GREAT DESIGNS IN STEEL

TWENTY YEARS

# INTEGRATED PROCESS & PERFORMANCE MODELS FOR RSW OF 1ST & 3RD GEN STEELS

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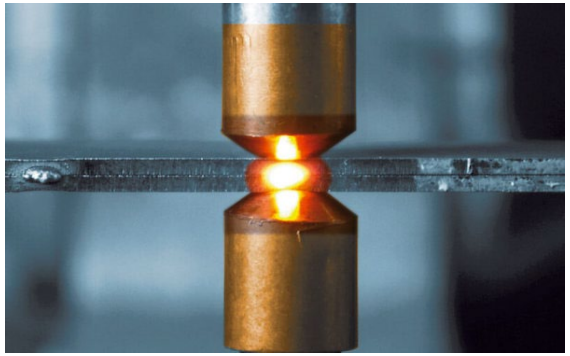
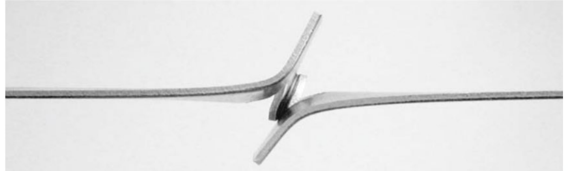
On Behalf of Auto/Steel Partnership

# BACKGROUND

- Resistance spot welding (RSW) – the most widely used joining process in the automotive industry
- Many combinations of stacks to be welded in a lightweight body structure due to different **steel grade**, **thickness**, **coating**, **2T**, **3T**, etc.
- Reducing the number of physical tests and prototypes can greatly speed up the automotive body design and engineering process
    - One solution is to computationally assess RSW joint performance



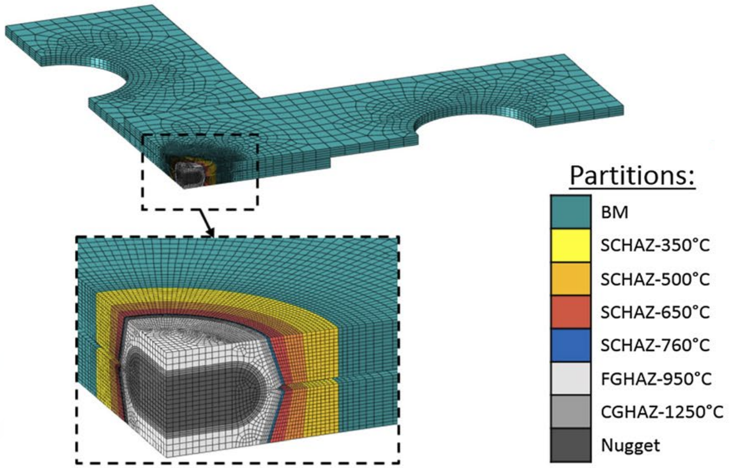


# TECHNICAL GAPS IN RSW MODELING

- Majority of models are for joint performance only, without the welding process knowledge.
  - **Prerequisites**: nugget size, indentation, notch shape, and micro-hardness map
  - A new model will be needed when the welding parameters and stacks change

- Highly inhomogeneous mechanical properties in the joint regions ranging from weld metal, coarse grained heat-affected zone (HAZ), subcritical HAZ to base metal

- Sophisticated failure models are needed to accurately capture joint behavior in complex loading conditions
  - Strain-based models are mesh dependent
  - Gurson-type, MMC, and Johnson-Cook models have been explored in the literature

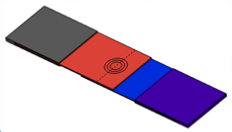



Picture from H. Rezayat et al., Metallurgical and Materials Transactions A, 2020.

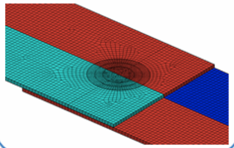
MMC – Modified Mohr-Coulomb

# PROCESS & PERFORMANCE MODEL

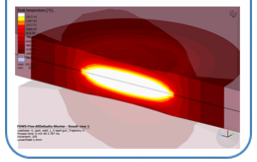
**Define stack**
- Weld size
- Thickness
- AWS/ASME



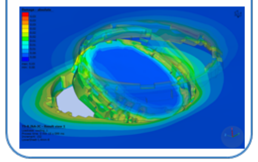
**Create model**
- Proper meshing
- Boundary conditions



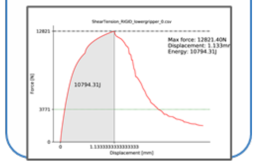
**Weld simulation**
- RSW simulation
- Fully coupled



**Performance**
- Weld results
- Damage model



**Data processing**
- Calculation of energy
- Force x Displ.



**Process model**:
- Coupled electro-thermo-mechanical finite element simulation
- Advanced contact formulation that detects fusion bonding and changes contact to glue

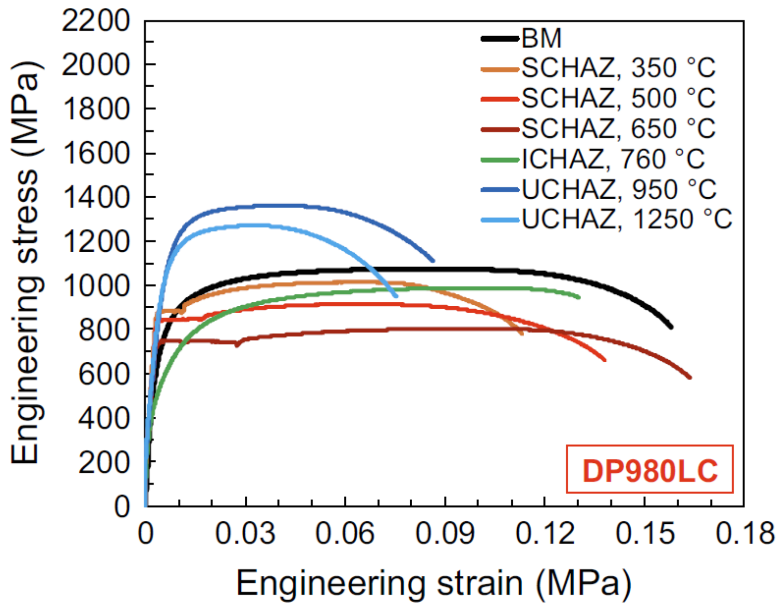
**Performance model:** mechanical simulation with failure

**Same mesh** and **glued connection** to facilitate automated integration of process and performance models

Predicting important aspects like:
- Temperature field
- 3D sample shape
- Indentation
- Notch shape
- Nugget size
- Microstructure
- Residual stress
- Plastic strain

# PROCESS & PERFORMANCE MODEL

- Steels studied: **DP980** and **3rd Gen-980**
- RSW process model:
  - **Key inputs**: Material bulk resistivity and electrical contact resistance
  - **Key outputs**: Nugget size, and local peak temperature
- Performance model:
  - **Key inputs**: Microstructure-specific stress-strain curves (e.g., those for HAZ)*
  - **Key outputs**: Load-displacement curve and failure mode in tension shear and cross tension
- Finite element solver: Simufact
- For each steel, one nugget size in tension shear configuration was used to calibrate the inputs such as electrical contact resistance and damage parameters
- The calibrated model was then extended to simulate other nugget sizes and joint configurations

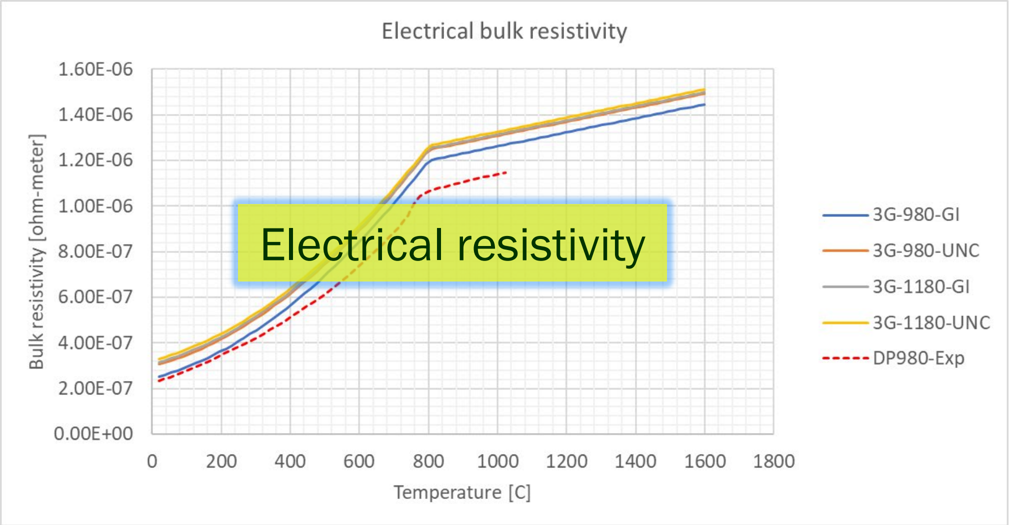


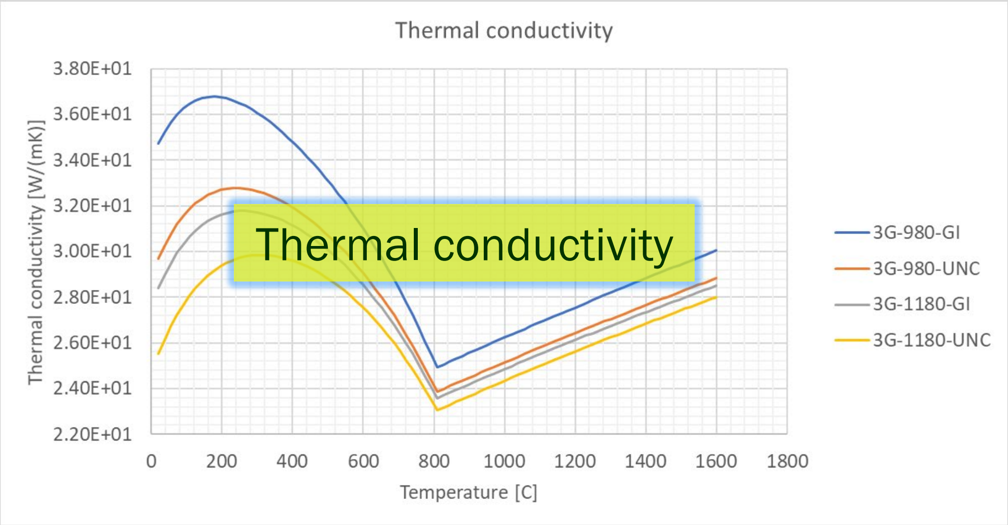

* Data taken from H. Rezayat et al., Metallurgical and Materials Transactions A, 2020.

# PROCESS & PERFORMANCE MODEL
# DP 980

# RSW PROCESS MODELING

- **General material data** – JMatPro, literature, Thermo-Calc calculations




- **Electrical contact resistance** – Analytical equation with parameters calibrated using a FDWS macrograph.

$$\rho(T,p) = r_0 \cdot \left(\frac{p - p_k}{p_0 - p_k}\right)^{\varepsilon_p} \cdot \left(\frac{T - T_{lim} + (T_0 - T) \cdot 2^{\frac{-1}{\varepsilon_T}}}{T_0 - T_{lim}}\right)^{\varepsilon_T}$$

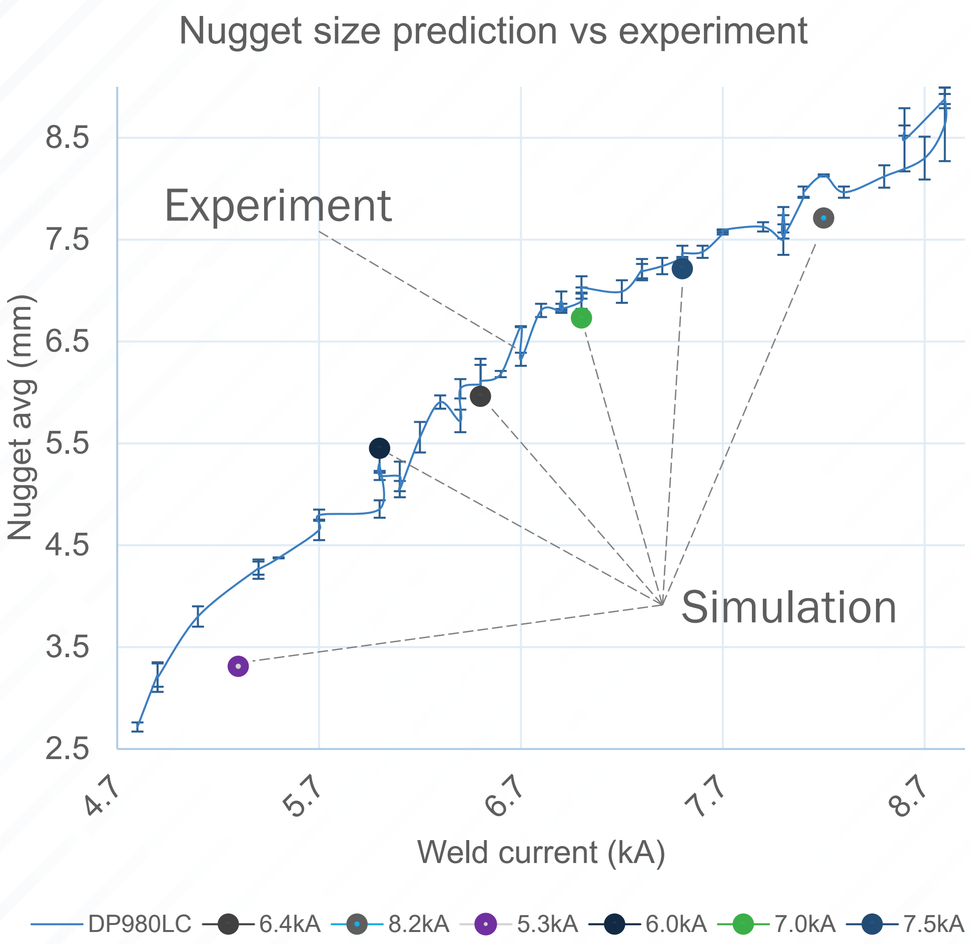
$r_0$ → base resistance
$p_k$ → corrective pressure term
$p_0$ → reference pressure
$T_0$ → room temperature (i.e., 293.15K)
$T_{lim}$ → half-value temperature
$\varepsilon_p$ → pressure contribution exponent
$\varepsilon_T$ → temperature contribution exponent

Kaars, J., Mayr, P., & Koppe, K. (2016). Generalized dynamic transition resistance in spot welding of aluminized 22MnB5. Materials and Design, 106, 139–145. https://doi.org/10.1016/j.matdes.2016.05.097

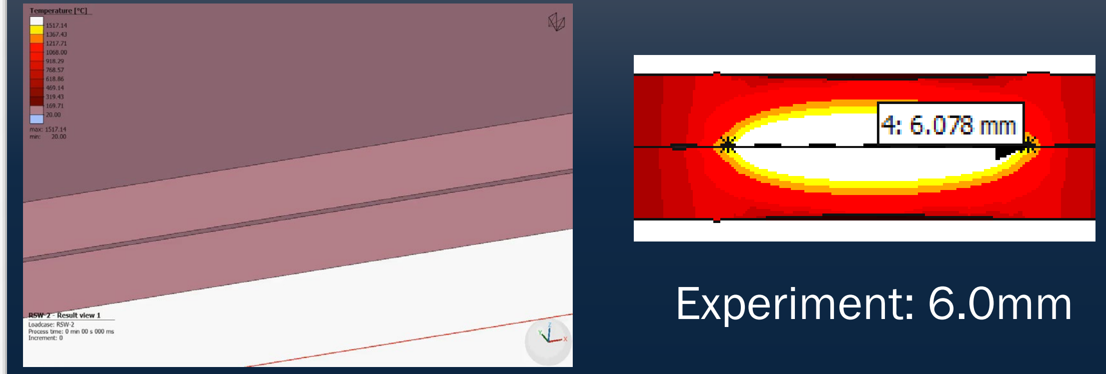
FDWS – Face diameter weld size

# RSW PROCESS – DP980LC

- Correlation with experimental data

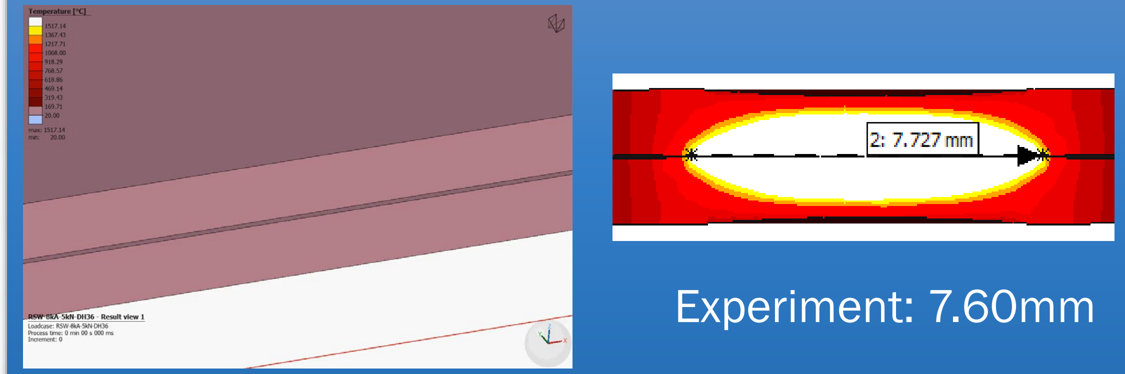



## 6.4kA - FDWS




Experiment: 6.0mm

## 8kA




Experiment: 7.60mm

**Calibration with FDWS (6.4kA) and correlation up to close-to-expulsion weld current (8.0kA)**

# PERFORMANCE MODEL – DP980LC

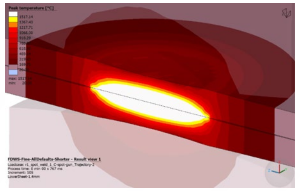
- Damage model: Johnson-Cook

Model parameters

| Constant | Param. | Value | |
|---|---|---|---|
| Damage parameter | $D_1$ | 2.0 | - |
| Damage parameter | $D_2$ | 1.0 | - |
| Damage parameter | $D_3$ | -0.9 | - |
| Damage parameter | $D_4$ | 0.0 | - |
| Damage parameter | $D_5$ | 0.0 | - |
| Damage display threshold | C | 0.0 | - |
| Element removal threshold | | 0.02 | - |
| Damage exponent | $n_D$ | 1.0 | - |
| Material degradation | | None (Indicator) | |

Weld simulation

- RSW simulation
- Fully coupled



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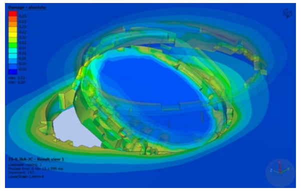
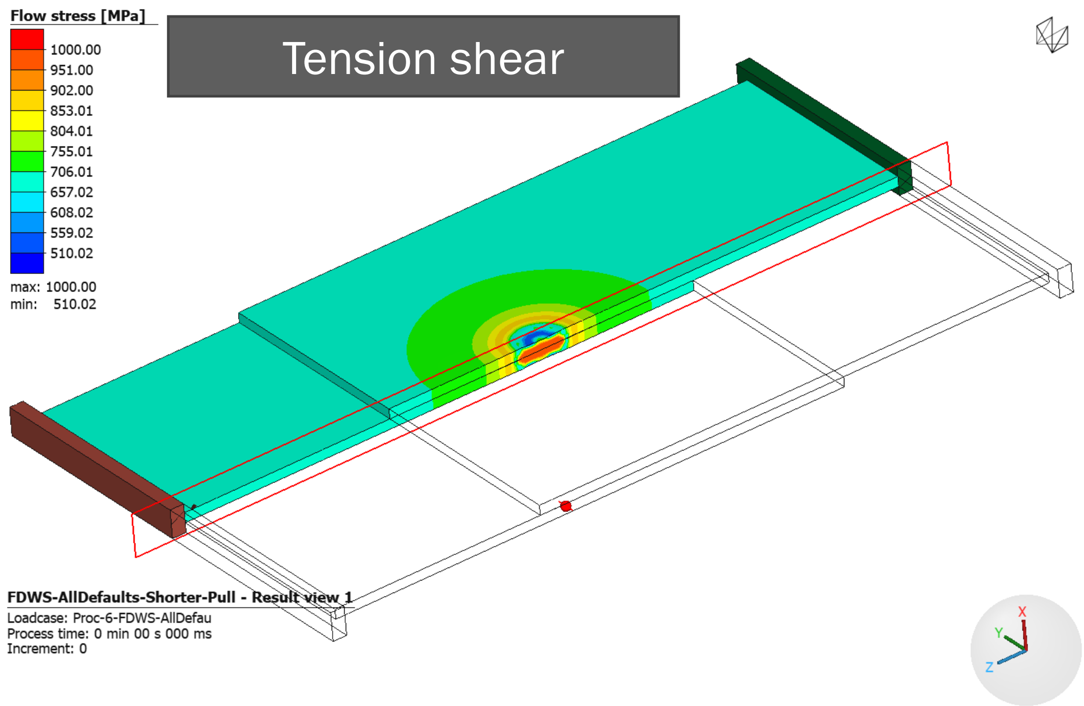
Performance

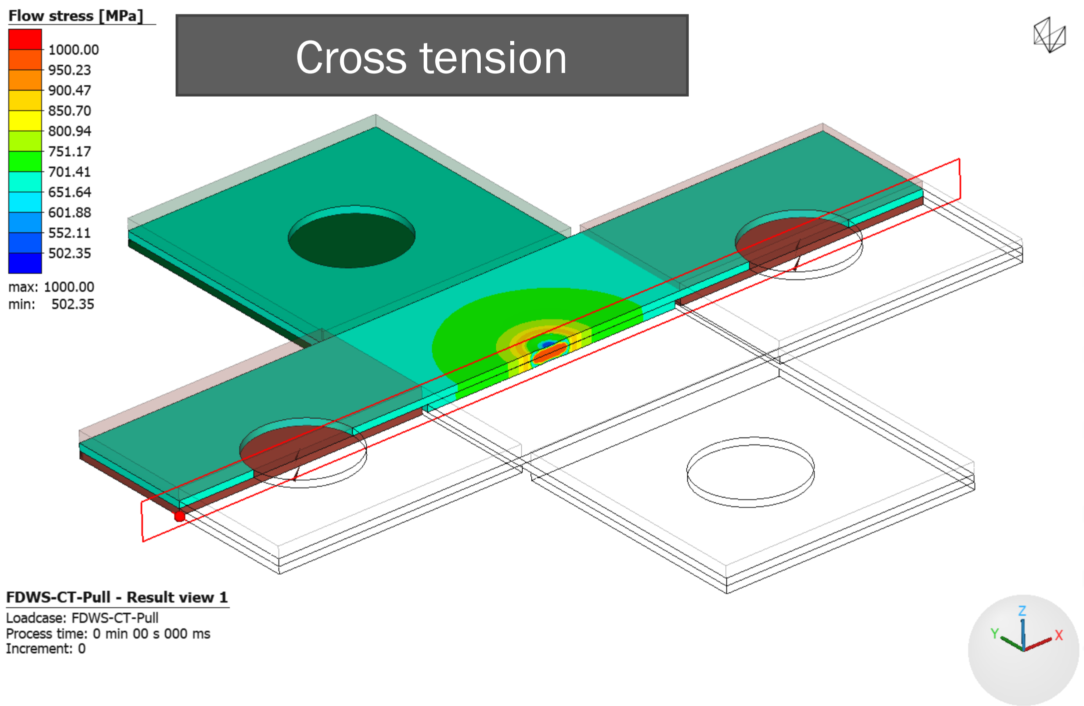
- Weld results
- Damage model



- Suitable for almost every type of cracks
- Accurate damage prediction if parameters are calibrated
- Failure treated via element removal during simulation

# PERFORMANCE MODEL – DP980LC

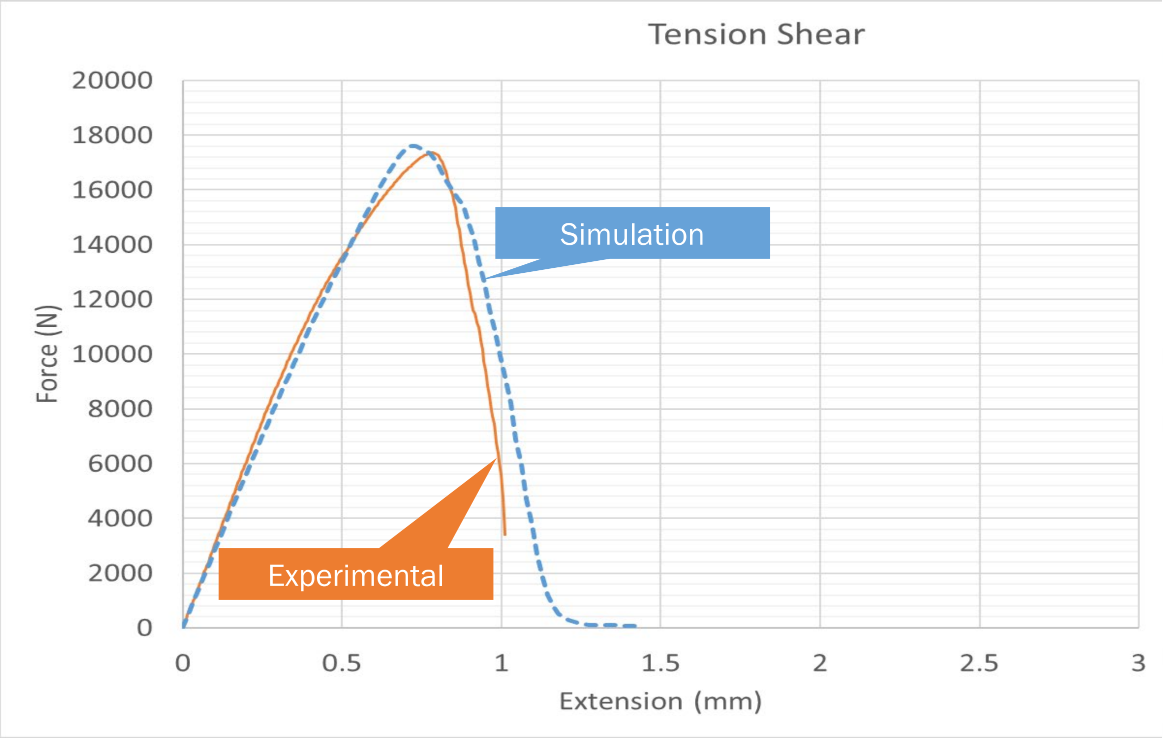


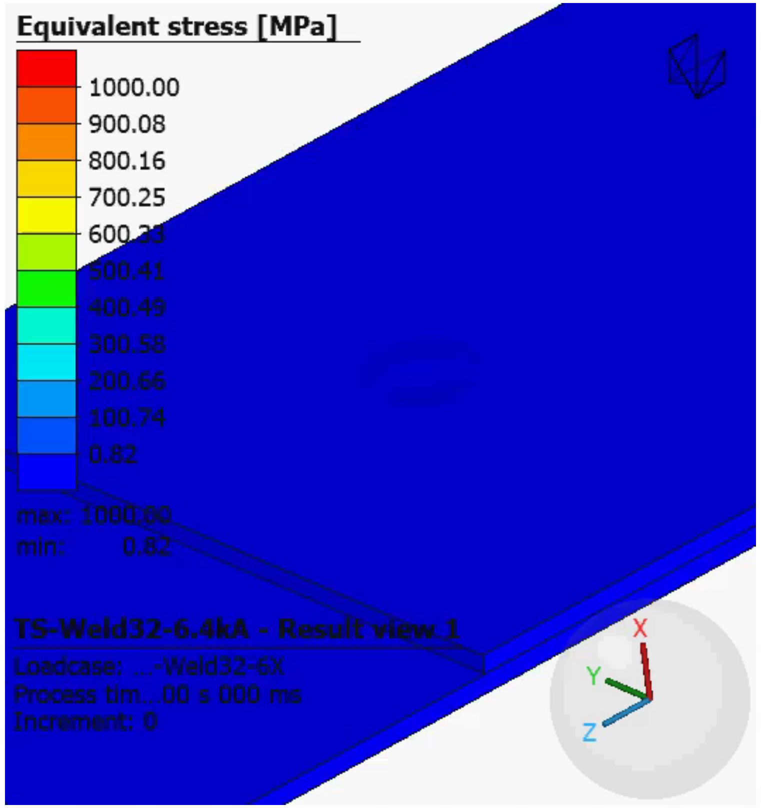




FDWS was used to calibrate the JC damage parameters in tension shear and then applied to cross tension

# PERFORMANCE MODEL – DP980LC

- Tension shear



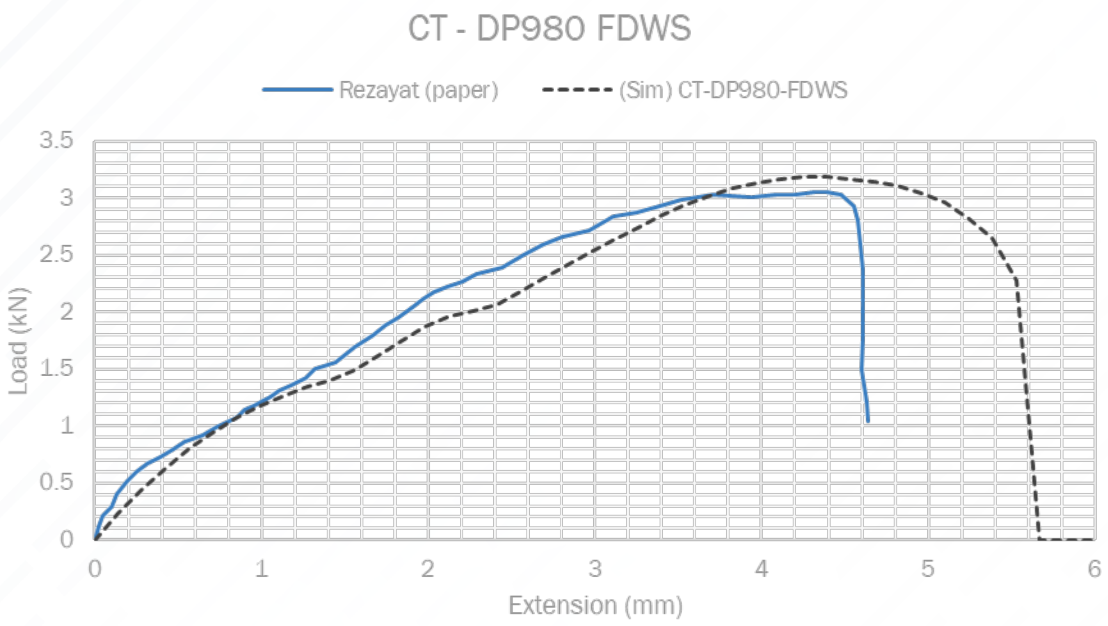



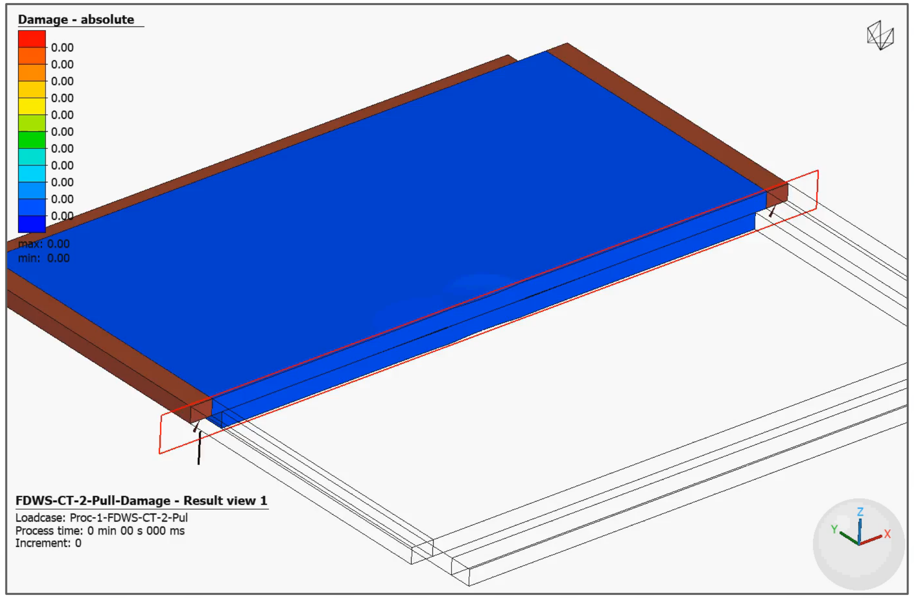

| | Experimental data | Simulation |
|---|---|---|
| Peak force | 17.5kN | 17.9kN |
| Extension | ~0.85mm | ~0.70mm |

Curve shape, peak force and extension until peak force showed good correlation

# PERFORMANCE MODEL – DP980LC

- Cross tension



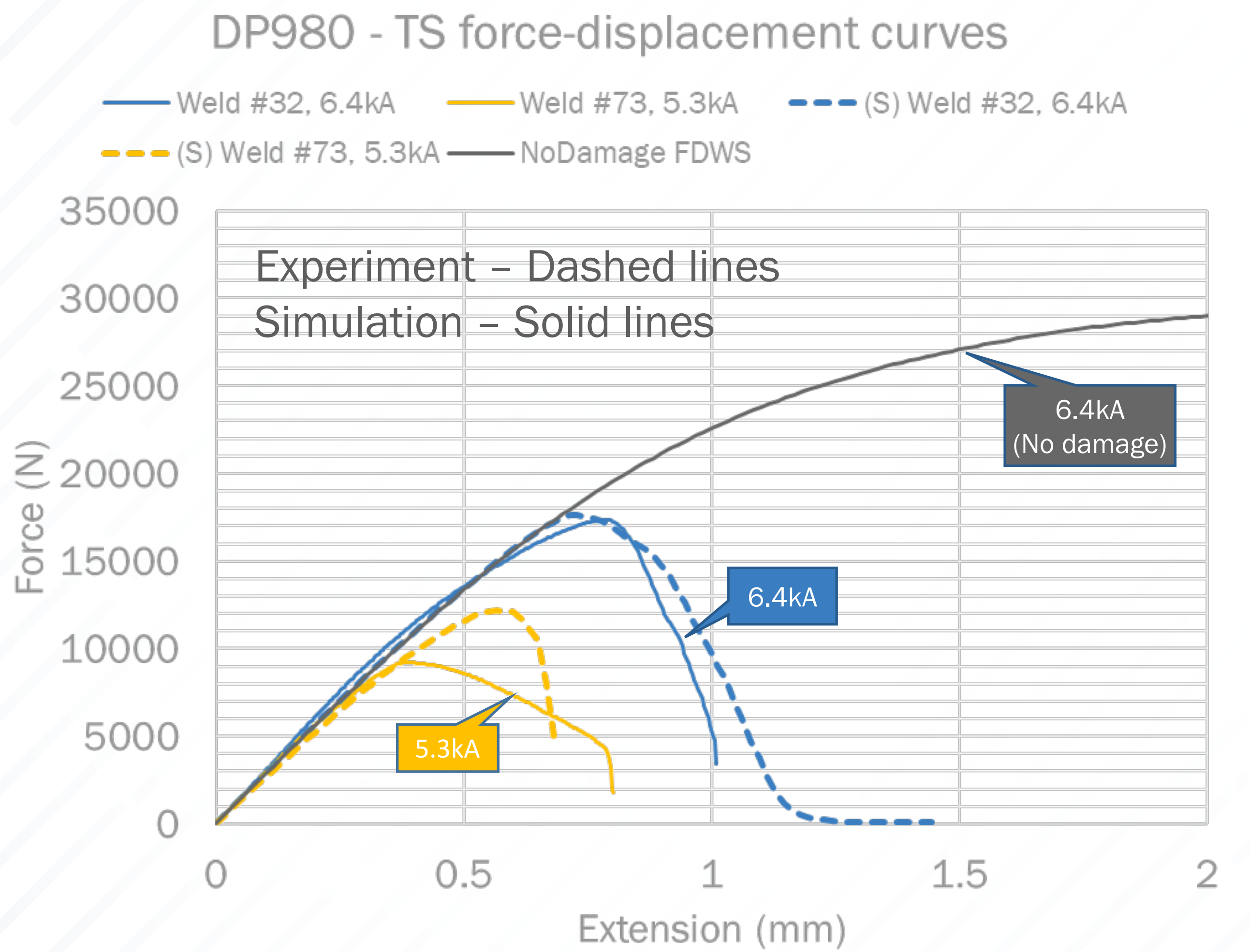

| | Experimental data | Simulation |
|---|---|---|
| Peak force | 3.0kN | 3.5kN |

Correlation of Local Constitutive Properties to Global Mechanical Performance of Advanced High-Strength Steel Spot Welds. Rezayat, H., et al., 2021

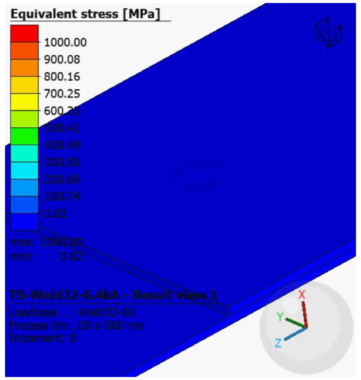
Curve shape, peak force and extension until peak force showed good correlation

# PERFORMANCE MODEL – DP980LC

- Capturing the effect of nugget size

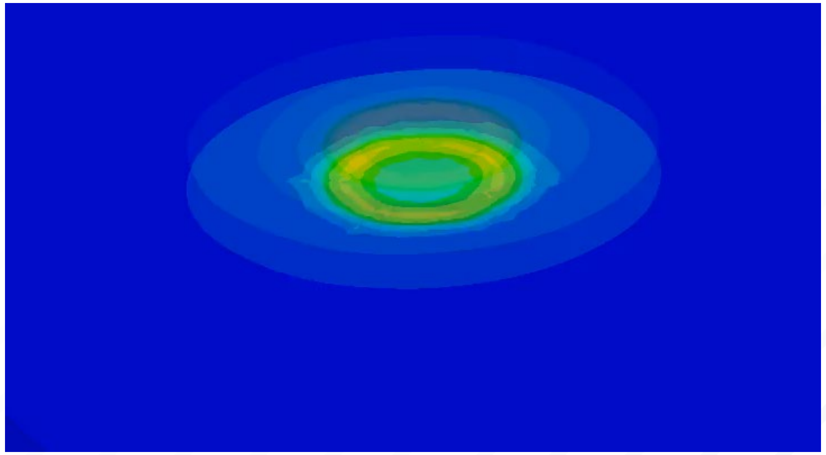



6.4kA




**Failure mode:** button or nugget pull-out

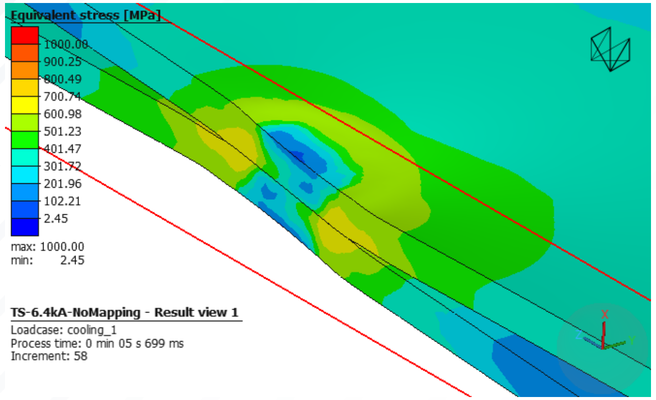
5.3kA



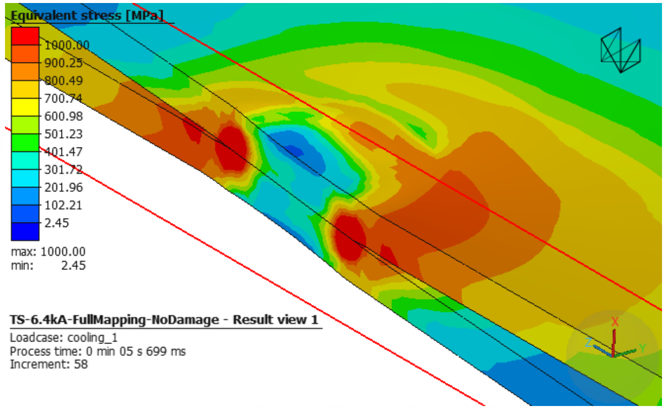
**Failure mode:** Interfacial failure

# FACTORS AFFECTING PERFORMANCE MODELING

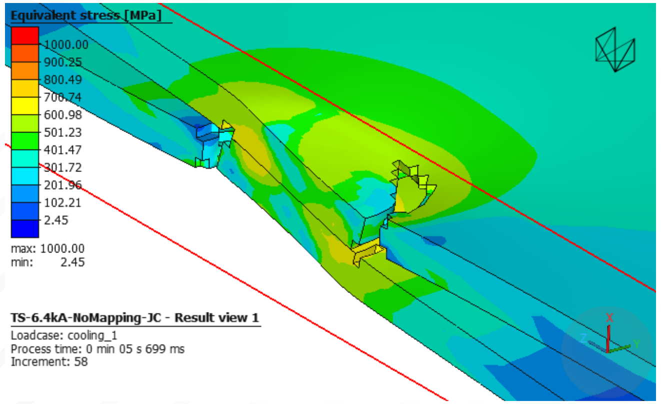
W/O HAZ properties



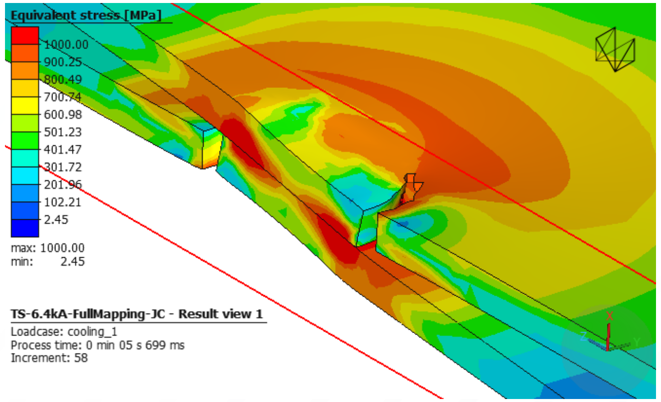

W/ HAZ properties

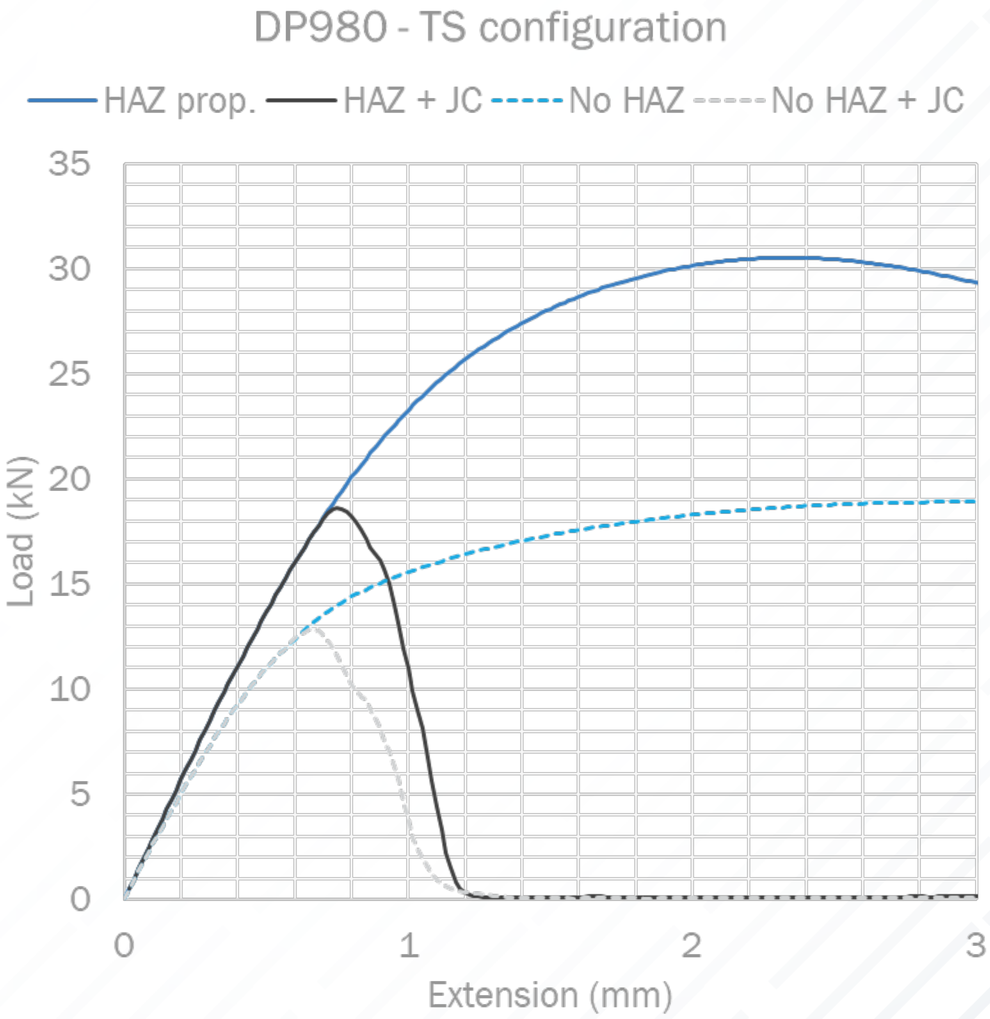



W/O HAZ properties + JC




W/ HAZ properties + JC

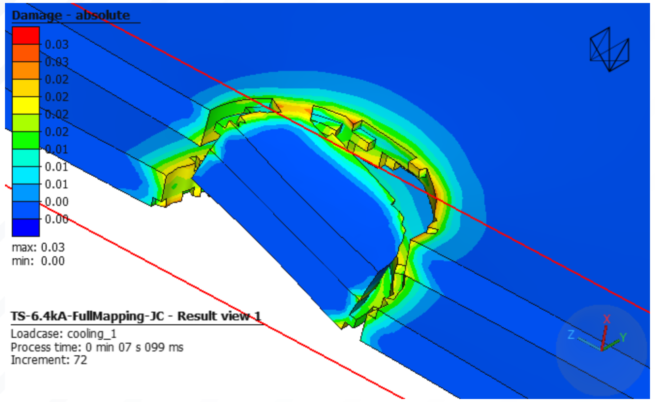


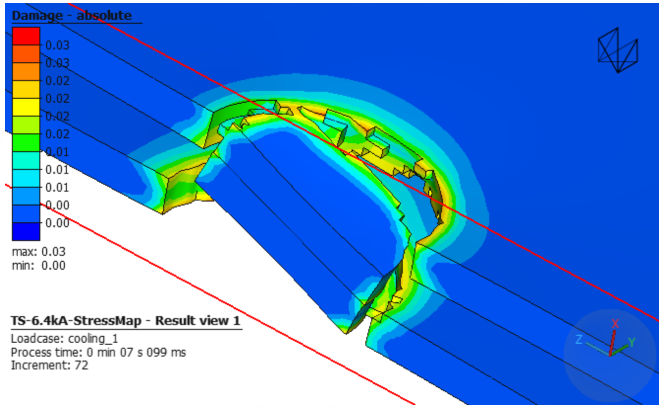

Without HAZ properties the peak force is underpredicted

# FACTORS AFFECTING PERFORMANCE MODELING

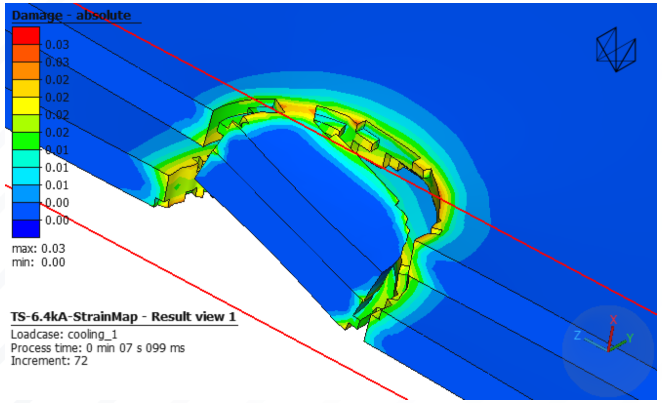
Stress + Strain



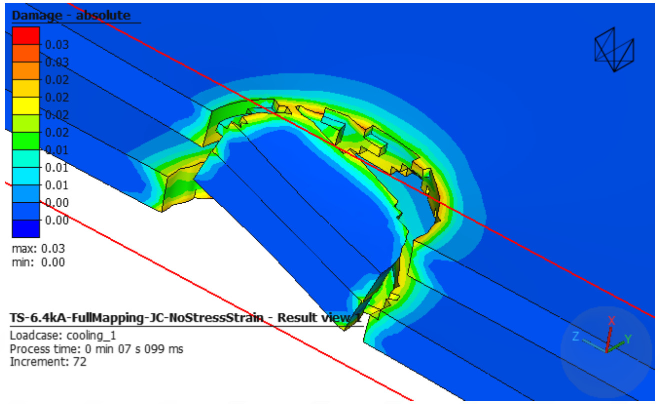

Stress

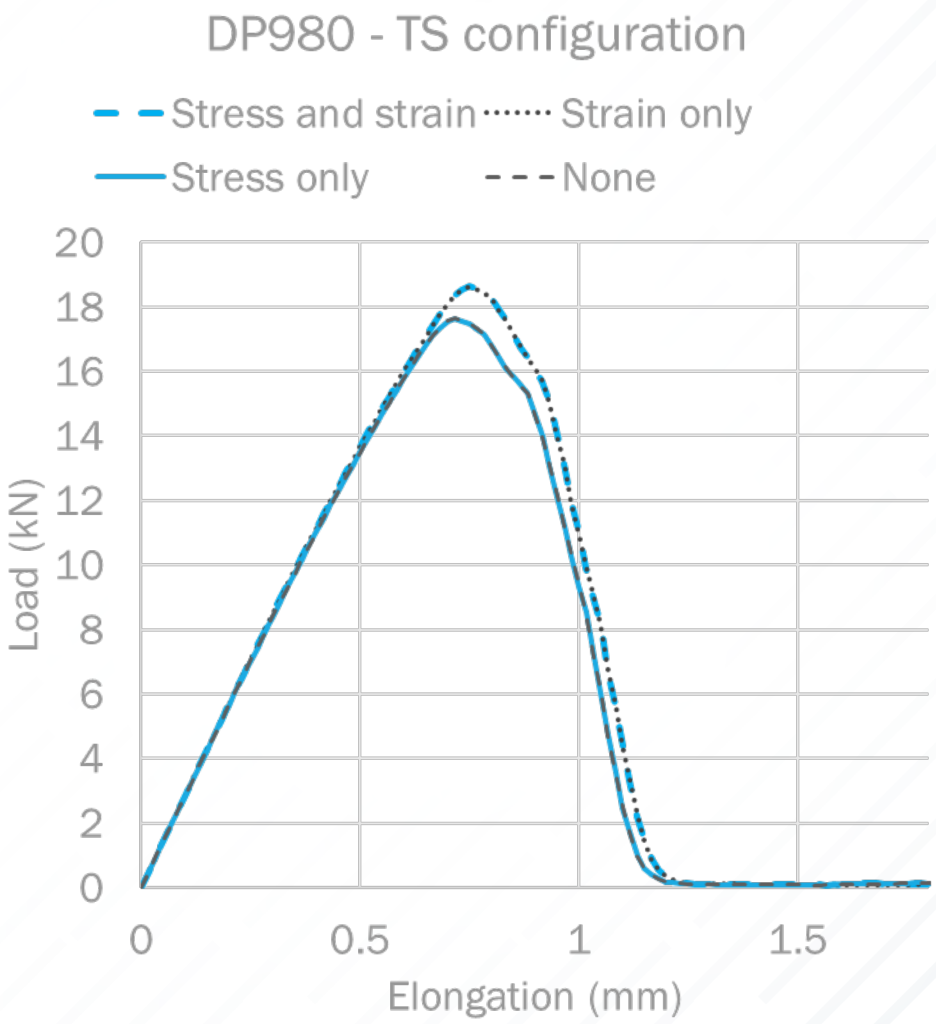



Strain only




None



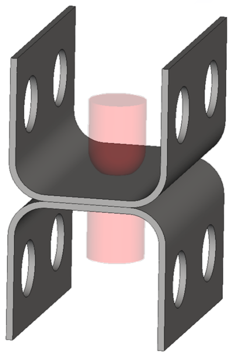




Residual stress and strain occurred during welding seem to be of secondary influence on performance

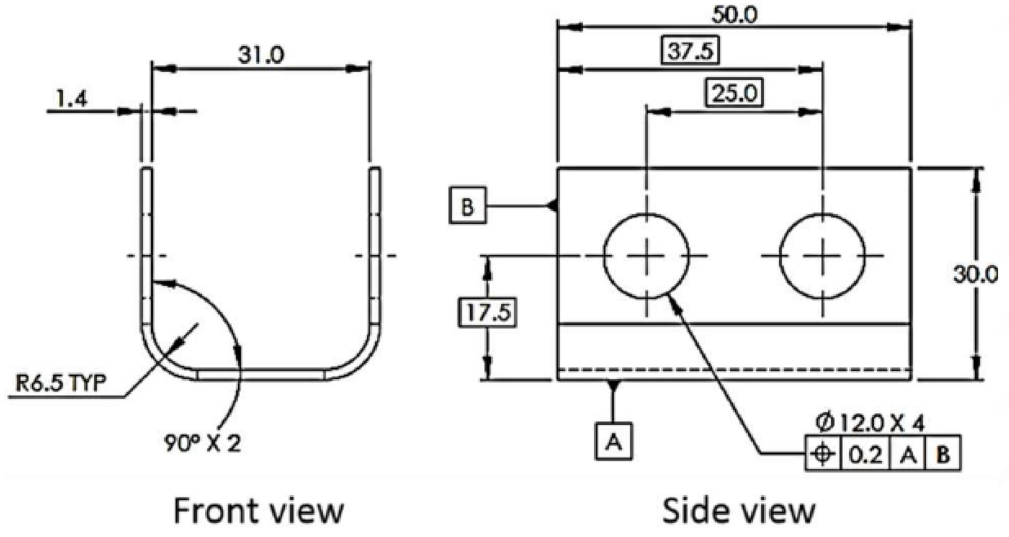
# PROCESS & PERFORMANCE MODEL
# 3RD GEN 980

# RSW PROCESS – 3RD GEN 980

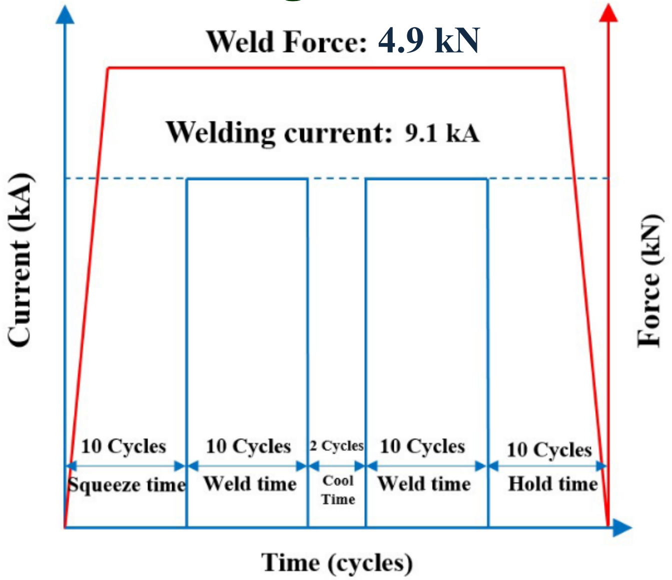
- KSII sample
  - 3rd Gen, 1.4mm thickness, 616MPa yield, 1013MPa tensile
  - Cu electrode with 7mm flat tip diameter
  - 9.1kA two-pulse current, 4.9kN force
  - Nugget diameter 7mm



KSII - Coupon geometry



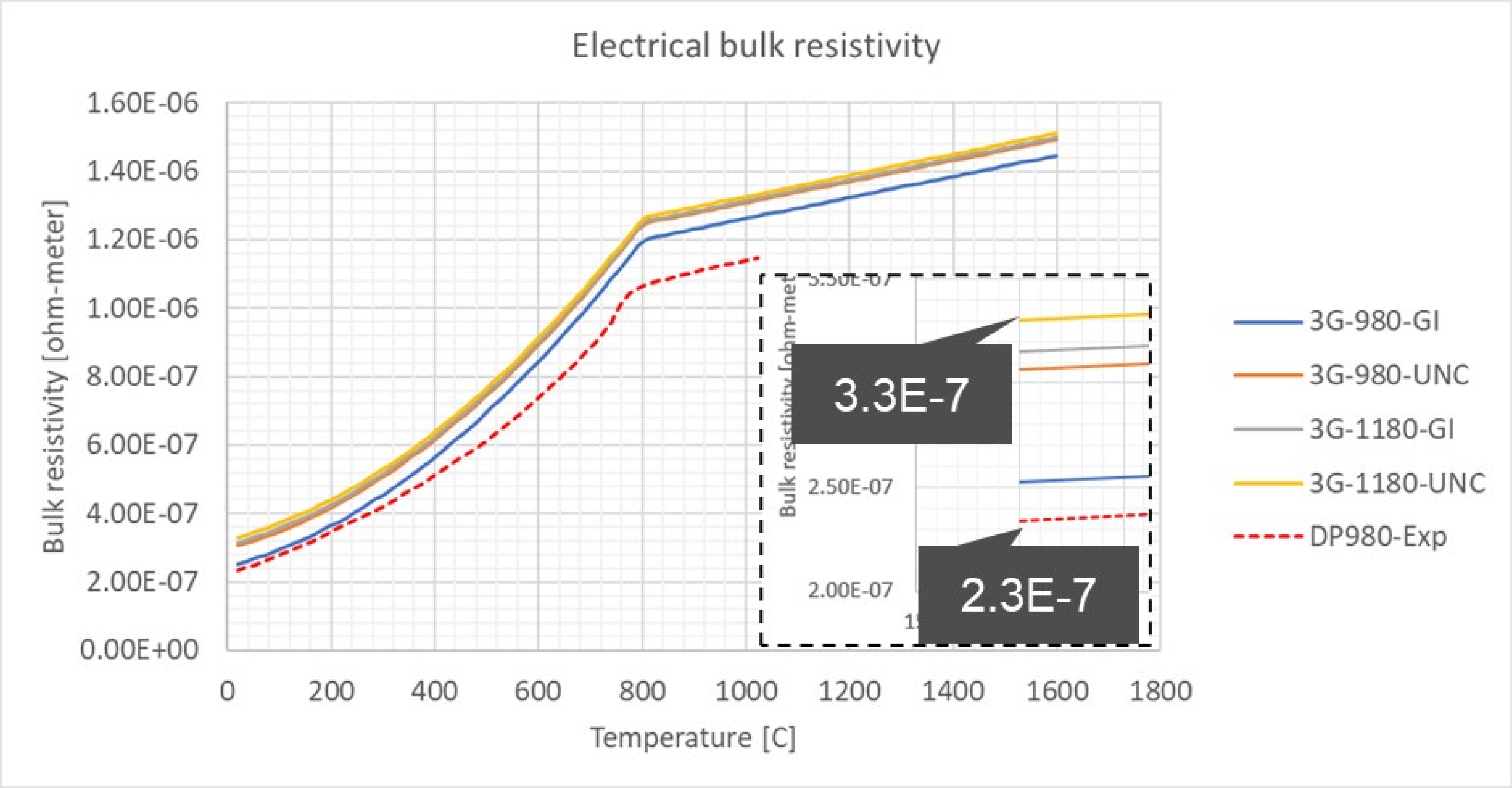

Welding schedule




M. Shojaee et al., Modeling of Combined Loading Mode on Third-Generation AHSS Resistance Spot Welds, Sheet Metal Welding Conference XIX, Paper 5B-5, 2021.

# RSW PROCESS – 3RD GEN 980

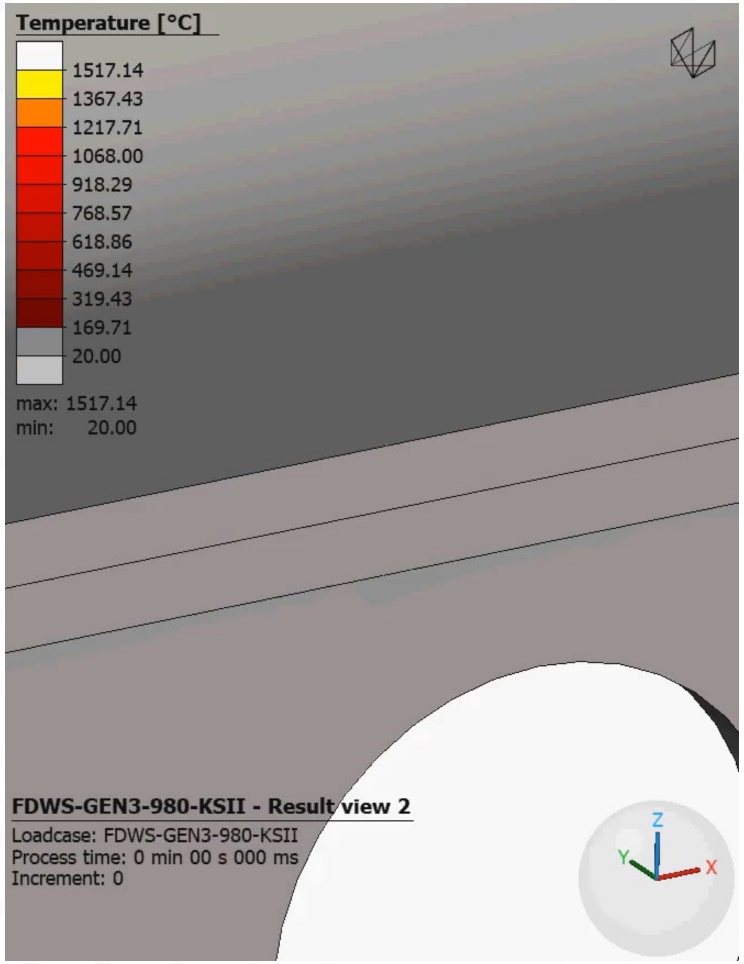
- **Bulk resistivity** – Room temperature data and Thermo-Calc calculations
- **Electrical contact resistance** – Same equation as that for DP980LC but with new calibrated parameters from 3rd Gen-980 macrograph



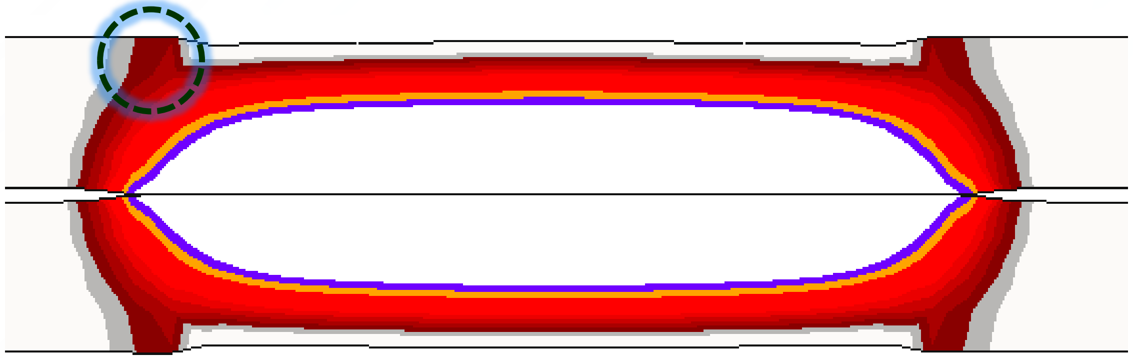

3rd Gen steels tend to have up to 33% higher bulk resistivity when compared to 1st Gen DP

# RSW PROCESS – 3RD GEN 980

- Correlation with experimental data

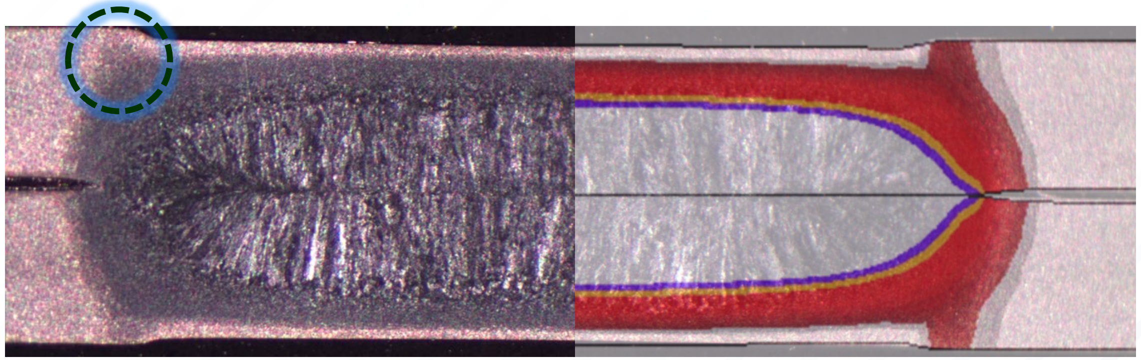



Simulation for FDWS 7.0mm



*17min calculation time

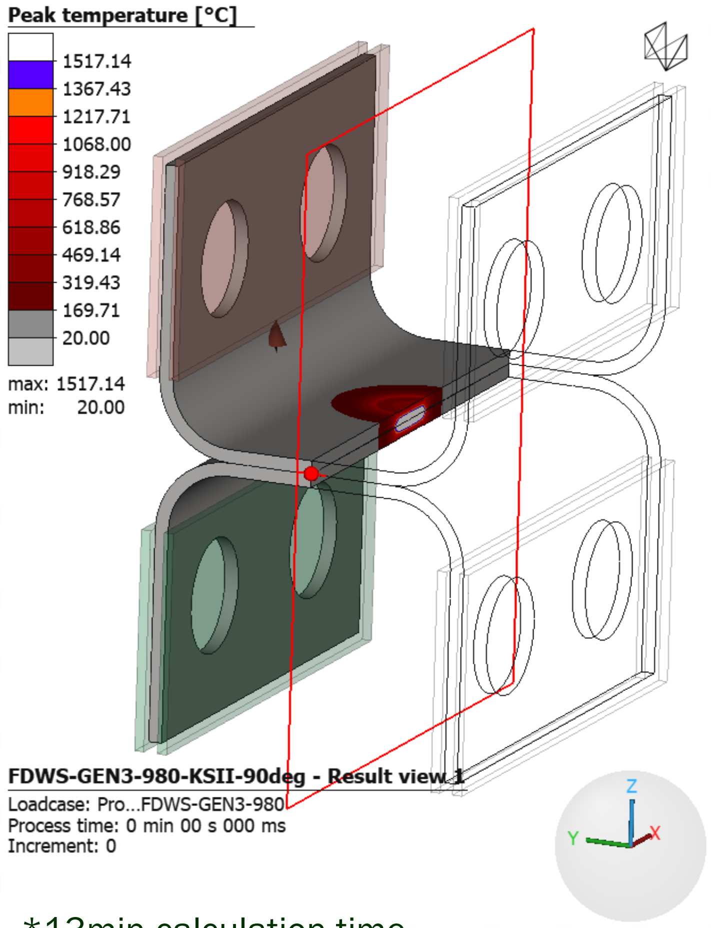
Comparison of experiment and simulation for FDWS

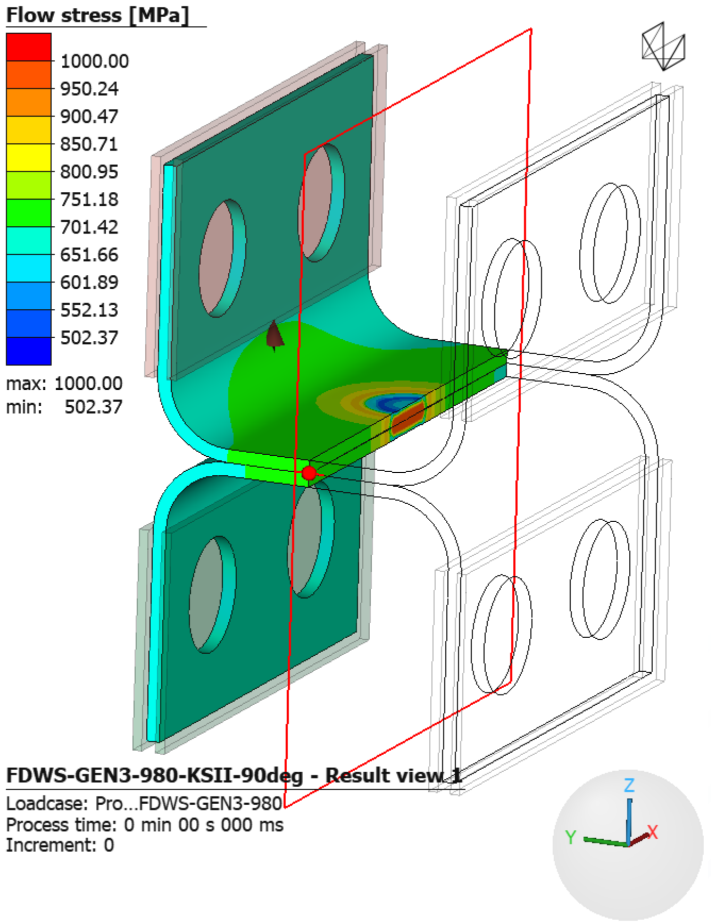


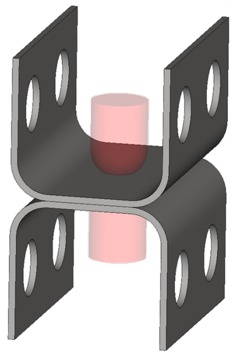
RSW process shows good adaptability to new materials and welding schedules

# PERFORMANCE MODEL – 3RD GEN 980

- Results from RSW simulation



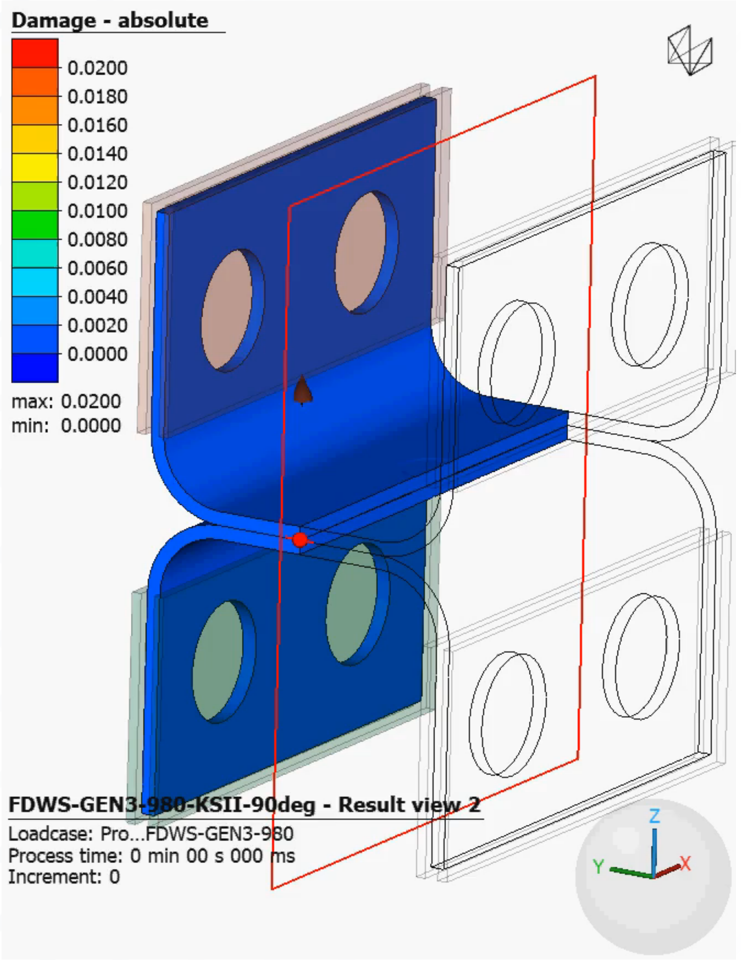
Showing a clipping plane at the center across the width. The model is full 3D with no symmetry planes used.

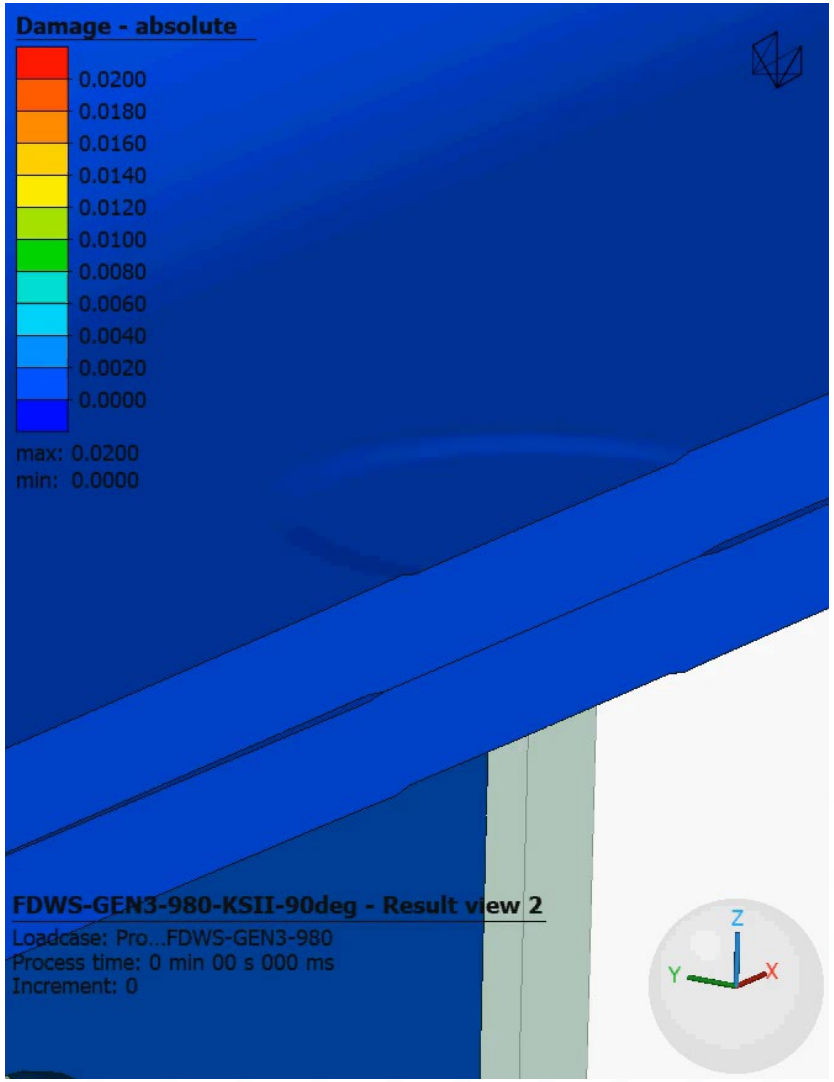
*13min calculation time

RSW results for the KSII configuration being transferred to the performance model

# PERFORMANCE MODEL – 3RD GEN 980

- KSII 90deg pull result




KSII 90deg (CT configuration) tensile test considering results from the RSW process

# CONCLUSIONS & FUTURE WORK

# TAKEAWAY POINTS

- **Highly-integrated process and performance models** implemented in Simufact are very promising to be used as a predictive tool
- RSW process model shows good **agreement and predictability for 1st and 3rd Gen steels**
  - Electrical contact resistance is a key factor for accurate process simulation
- Performance model using Johnson-Cook captured the failure behavior for DP980 in tension shear and cross tension; 3rd Gen-980 is work in progress.
  - Microstructure-specific stress-strain curve is a key factor for accurate performance simulation

# FUTURE WORK

- **Future work**

  - Evaluate performance of other failure models for different welding schedules and capture failure mode

  - Extend the process model to predict occurrence of liquid metal embrittlement based on local stress, strain and temperature histories

# ACKNOWLEDGMENTS

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# FOR MORE INFORMATION


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**More Questions?** Meet Fernando at the Auto/Steel Partnership booth after this presentation.