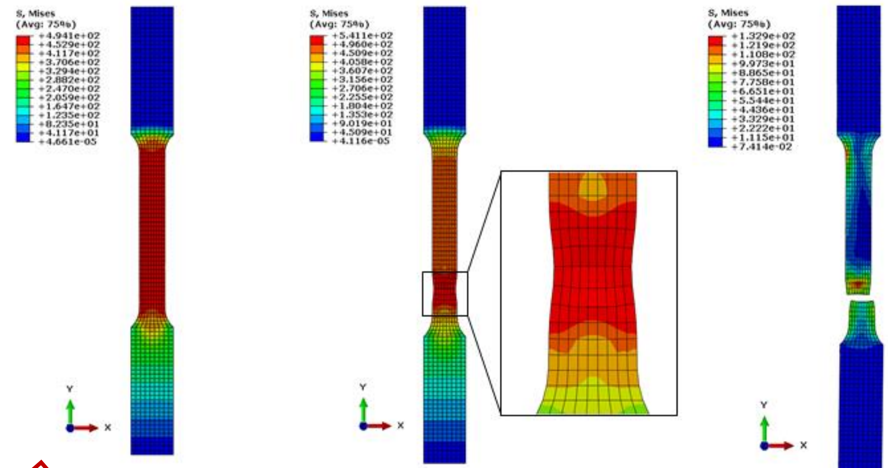
Numerical Analysis: Material

Microhardness Profile

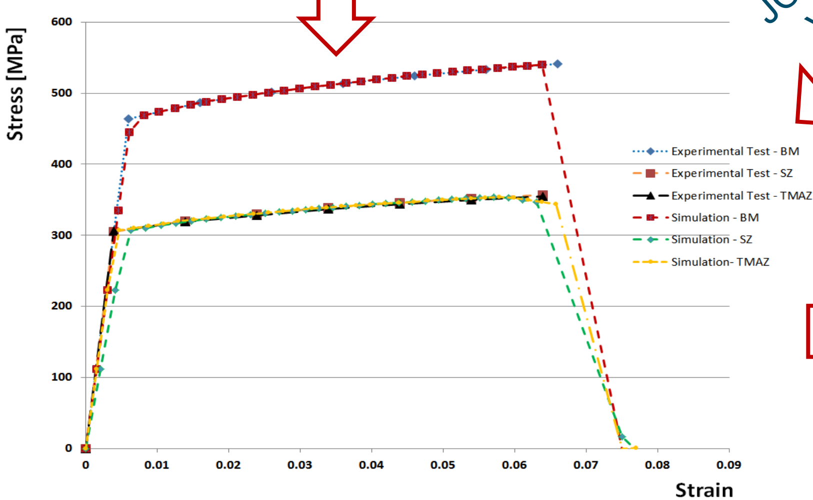


Tabor´s relation

Material and JC Constants Validation



Tensile Test Simulation



Stress x Strain curves for the individual weld regions

JC Constants

Johnson-Cook Damage Criterion Model

$$\bar{\varepsilon}_f^{pl} = \left[d_1 + d_2 e^{\left(d_3 \frac{p}{q}\right)}\right]\left[1 + d_4 \left(\frac{\dot{\bar{\varepsilon}}_f^{pl}}{\dot{\varepsilon}_0}\right)\right](1 + d_5 \theta)$$

Stress | Displacement rate | Temperature

JC Constants	d_1	d_2	d_3	d_4	d_5
	0.08	0.045	-0.7	0	0

Numerical Analysis: Numerical Model

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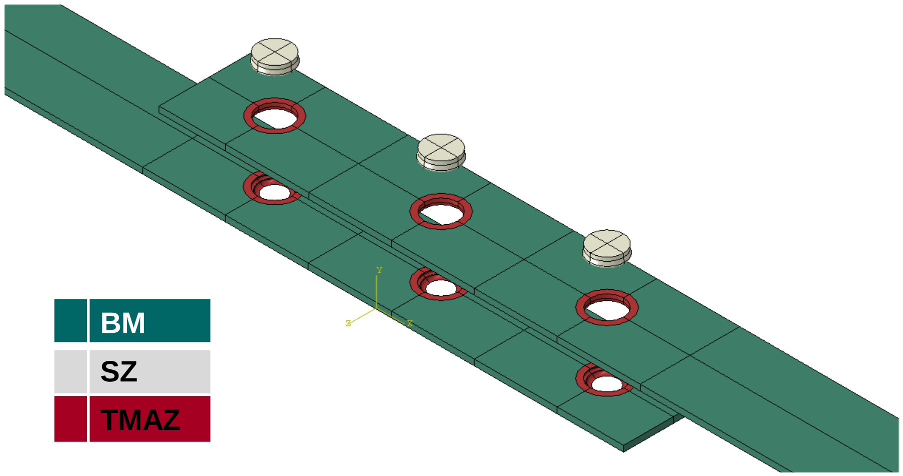
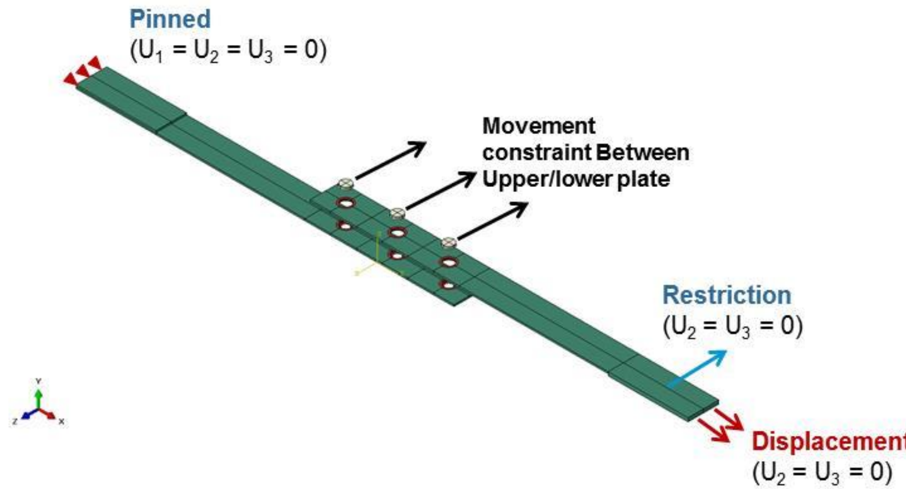
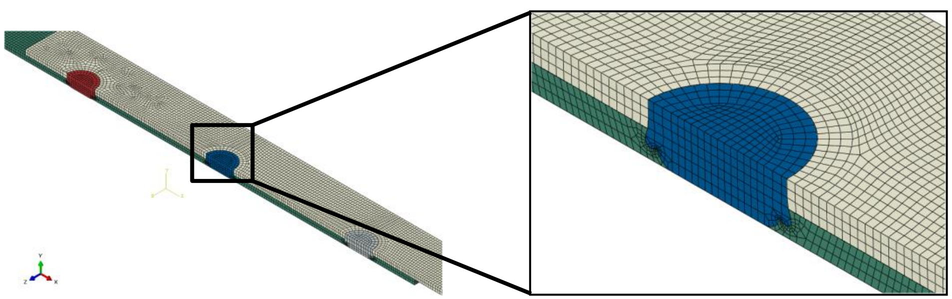
Material



Interaction/Boundary Conditions



Mesh size

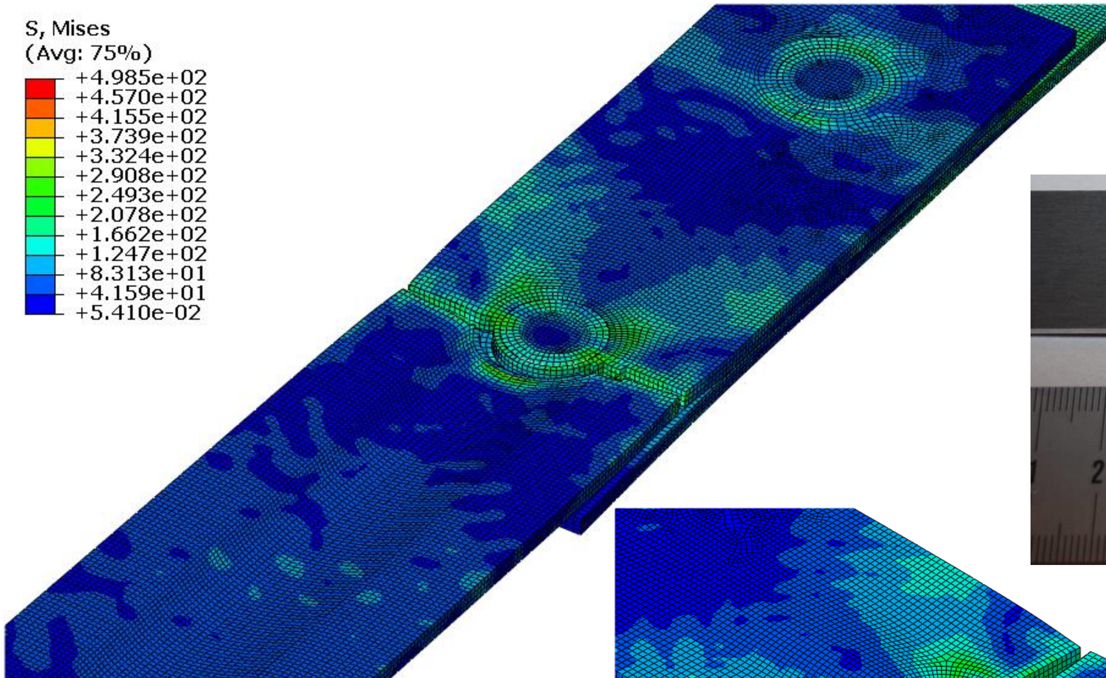


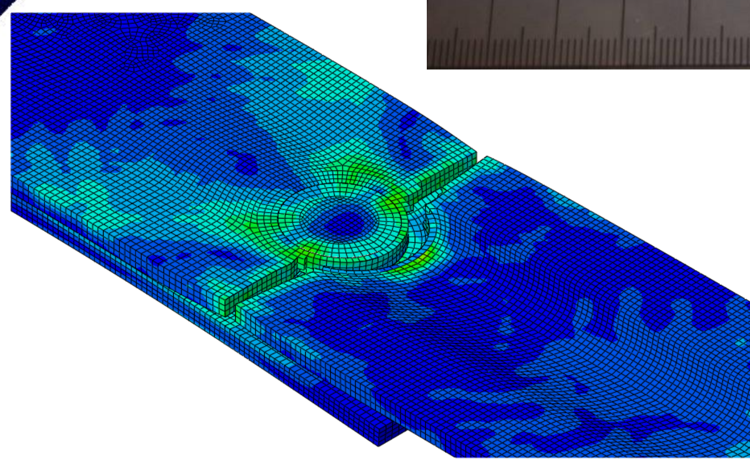
Part	Nodes	Elements C3D8R
HLT1.6-9-2D-5D-2	335145	265951
HLT1.6-9-2D-5D-3	350598	269474

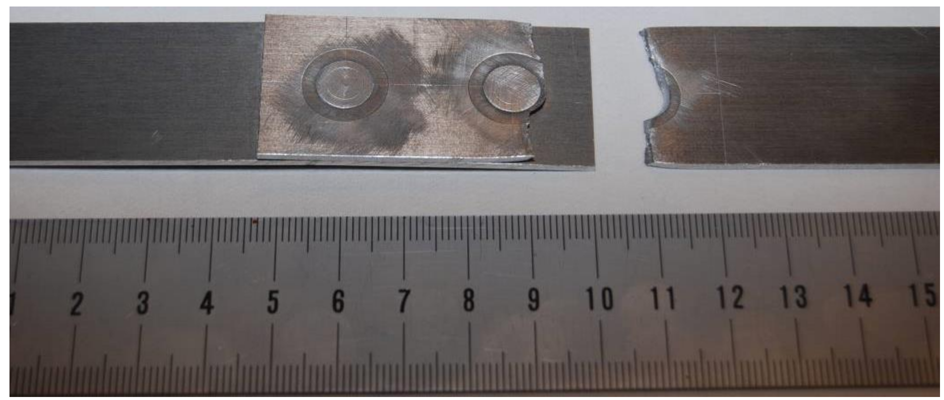
Numerical Analysis: Results

Lap shear model, HLT1.6-9-2D-5D-2

Fracture Mode ✓ Sheet failure







Numerical Analysis: Results

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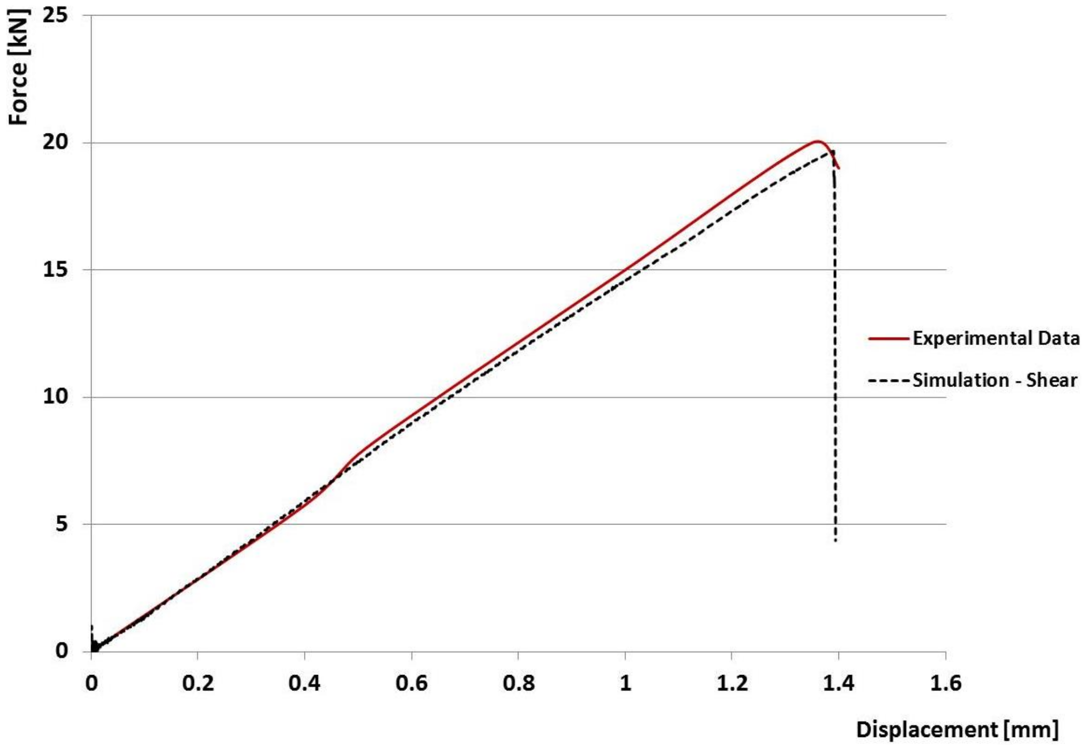
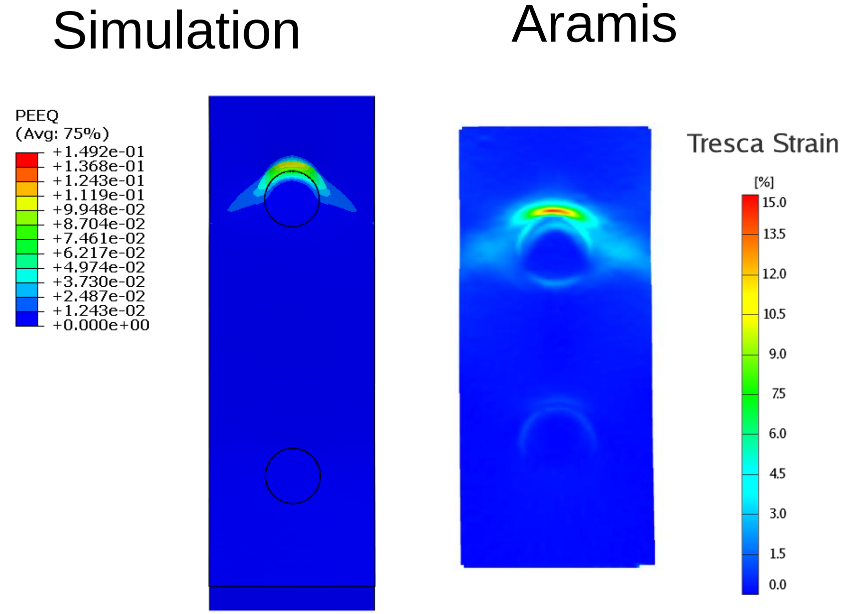
Lap shear model validation



Lap shear model, HLT1.6-9-2D-5D-2



Coherent agreement between experimental and computational model

Numerical Analysis: Model Validation

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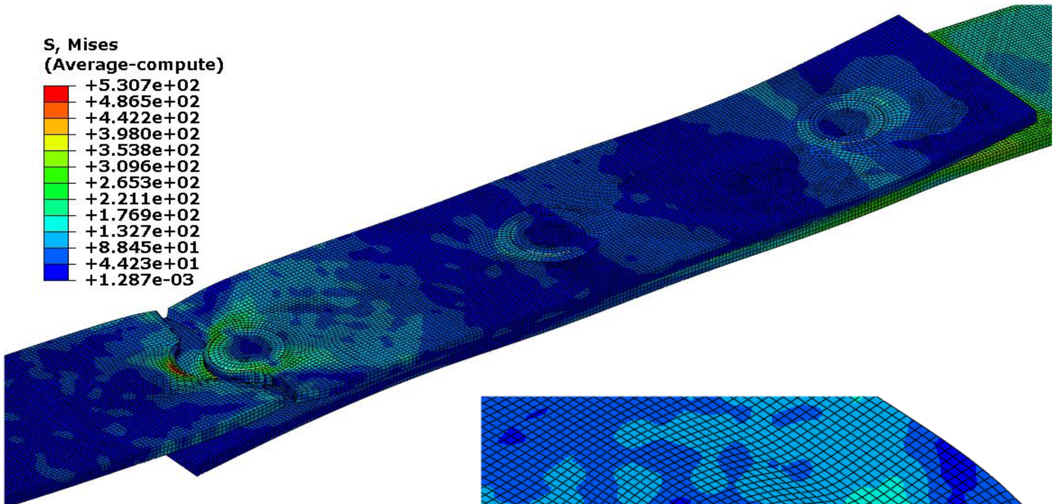
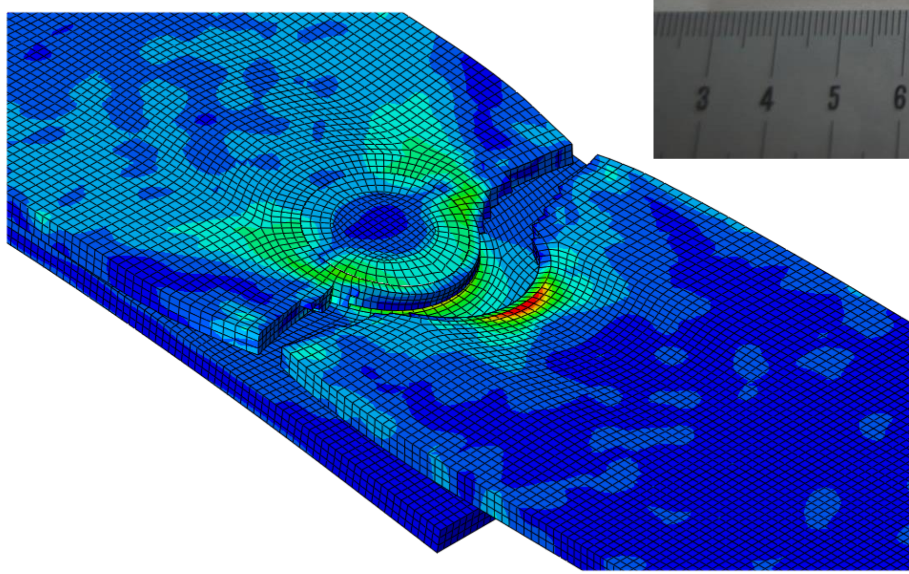
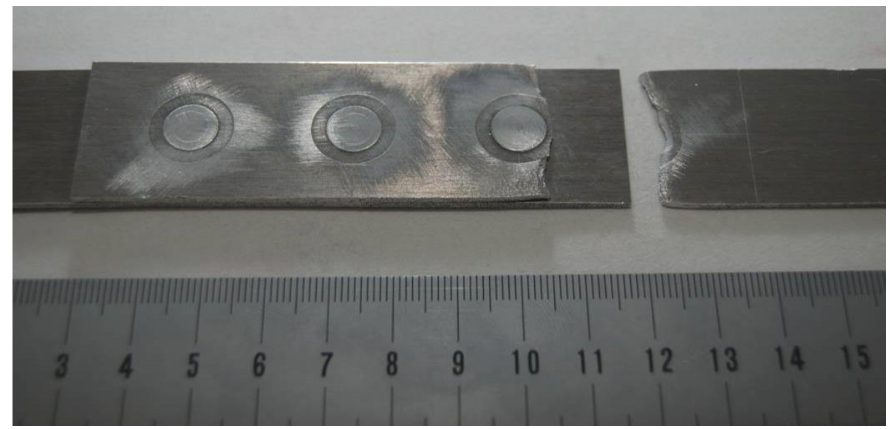
Fracture Mode ✓ Sheet failure

Lap shear model, HLT1.6-9-2D-5D-3







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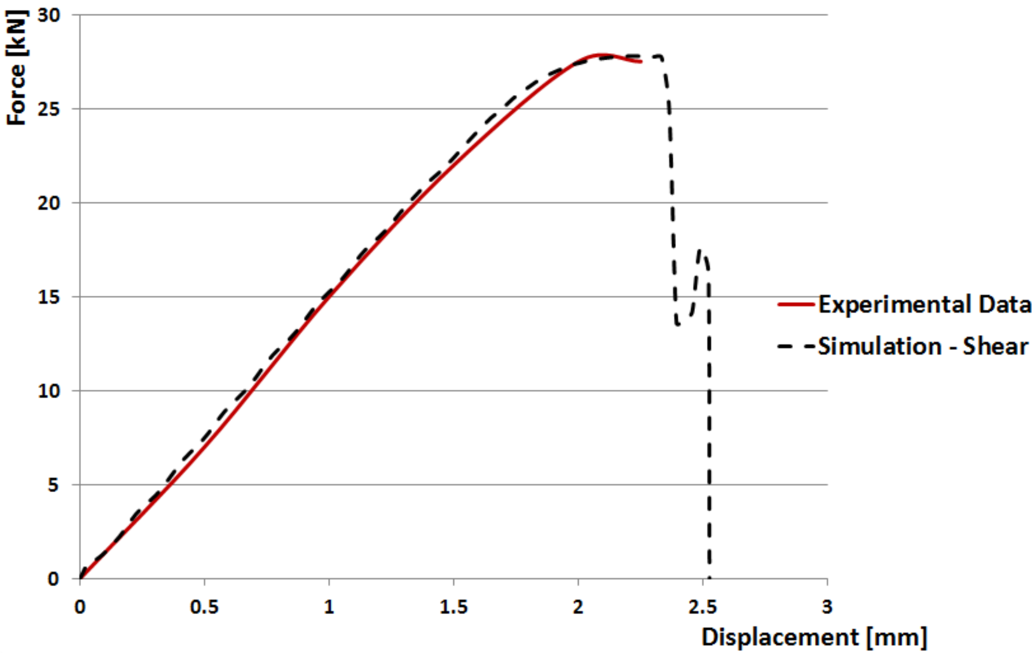
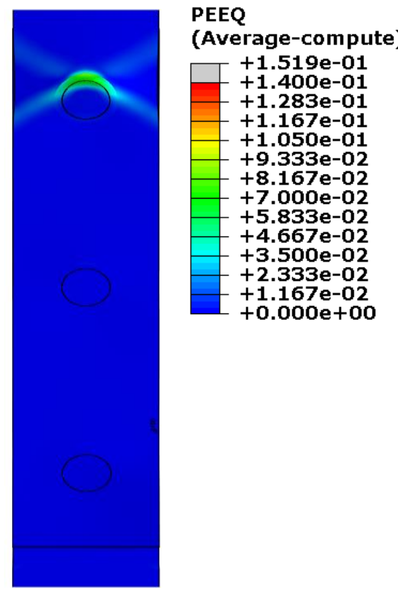
Numerical Analysis: Model Validation

Lap shear model, HLT1.6-9-2D-5D-3

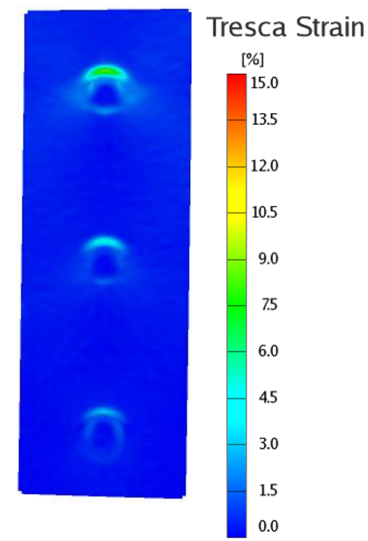
Lap shear model validation

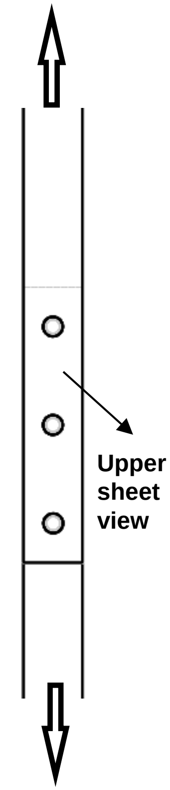


Simulation



Aramis

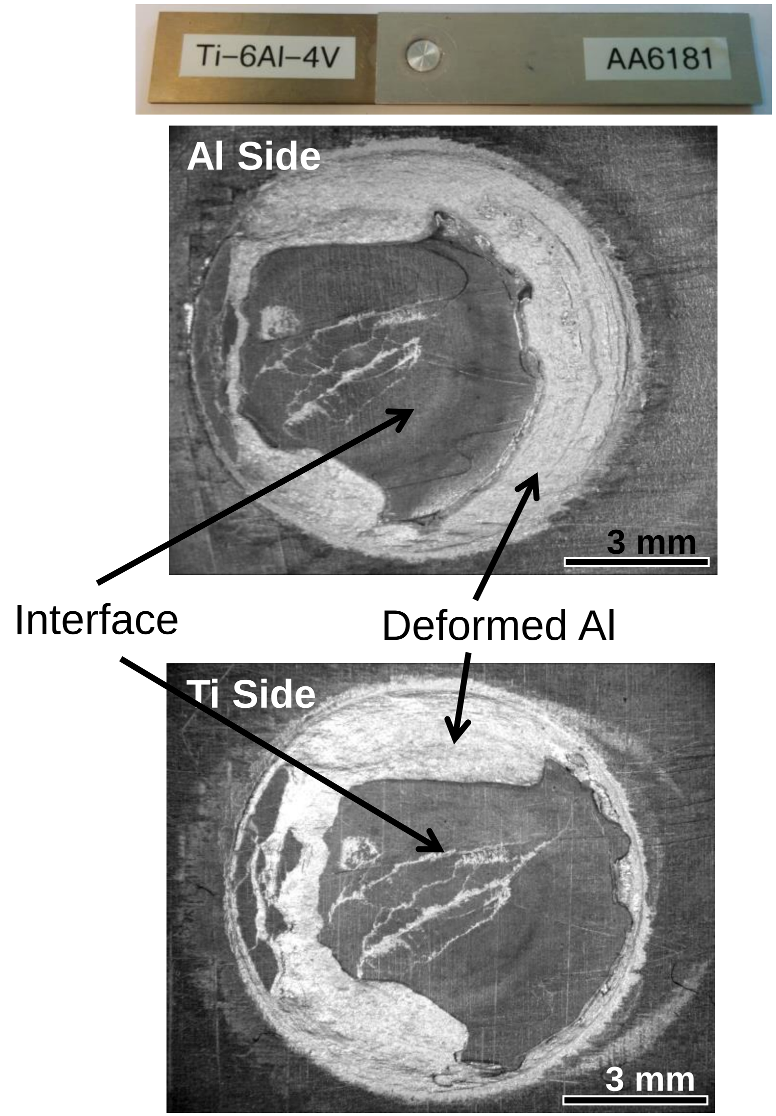


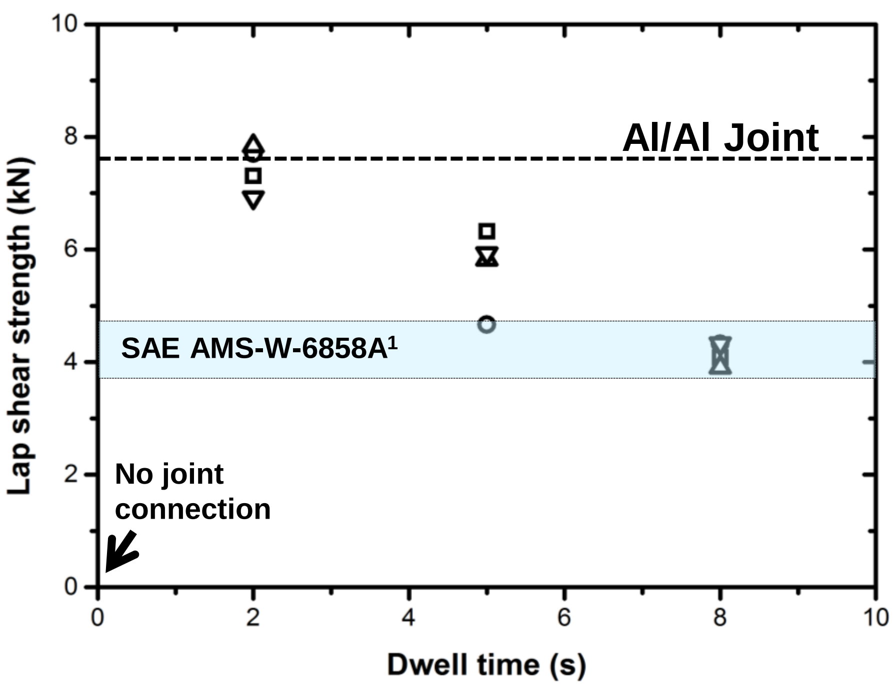


Coherent agreement between experimental and computational model

Results AA5754 / Ti64 Dissimilar Joints

- AA5754 (2 mm) and Ti-6Al-4V (2.5 mm)
- Rotational speed: up to 2500 rpm
- Plunge depth: up to 1.8 mm
- Dwell time: 0 – 8 s
- The mechanical properties of Al/Ti weld is comparable with Similar A/Al joint





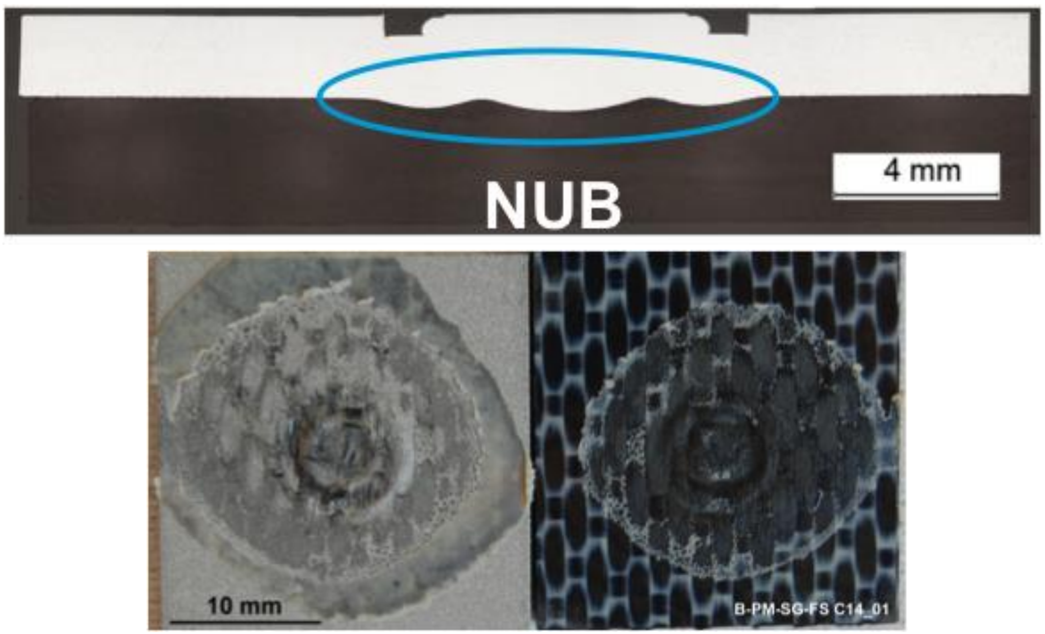
[1]SAE AMS-W-6858A: Standard for "Welding, Resistance: Spot and Seam"

Results AA2024-T351 / CF-PPS

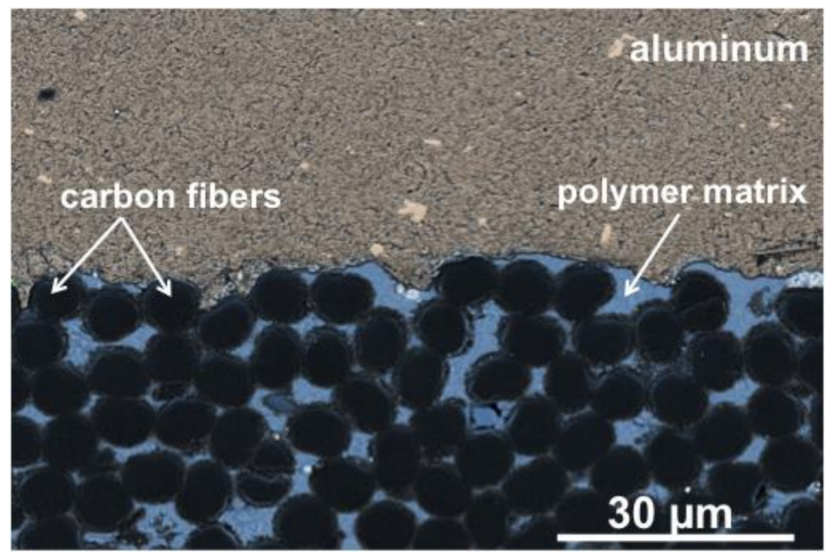
AA 2024-T351 / CF-PPS

- Adhesive forces (consolidated polymeric matrix)
- Macro- (deformation of metallic partner) and micro-mechanical anchoring (crevice and pore filling as well as fiber entrappment at the interface)

Macro-mechanical Anchoring



Micro-mechanical Anchoring

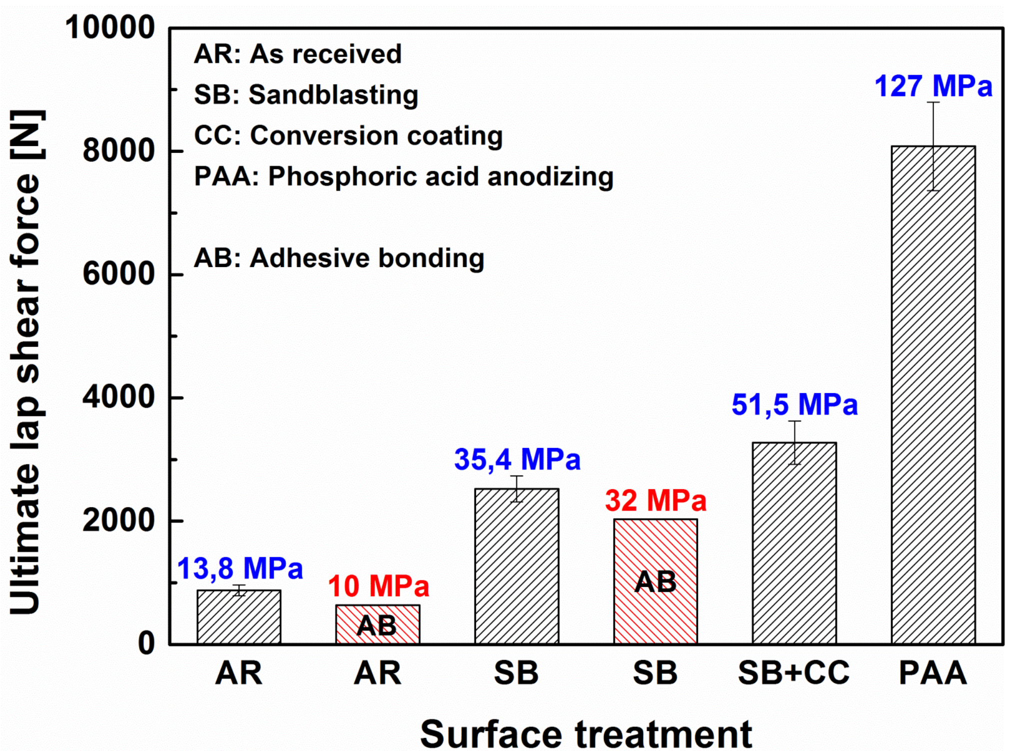


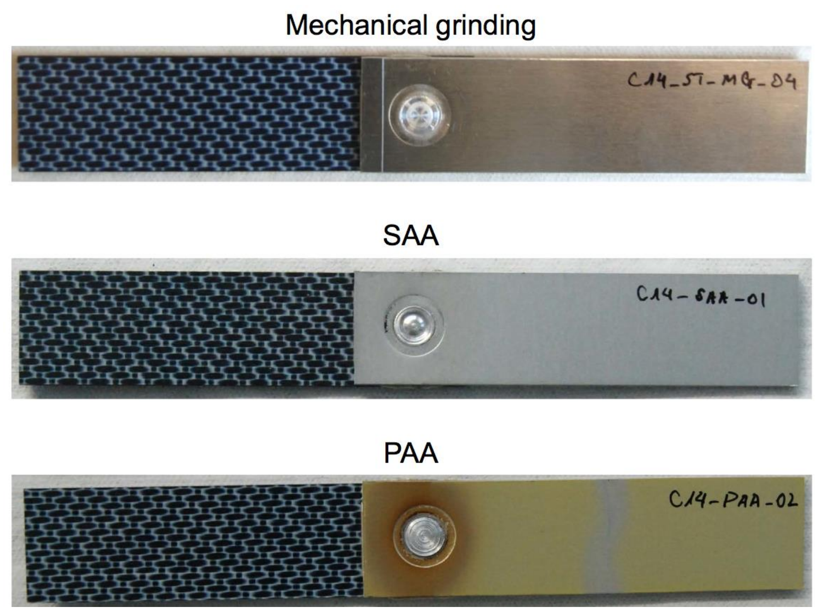
Results AA2024-T351 / CF-PPS

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Lap Shear Strength: Al 2024-T351 / CF-PPS

- High mechanical strength (equal or better performance than adhesively bonded joints)
- Appropriate for all common metal surface treatments in aircraft and automotive

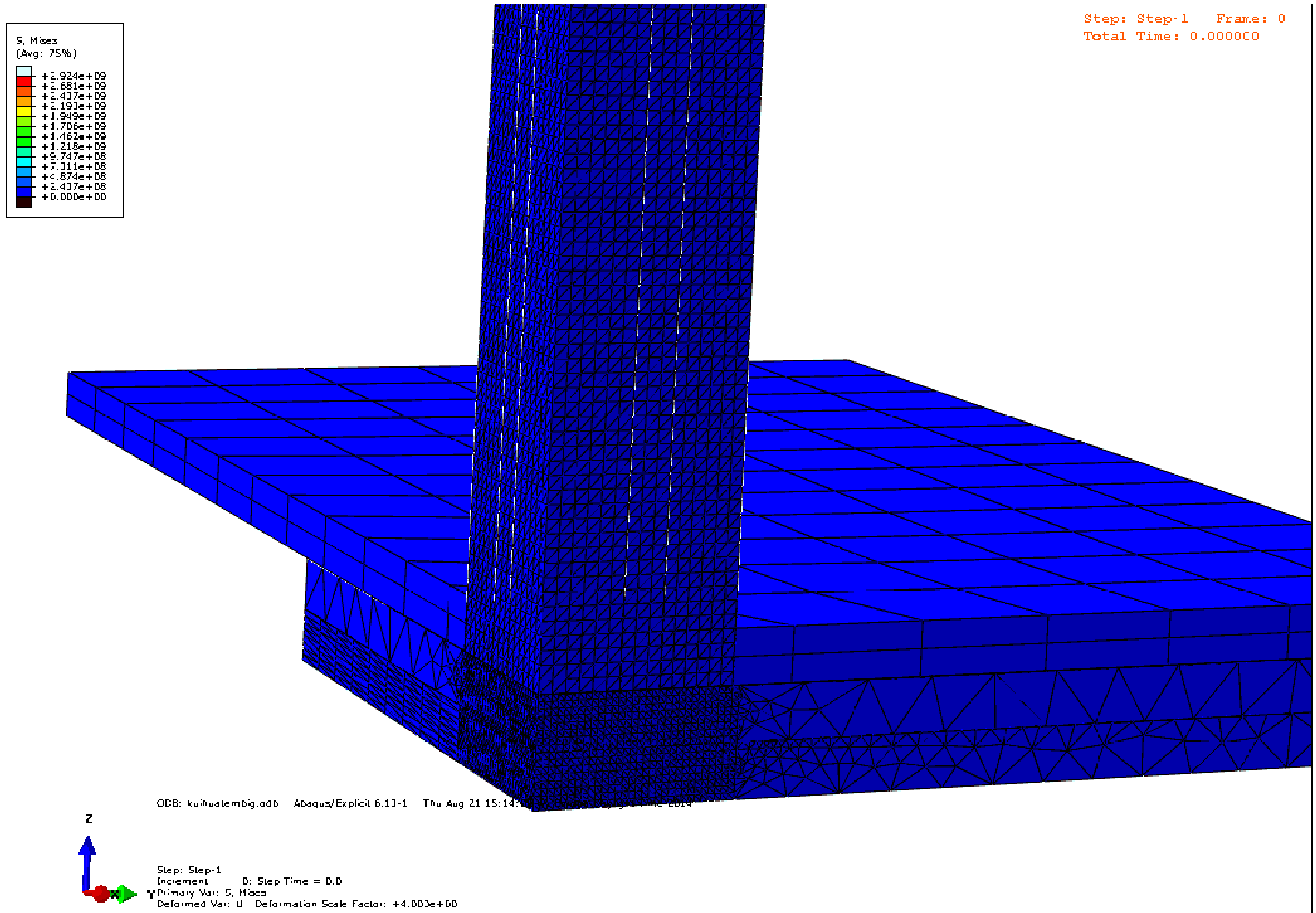




Final Remarks

- Robust process parameters to join Al aircraft alloys have been developed based on sound statistical basis
- The shear stress levels achieved fulfil in principle the requirements of the aircraft industry under static loading
- The lap shear models developed in this work are able to test different geometric arrangements with accuracy
- Damage tolerance relevant allowables should be determined to support the introduction of this technology in primary structural elements
- Understanding of the thermomechanical phenomena should enhanced by modelling studies
- IIW WG-B4 Standardisation Committee on Friction Based Spot Welding Processes

Outlook: Thermo-Mechanical Process Model



Outlook: Group Sponsored Project

Damage Tolerance Behaviour

- To measure crack initiation and propagation data that can characterise and control the structural integrity and durability of spot welded joints (single spot weld).
- To conduct fatigue tests on welded lap joints (multiple spot-welds) under realistic service loading spectra.
- To develop a single spot-weld model to characterise the influence of multi-material properties, residual stress and failure modes due to typical defects and stress concentration features.
- To develop a multiple spot-welds model for predicting the integrity, durability and damage tolerance of spot welded joints.
- To establish design method and parameters for service durability and damage tolerance of "spot welded fasteners", and to conduct sensitivity studies of such parameters.

Fabrication Aspects

- Development / adaptation of the process technology for tartaric acid anodized (TSA) and/or boric sulphuric acid anodizing (BSAA) treaded surfaces
- Development / adaptation of the process technology for joints with sealants
- Validation of corrosion resistance in a reference environment
- Evaluation/development of NDT techniques for detection of manufacturing and in service defects