GREAT DESIGNS IN STEEL

PRACTICAL METHODS FOR AVOIDANCE OF LIQUID METAL EMBRITTLEMENT IN RESISTANCE SPOT WELDS OF ADVANCED HIGH STRENGTH STEELS

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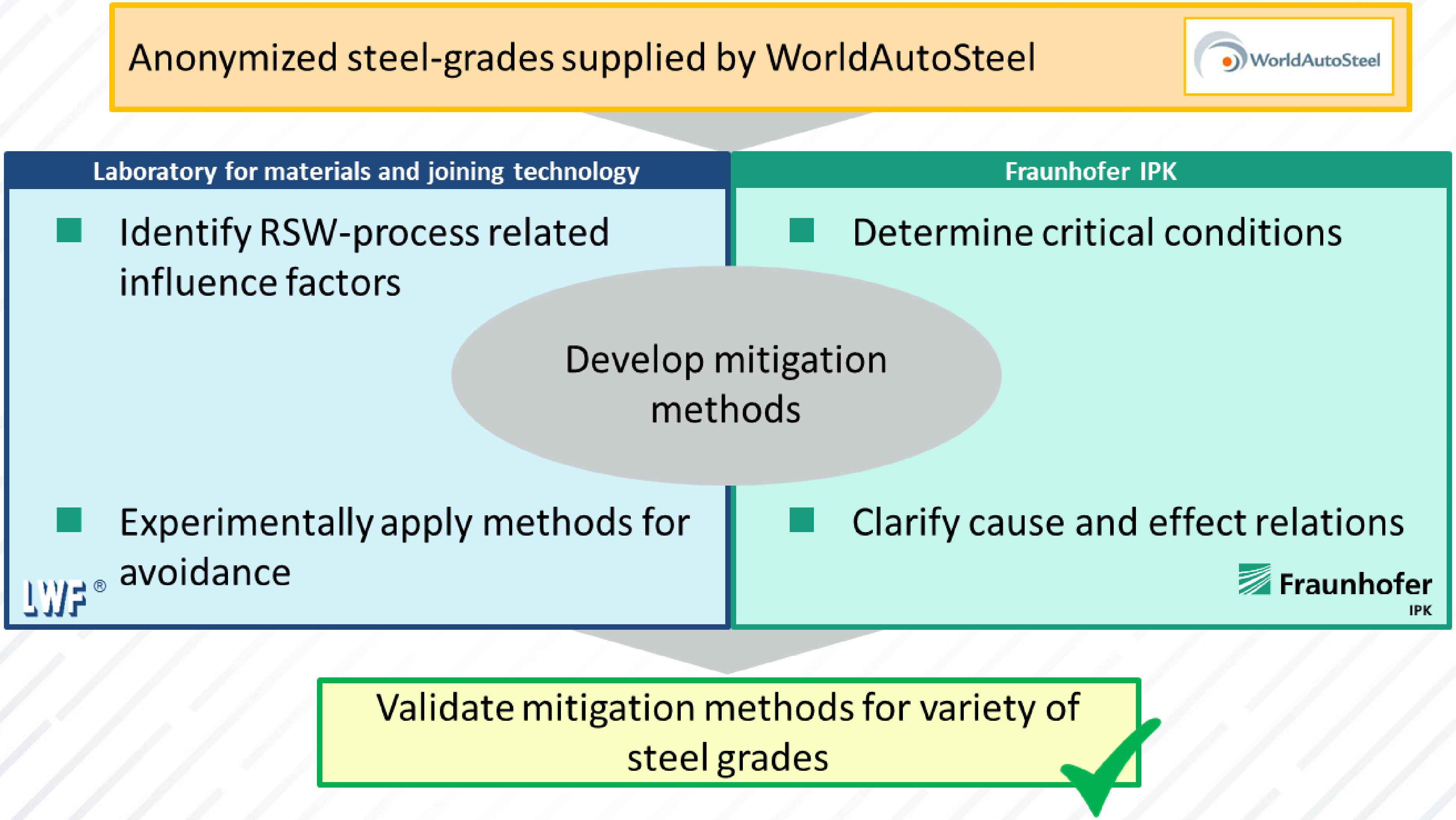
TEAM AND ORGANIZATION



Anonymized steel-grades supplied by WorldAutoSteel

Laboratory for materials and joining technology

- Identify RSW-process related influence factors
- Experimentally apply methods for avoidance

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- Determine critical conditions
- Clarify cause and effect relations

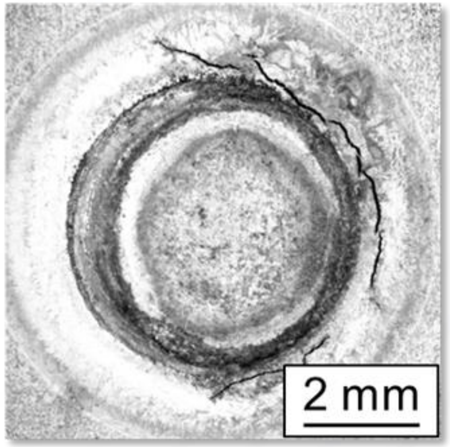
Develop mitigation methods

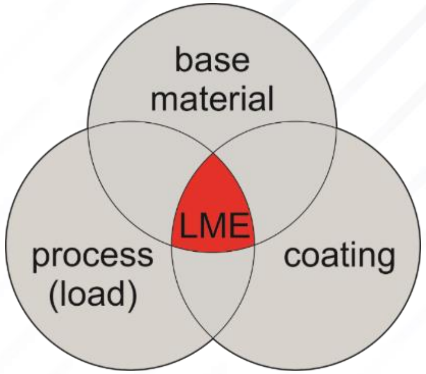
Validate mitigation methods for variety of steel grades ✓

LIQUID METAL EMBRITTLEMENT

What is Liquid Metal Embrittlement (LME)?

- Infiltration of liquefied zinc coating into grain boundaries
- Causing cracking during resistance spot welding (RSW)

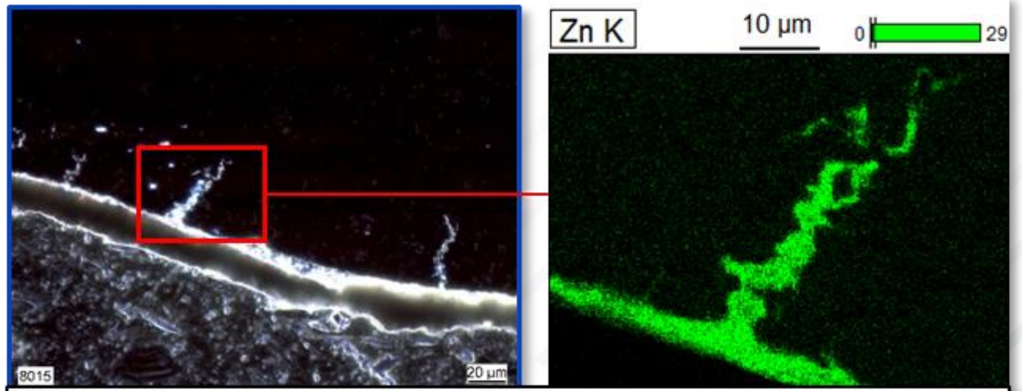




Focus of research project

- Identification of process related influence factors
- Combination of experimental and simulative approach

→ **Develop and experimentally validate avoidance strategies**



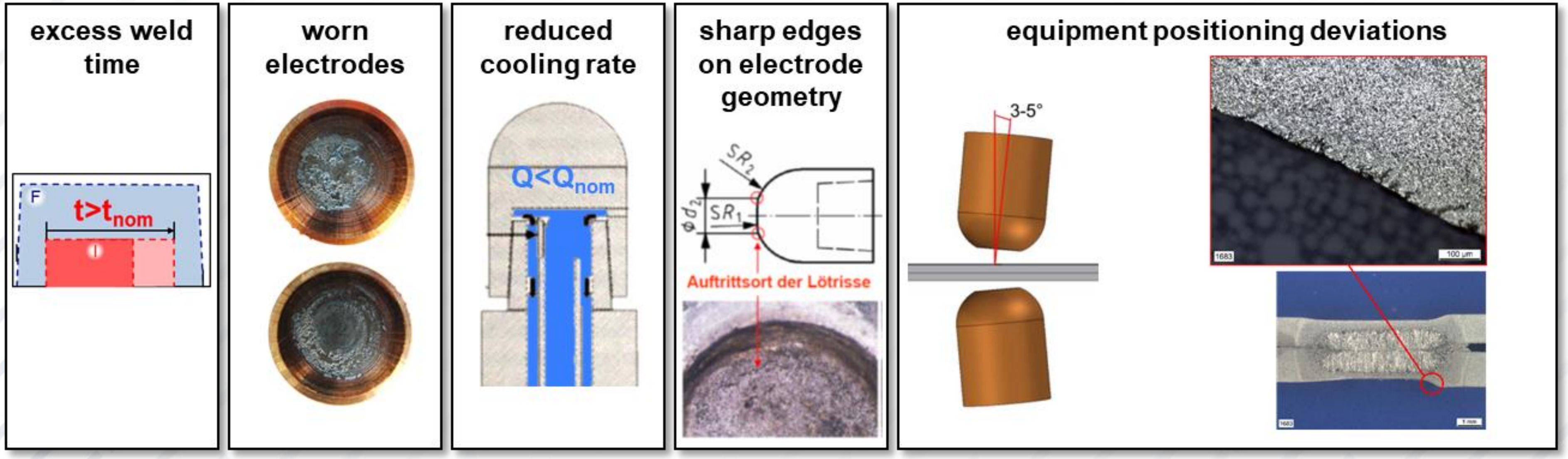
LME related crack

INFLUENCE FACTORS

OVERVIEW

Combining of steel grades to wide variety of material-thickness-combinations (MTC)

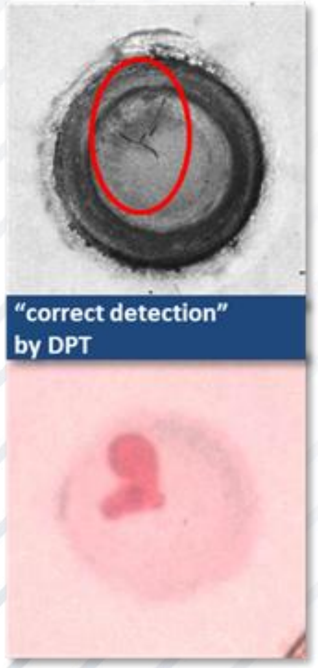
- Welding process according to ISO 18278-2
  - Without process deviations no cracking was observed
- Process deviations as influence factors on LME formation
  - Majority of process deviations caused light cracking

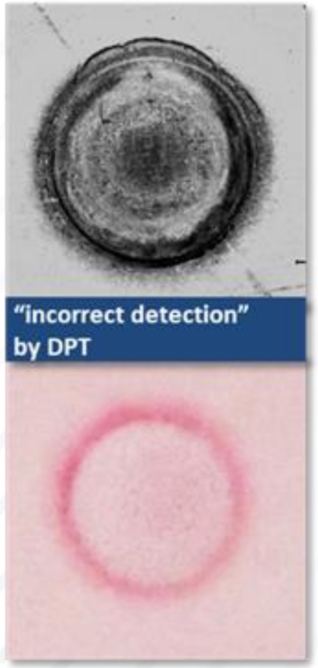


→ Confirmed LME as cracking mechanism by SEM/EDS analysis and de-zincing of sheets

INFLUENCE FACTORS
EXPERIMENTAL ANALYSIS TECHNIQUES

- Dye-penetrant testing (DPT) may lead to incorrect results (false crack detections)
- Local removal of zinc after welding enables uncovering of zinc covered cracks
  - Basis for quantification of cracking intensity
- Local removal of zinc before welding allows for complete LME avoidance
  - Creation of crack free reference specimen


“correct detection” by DPT


“incorrect detection” by DPT


Coating removed post welding

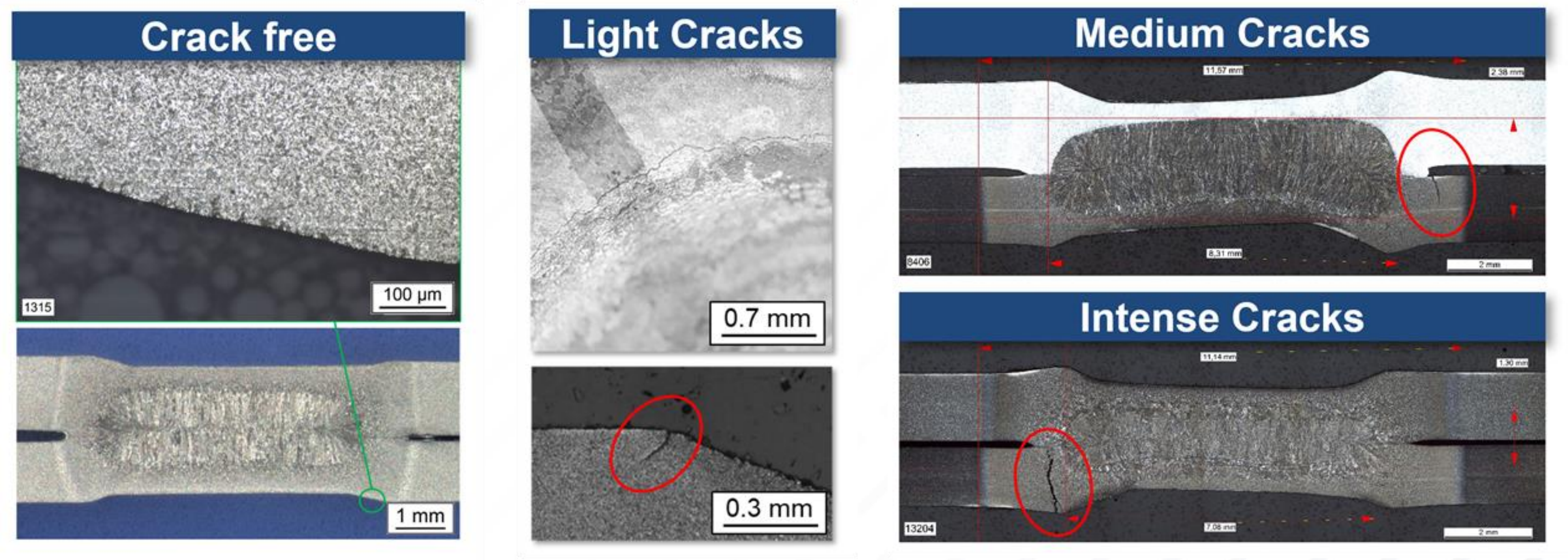

Coating removed before welding

INFLUENCE FACTORS
CRACK INTENSITIES

Wide range of crack intensities investigated…

- Thinner MTCs: crack free welds even on extreme weld setups (e.g. 4x weld time)
- Thicker MTCs: Light cracking for most process deviations

  → Medium to intense cracking only as consequence of elongated weld time
- Reproducible crack formation at highly deformed spot weld areas

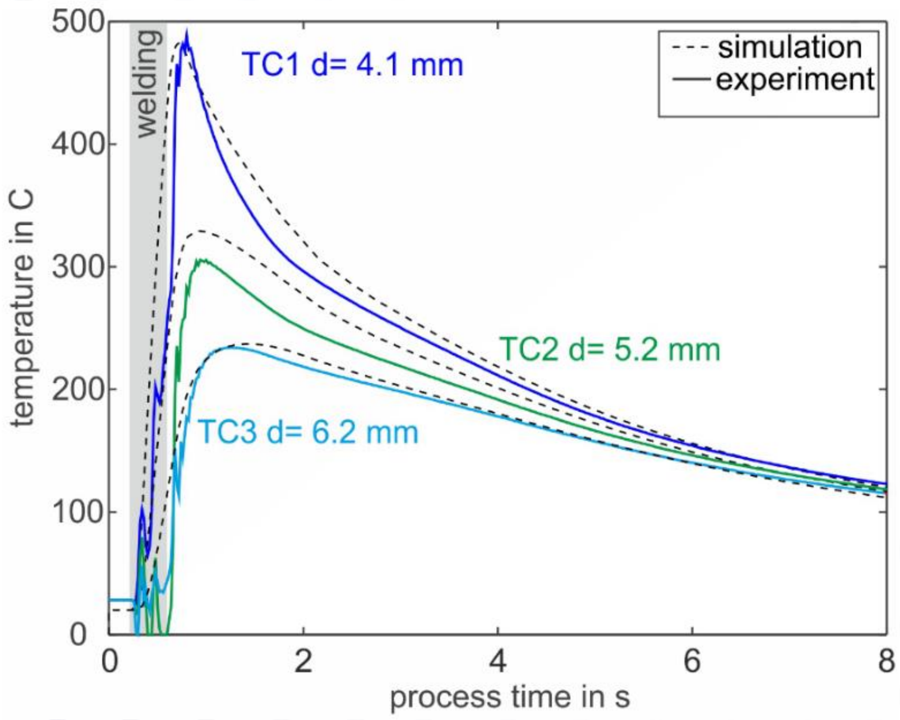


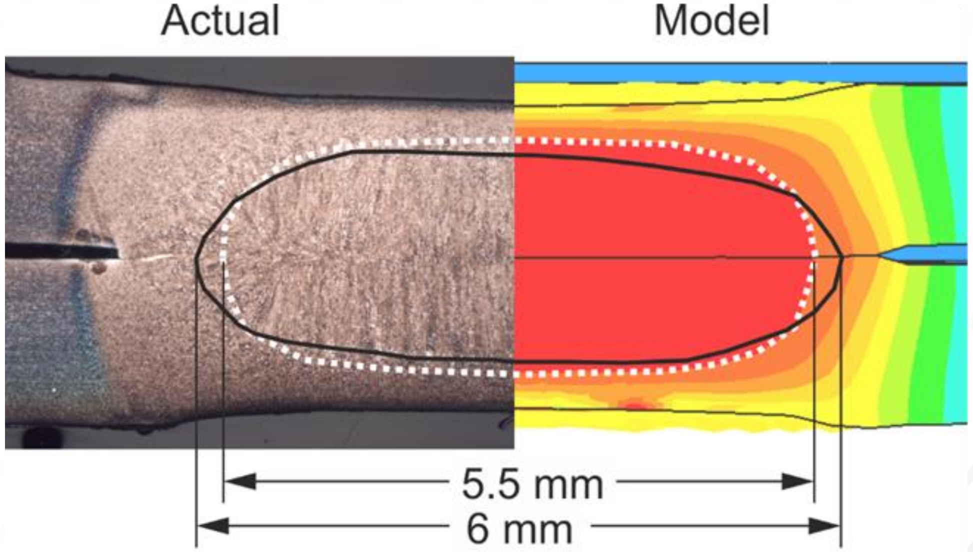
→ Identified LME influence factors: Sheet thickness and energy input

INFLUENCE FACTORS

SETUP OF SIMULATION MODEL - VALIDATION

- 3-D electro-thermo-mechanical simulation model
- Temperature dependent material properties scaled from literature
- Validation via surface temperature measurements and cross-sections





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INFLUENCE FACTORS

SETUP OF SIMULATION MODEL – TEMPERATURE DEVELOPMENT

- Simulation results match experimental temperature flow and nugget size
- Small deviations are acceptable because of…
  - Experimental scatter, simulation simplifications and assumptions

→ Predictive use of the simulation possible

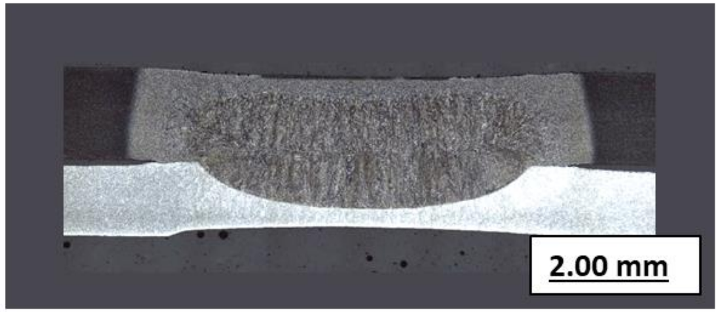
INFLUENCE FACTORS

SHEET THICKNESS

Cracking is more likely to occur when welding thick sheets at I_{max}

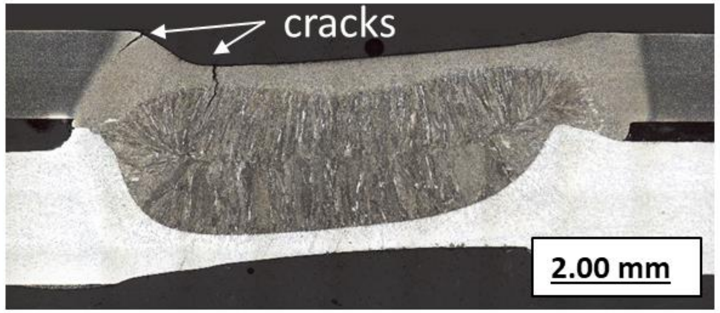
- 1.34 mm DP1200 onto 1.00 mm mild steel → No cracking
- 1.34 mm DP1200 onto 2.00 mm mild steel → Reproducible cracking

Top layer: 1.34 mm DP1200
Bottom layer: 1.00 mm mild steel



Force: 3.5 kN, Time: 240 ms
I_{min}: 6.2 kA / I_{max}: 8.4 kA
d_n at I_{max}: 5.70 mm

Top layer: 1.34 mm DP1200
Bottom layer: 2.00 mm mild steel



Force: 4.0 kN, Time: 320 ms
I_{min}: 7.5 kA / I_{max}: 9.4 kA
d_n at I_{max}: 6.75 mm

→ Different welding parameters and nugget dimensions

INFLUENCE FACTORS

SHEET THICKNESS

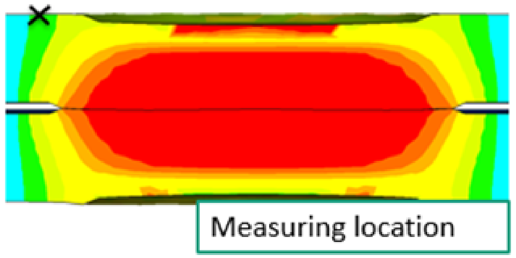
For thick mild steel case…

- Energy input ~60% higher due to welding parameters
- Significant duration in ductility trough (700 °C - 900 °C)

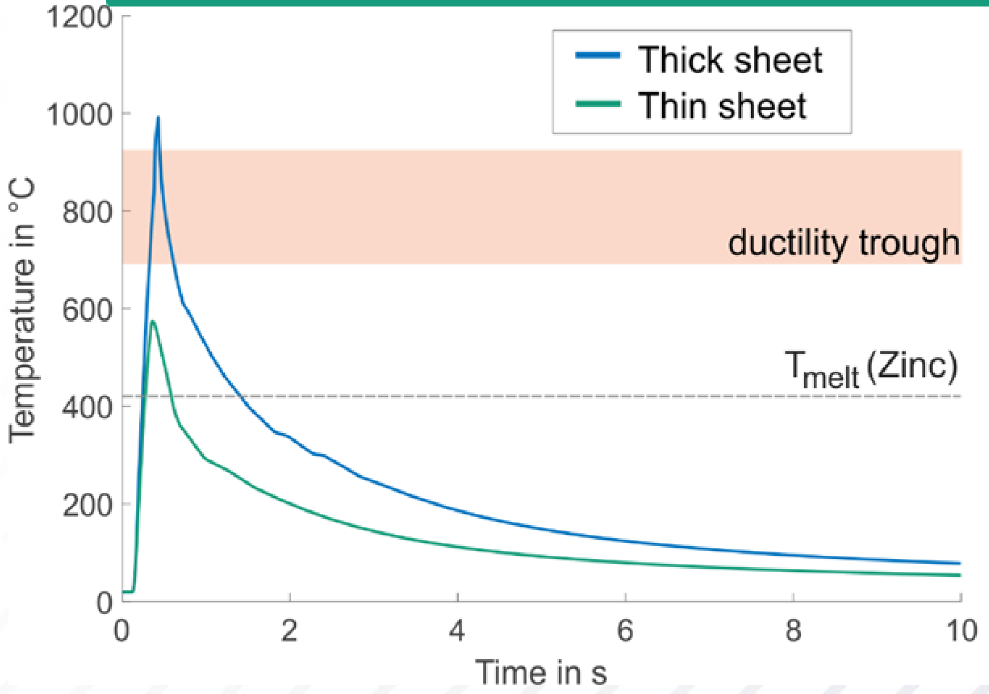
→ Thick case stays ~4.5 times longer at critical zinc temperatures

→ **MTCs requiring more energy-input have an increased LME-susceptibility**

→ **Thicker MTCs require longer time for heat dissipation (increased cracking risk)**



Temperature over welding process

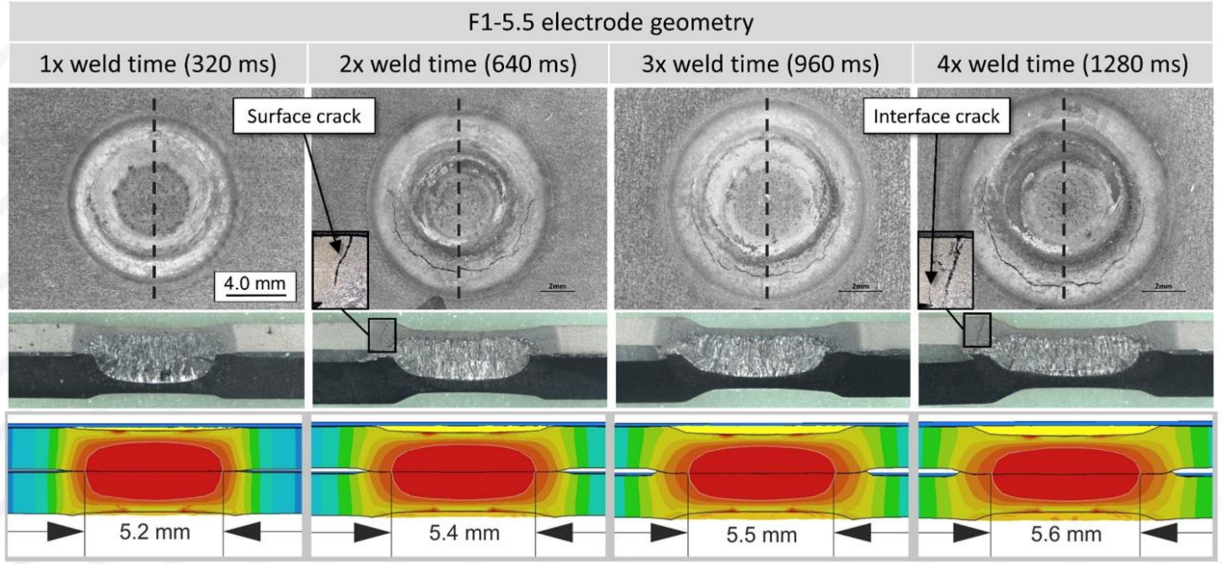


INFLUENCE FACTORS

HIGH ENERGY INPUT

For extension of weld time…

- Observed cracking intensity increases
- Indentation and sheet separation intensify
- Nugget is flattened – no significant increase in nugget volume



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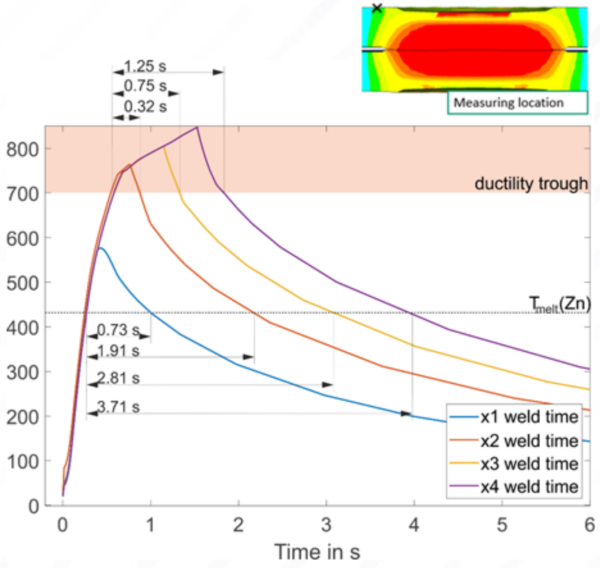


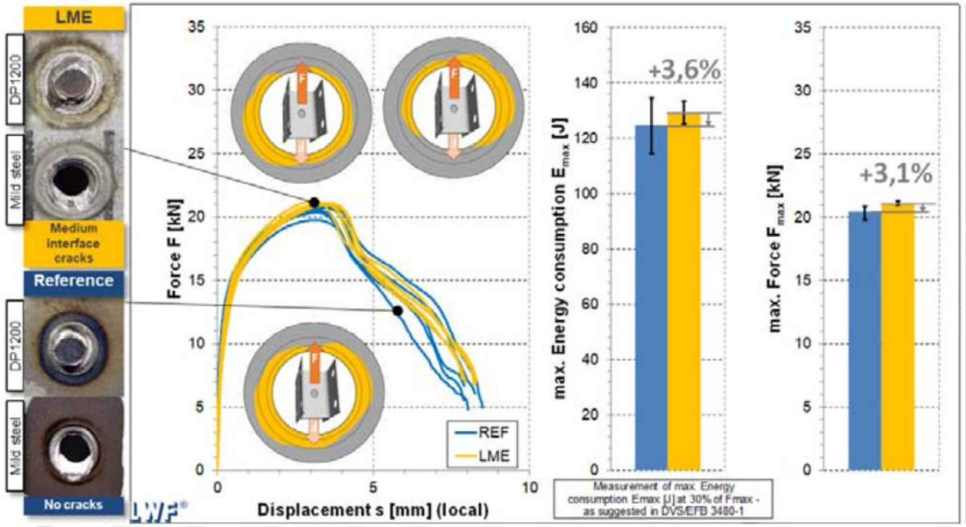
→ Elongated weld times increase exposure to critical temperatures

→ Enforcement of high intensity LME cracks for destructive testing:
Extreme heat-input by prolonging of weld time on thicker MTCs

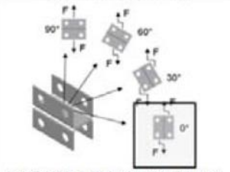
MECHANICAL STRENGTH IMPACTS OF LME

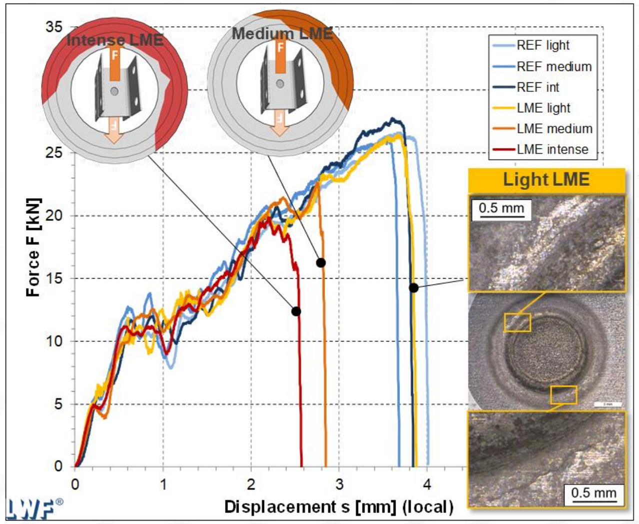
CT-Scan supported testing of 3 crack intensities…

- Intense cracks (> 50 % sheet thickness) → significant impact on mechanical joint strength
- Medium cracks (20 – 50 % sheet thickness) → impact depending on load type and MTC
- Small cracks (< 20 % sheet thickness) → no impact on mechanical joint strength

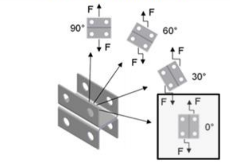


Testing method	Quasi-static load
Testing speed	10mm/min
Displacement registration	GOM (optical)
Joining technique	Resistance Spot Welding
Material top	DP1200 1.58 mm
Material bottom	Mild steel 2.00 mm
Number of specimen	n = 5
Specimen geometry	LWF-KSII specimen (IW 34mm)





Testing method	Crash load
Testing speed	1.5 m/s
Displacement registration	GOM (optical)
Joining technique	Resistance Spot Welding
Material top	DP1200 1.34 mm (8317-type)
Material bottom	MS1400 1.50 mm (1520-type)
Number of specimen	representative specimen shown
Specimen geometry	LWF-KSII specimen (IW 34mm)



No impact of medium cracks:
interface cracks, shear-tensile quasi-static load, DH1200 with mild steel

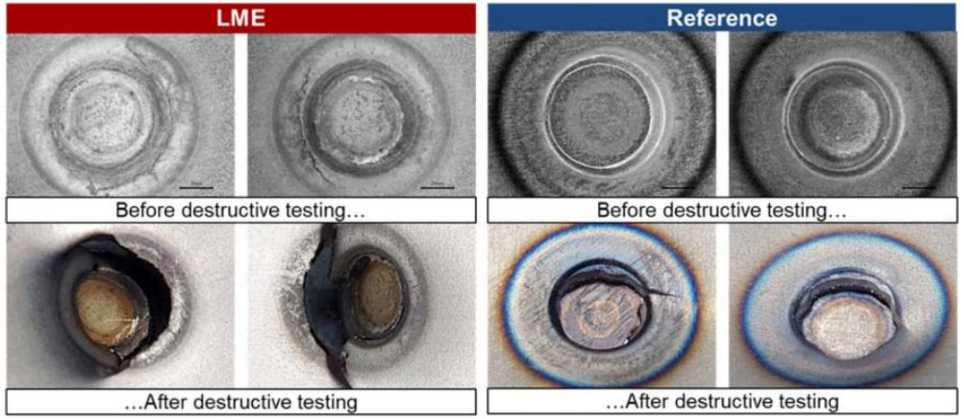
Impact of medium cracks:
surface cracks, shear-tensile crash load, DH1200 with MS1400

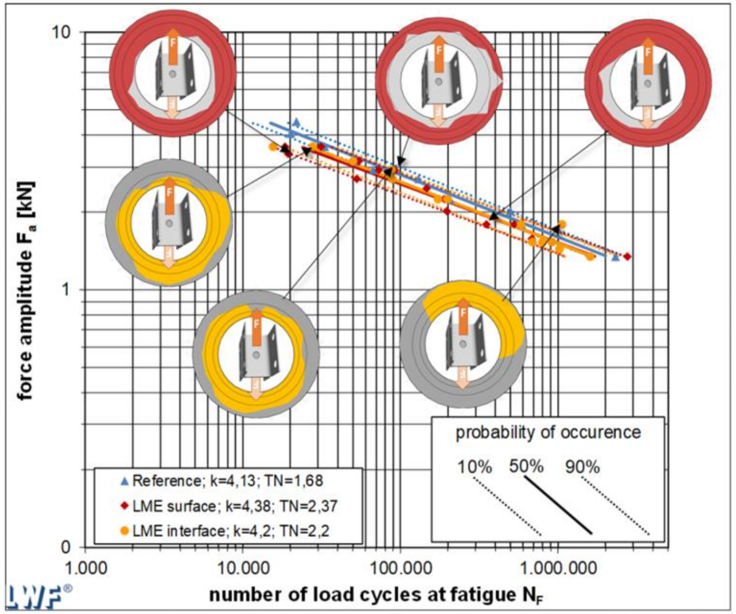
MECHANICAL STRENGTH IMPACTS OF LME

CT-Scan supported testing of 3 crack intensities…

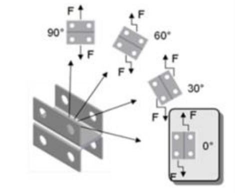
- Intense cracks (> 50 % sheet thickness)

→ No significant impact on fatigue life





testing method	cyclic load
testing frequency	f = 63 Hz
load ratio	R = 0,1
abort criterion	N = 2.000.000 / Δf = 5 Hz
joining technique	resistance spot welding
material top	DP1200 1.34mm
material bottom	mild steel 2.00mm
specimen geometry	



LWF-KSII specimen (IW 34mm)

Comparison of fracture pattern during quasi-static destructive testing of LME-afflicted and LME-free spot welds

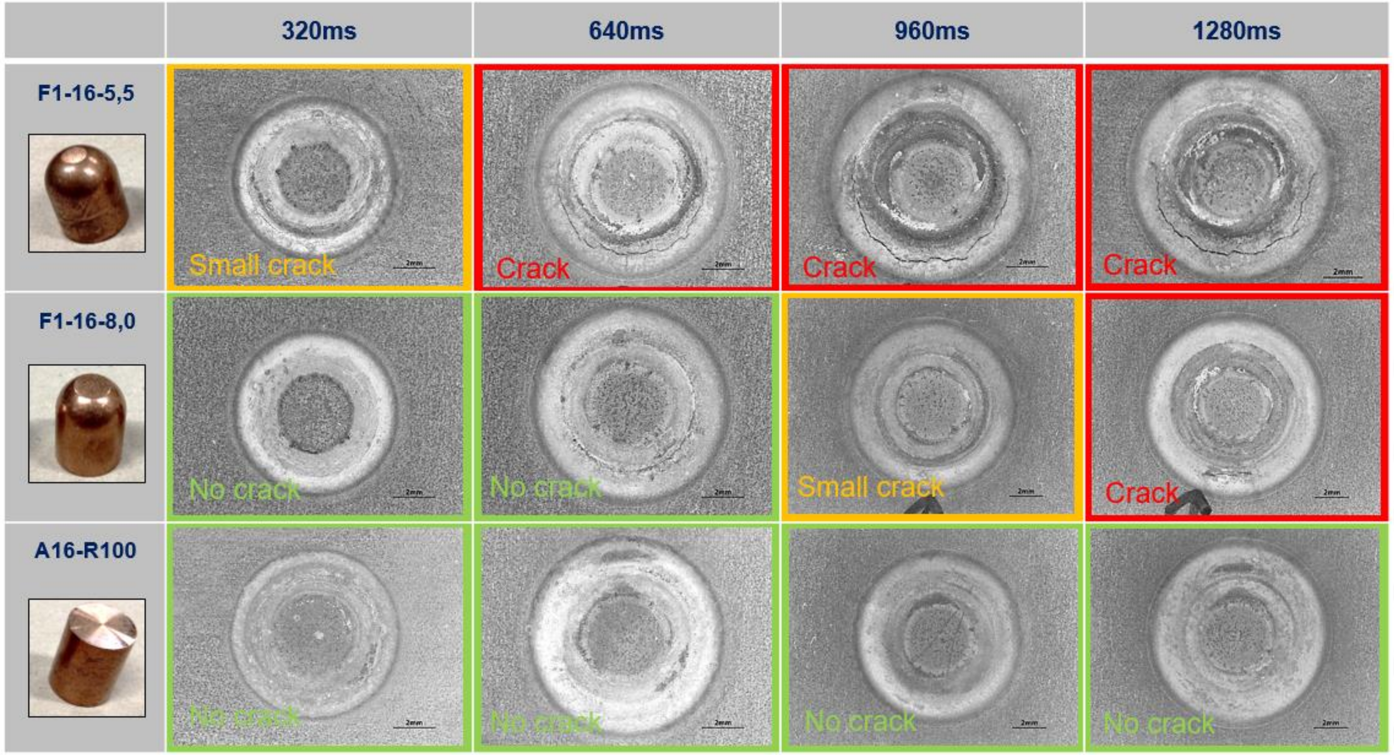
No impact of intense cracks:
Surface / interface cracks, shear-tensile cyclic load, DH1200 to mild steel

CONTROL AND PREVENT LME

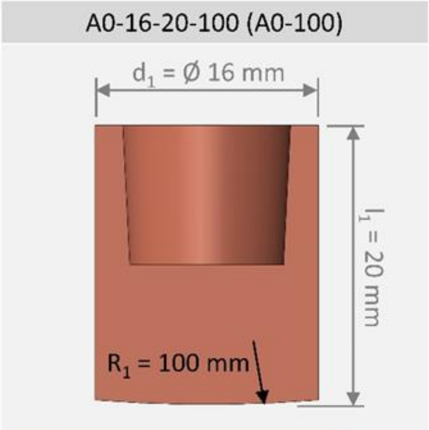
ADAPTION OF ELECTRODE GEOMETRY

Experimental setup

- ISO5821-caps: F1-5.5, F1-8.0, A0-R100
- Similar nugget diameter: current +5% for F1-8.0 and +10% for A0-R100



	320ms	640ms	960ms	1280ms
F1-16-5,5	Small crack	Crack	Crack	Crack
F1-16-8,0	No crack	No crack	Small crack	Crack
A16-R100	No crack	No crack	No crack	No crack



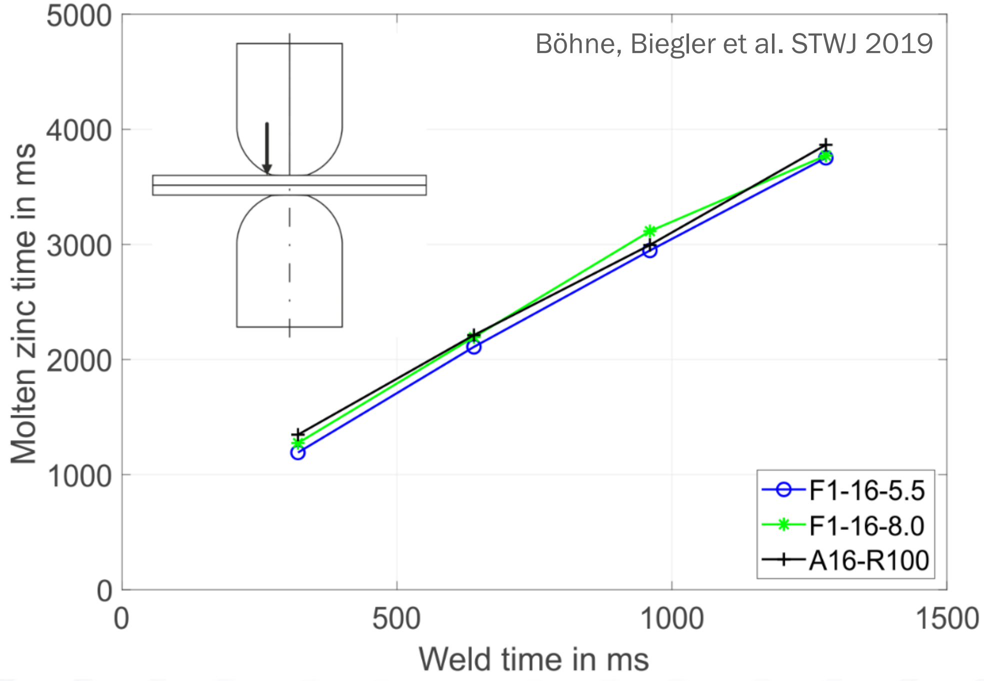
Flat-headed electrode cap

CONTROL AND PREVENT LME

ADAPTION OF ELECTRODE GEOMETRY

FE-Analysis of temperature development

- The simulated molten zinc time is similar for all electrode caps at edge of nugget
- The temperature exposure cannot explain differing LME susceptibility



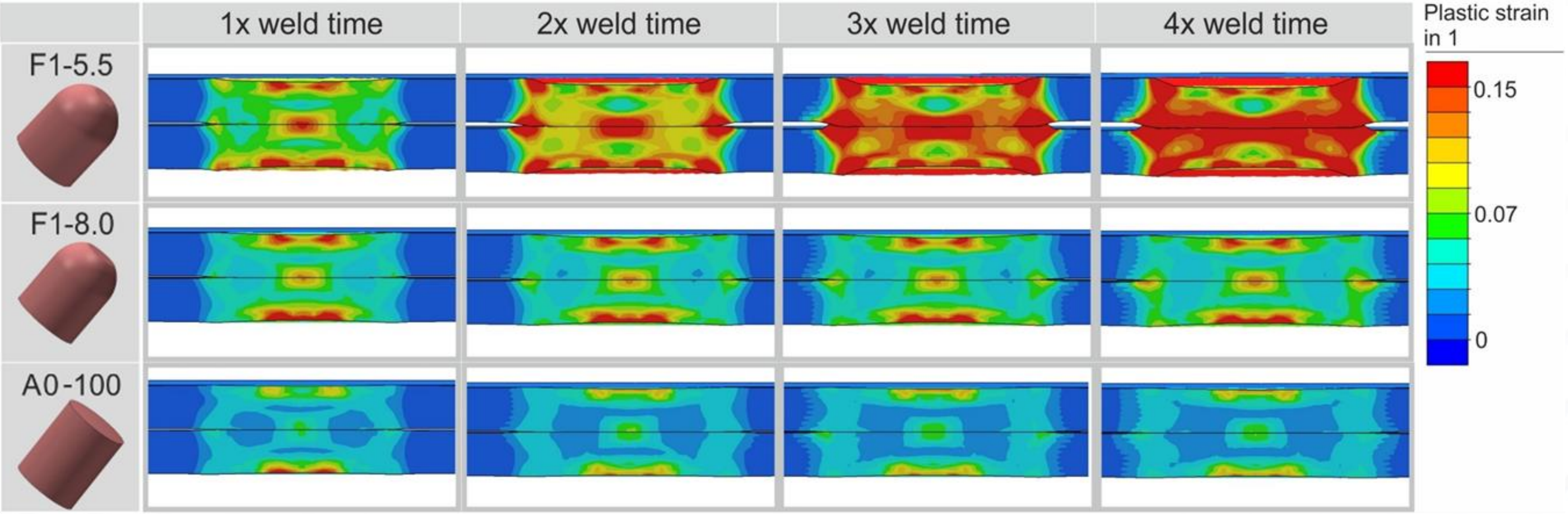
→ Next step: Consideration of plastic strain at the indentation

CONTROL AND PREVENT LME

ADAPTION OF ELECTRODE GEOMETRY

FE-Analysis of plastic strain development

- Significantly increased plastic strain for 5.5 mm electrode cap
- The strain remains constant for F1-8.0 and A0-R100 electrode



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→ Electrode caps with large working planes reduce LME susceptibility significantly

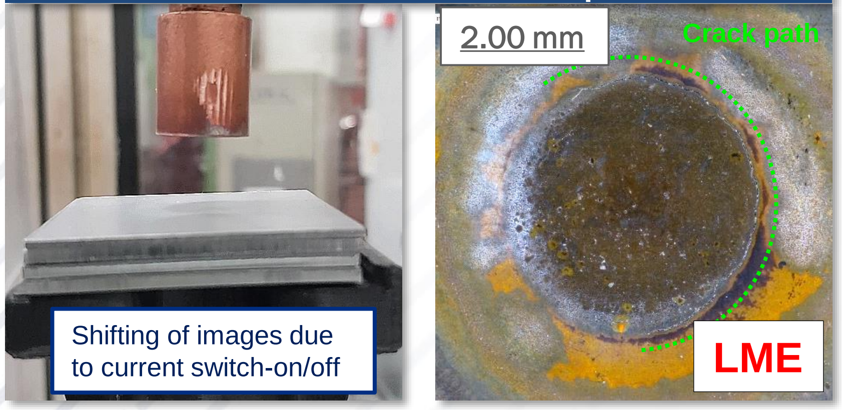
CONTROL AND PREVENT LME

ADAPTION OF HOLD TIME – EXPERIMENT

Comparison of two high heat input welding processes

- Combination of 1.58 mm DH1200 with 1x and 3x layer of 2.00 mm mild steel
- Welding with cap type A0 (flat) at 4x weld time and I_{max}
- Hold times varied between 10 ms, 200 ms, 800 ms
- Focus on behavior after electrode lift-off

200 ms hold time → Cracked spot weld



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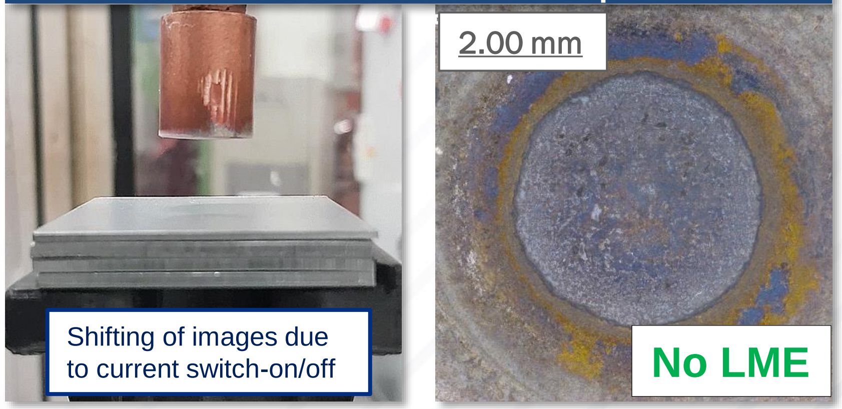
800 ms hold time → Crack free spot weld



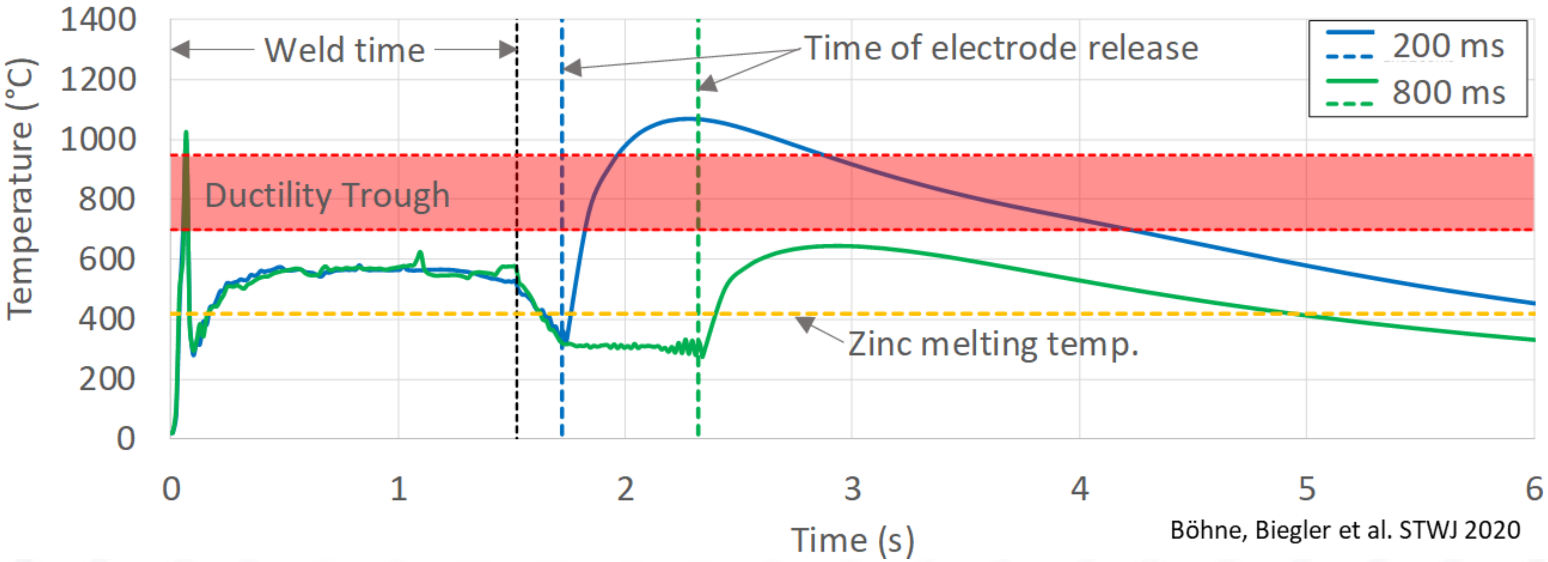
Shifting of images due to current switch-on/off

→ Prevention of LME cracks by adaption (extension) of hold time?

CONTROL AND PREVENT LME

ADAPTION OF HOLD TIME – FE-ANALYSIS

- Rapid re-heating of surface after electrode lift-off
- Re-heating drastically intensified for shorter hold time (200 ms)
- Parallel formation of tensile stresses predicted by simulation



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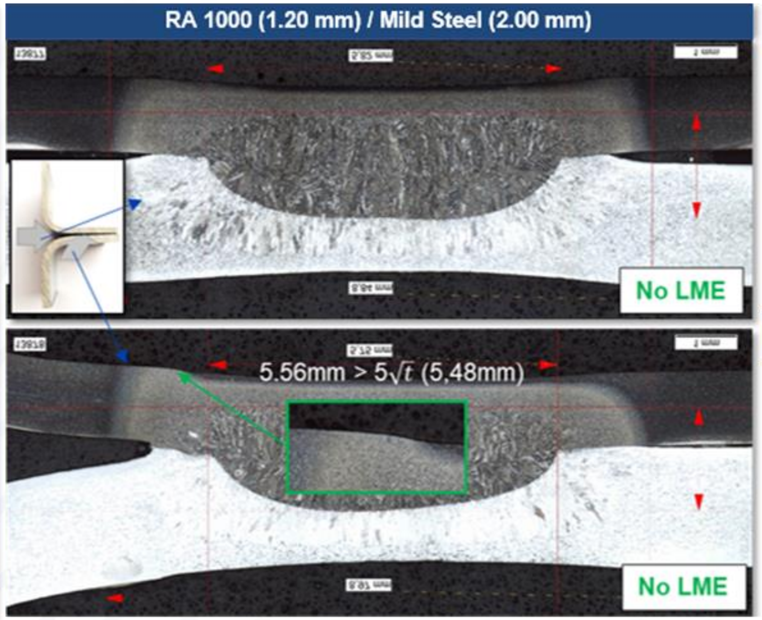
→ Similar behavior observed for multiple MTCs

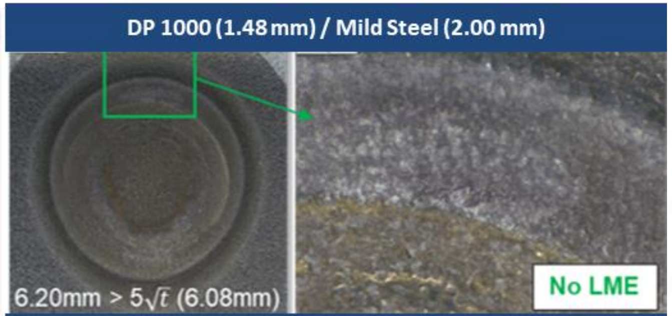
→ Correct adaption of hold time crucial to prevent LME cracks!

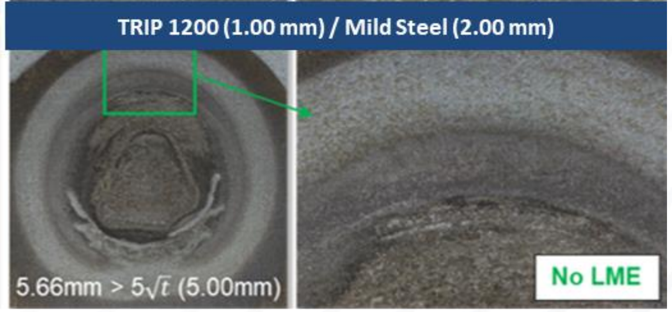
CONTROL AND PREVENT LME

VALIDATION OF OPTIMIZED WELDING PROCESS

- Testing on hat profiles with gaps - targeted weld nugget diameter $(5\sqrt{t})$
- Reference process with 5.5 mm tip: spatter and crack-afflicted
- Process optimization by tip-dressing to larger electrode tip diameter


RA 1000 (1.20 mm) / Mild Steel (2.00 mm)


DP 1000 (1.48 mm) / Mild Steel (2.00 mm)

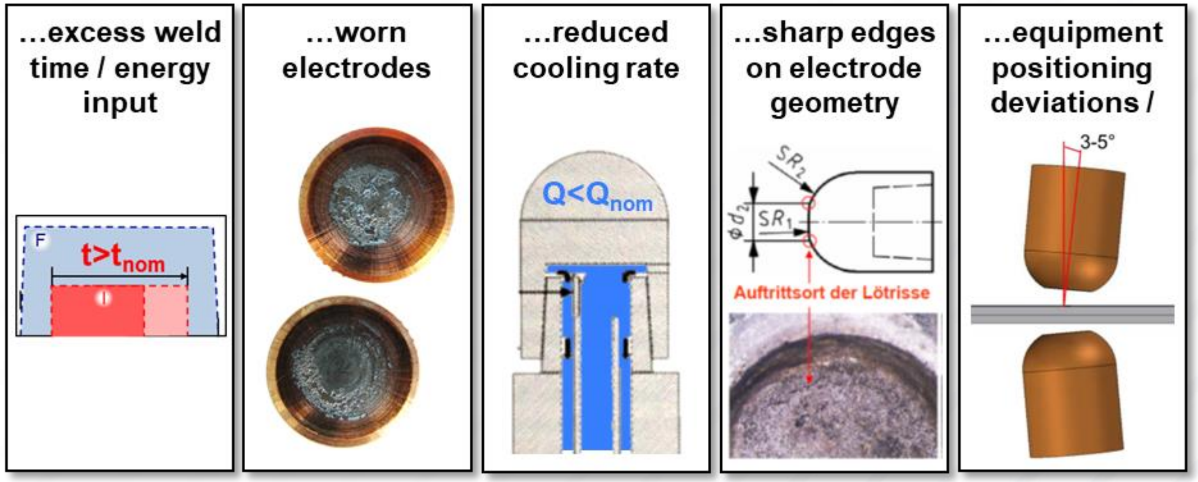

TRIP 1200 (1.00 mm) / Mild Steel (2.00 mm)

→ Optimized process with 8.0 mm tip: spatter and LME free welding process
→ Successful transfer onto multiple LME-susceptible materials from AHSS-Portfolio

SUMMARY

Experiments and numerical simulation used to investigate LME during RSW

- Influence factors on LME formation identified and analyzed
- Mechanical impact of LME on joint strength investigated
- Methods for LME avoidance developed and validated



Avoid spot welding with…

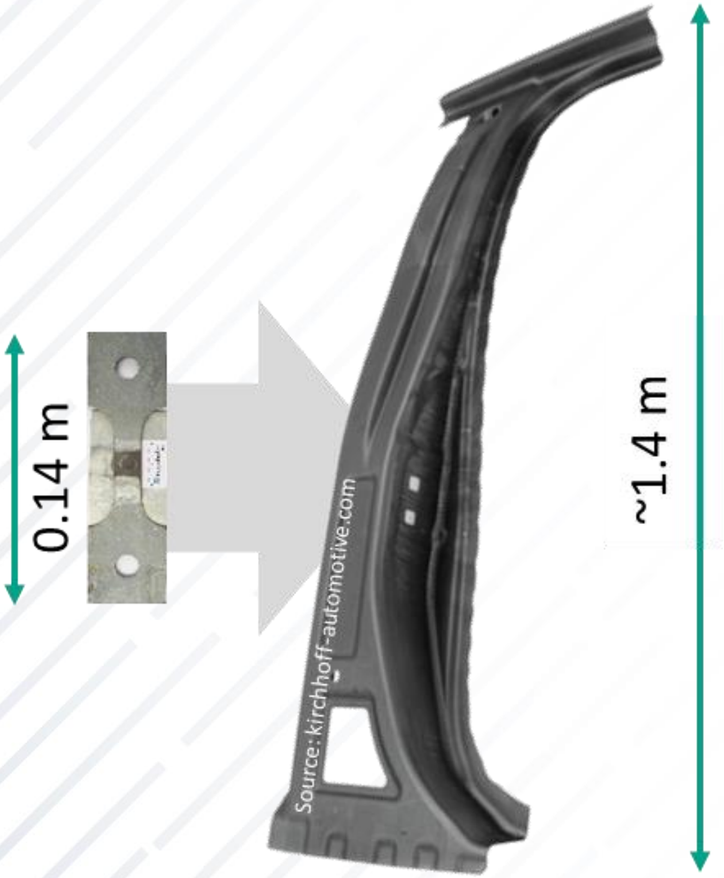
- …excess weld time / energy input
- …worn electrodes
- …reduced cooling rate
- …sharp edges on electrode geometry
- …equipment positioning deviations /

Larger diameter electrode tips reduce LME susceptibility significantly

Adjust hold time according to energy input and sheet thickness

OUTLOOK

LME PROJECT EXTENSION: INDUSTRIAL COMPONENT TESTING



Source: kirchhoff-automotive.com

Where does LME occur in an industrial component?

- Experimental investigation of crack occurrence and magnitude in relation to clamping, process conditions and part tolerances

Why does it occur?

- Simulative analysis of stresses, strains and critical temperatures for the whole part

Does it matter?

- Correlation of crack sizes and locations with results of material tests to judge crack impact on whole-part performance

→ Develop integrated guidelines to avoid LME in the planning stage

FOR MORE INFORMATION

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