THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Application of Smoothed Particle Hydrodynamics Method in Simulation of High-Velocity Impact Welding

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INTRODUCTION

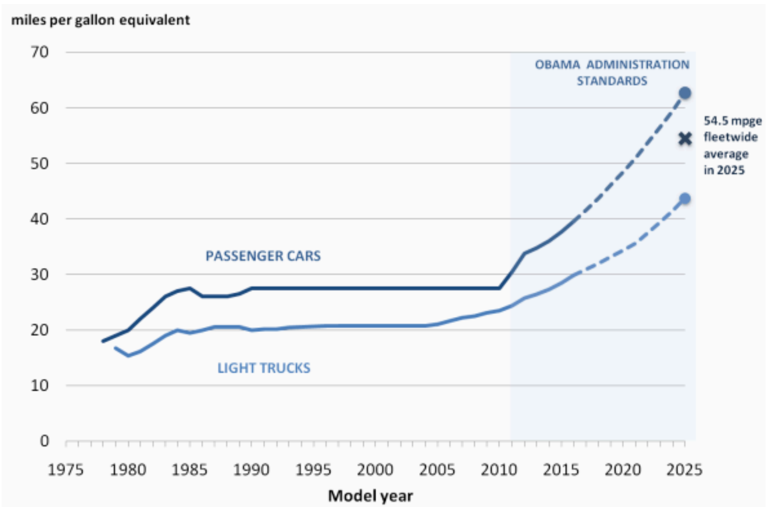
Vehicle Weight Reduction

- CAFE Standard (Corporate Average Fuel Economy) → reduce CO_2
  - ➢ 1990-2010 → 27.5 MPG
  - ➢ By 2025 → 54.5 MPG!

2.4L 2018 Honda CR-V-LX

next 7 years? =

278cc Vespa Giada



CAFE standard proposed by Department of Transportation (http://www.cargroup.org)

- What would be the best strategy?
  - ➢ Weight reduction by using multi-material structure
    - ❖ Steel, aluminum, magnesium, and composites
    - ❖ Need ways to join them together!

INTRODUCTION

Dissimilar Joining

- **Fusion Welding**
  - Examples: arc welding, resistance spot welding
    - Pros: well-understood, cheap (<2¢ per weld)
    - Cons: Intermetallic compound (IMCs), Heat-affected zone (HAZ)


RSW process
(http://www.christensenindustries.com)

- **Mechanical Fastening (often with adhesives)**
  - Examples: flow drill screws, self-piercing rivets
    - Pros: corrosion resistance, no part preparation
    - Cons: added weight

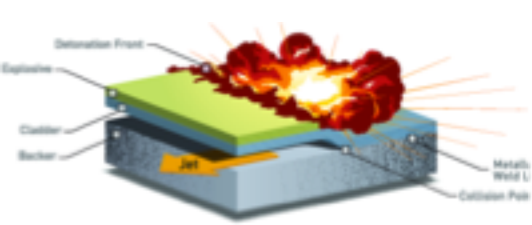

RIVTAC process
(http://techcormiddleeast.com)

- **Solid-State Welding**
  - Examples: ultrasonic welding, high-velocity impact welding
    - Pros: No HAZ, no distortion, fast, join strong alloys, etc.
    - Cons: not well-understood in small scale applications

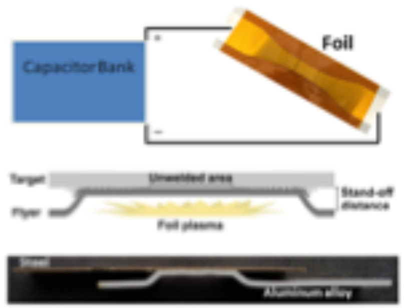
HIGH-VELOCITY IMPACT WELDING

HVIW

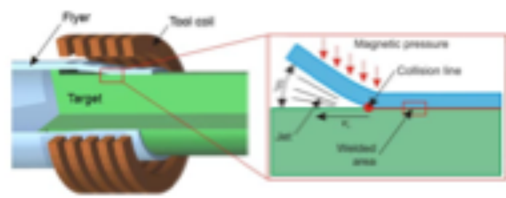
Explosive welding | Vaporizing foil actuator welding | Magnetic pulse welding | Laser impact welding



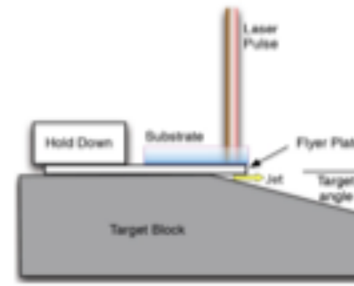
Mousavi et al. (2005)



Daehn et al. (2015)



Lueg-Althoff et al. (2014)



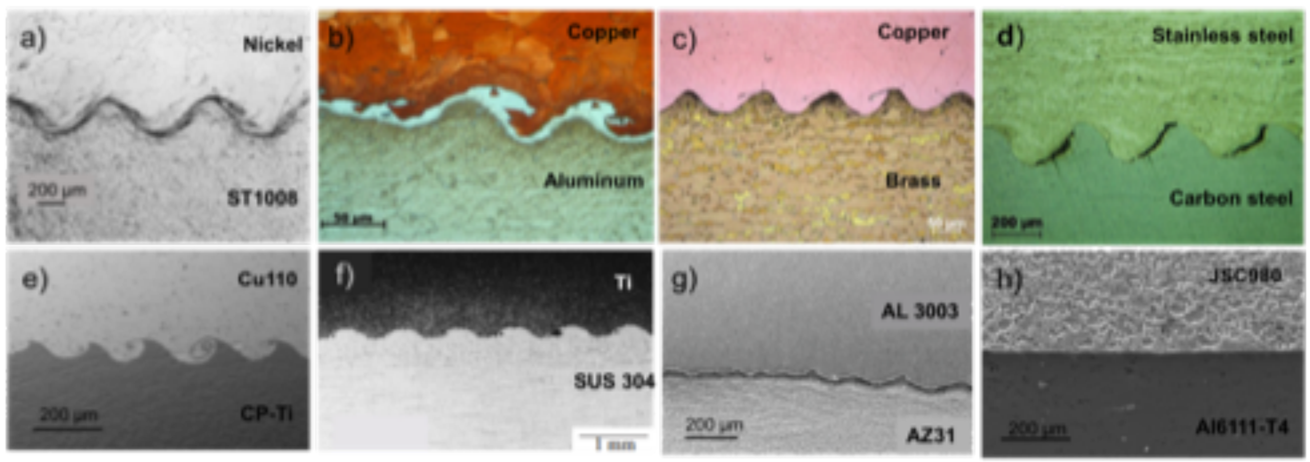
Daehn et al. (2009)

m 1 | 10^{-1} | cm 10^{-2} | mm 10^{-3}

- In all methods, a flier is accelerated to collide with a target
- A proper impact removes surface oxides and brings nascent surfaces into intimate contact, thus forming a metallurgical bond
- Critical parameters: impact velocity (300-1000m/s), impact angle (8º-25º)

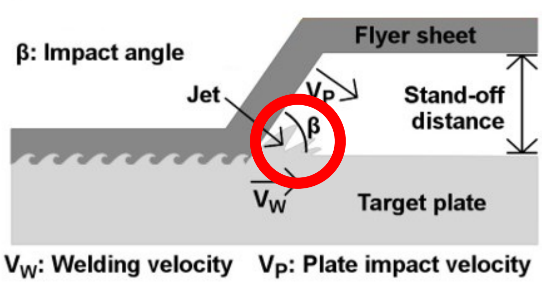
HIGH-VELOCITY IMPACT WELDING

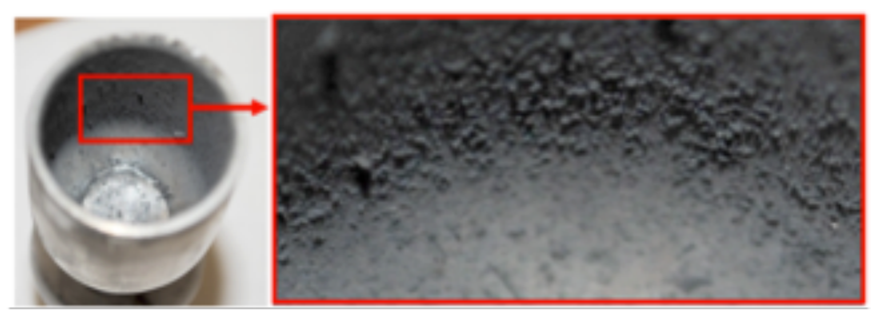
- Well-defined amplitude and wavelength: O(10μm) and O(100μm) respectively



Weld interface a) Ni-St, Cowan et al. (1971) b) Cu-Al, Raoelison et al. (2014) c) Cu-Br, Faes et al. (2010) d) St-St, Mendes et al. (2013) e) Cu-Ti, Vivek et al. (2013) f) Ti-St, Manikandan et al. (2006) g) Al-Mg alloy, Kore et al. (2009) h) Al-St, Nassiri et al. (2017)

- Jetting Phenomena



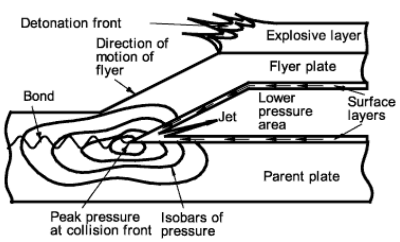


R.N. Raoelison et al. (2016)

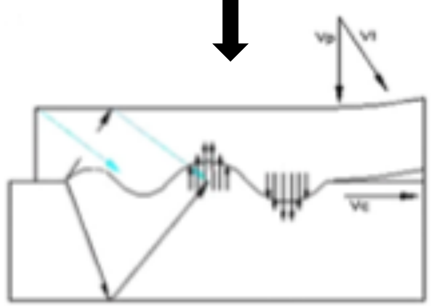
WAVE FORMATION THEORIES

Wave Formation Theories

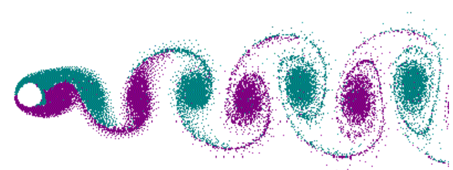
- **Indentation Mechanism**
  - Abrahamson, G. (1961)
  - Bahrani, A. et al. (1967)
- **Stress Wave Mechanism**
  - El-Sobky, H. et al. (1975)
- **Vortex Shedding/Jetting**
  - Cowan, G. et al. (1971)
  - Kowalick, J. et al. (1971)
- **Kelvin-Helmholtz (Fluid Instability)**
  - Hunt, J. (1968)
  - Nassiri, A. (2016)



http://materialteknologi.hig.no (2005)



Ben-Artzy et al. (2005)



Siqueira (2005)

http://amusingplanet.com (2013)

NUMERICAL SIMULATIONS

- HVIW is a highly-dynamic event!
  - Strain rate 10^6 - 10^8 s^{-1}
    - Mesh distortion
  - Very fine mesh is required to visualize the interface
    - Stability condition
    - Stable time increment

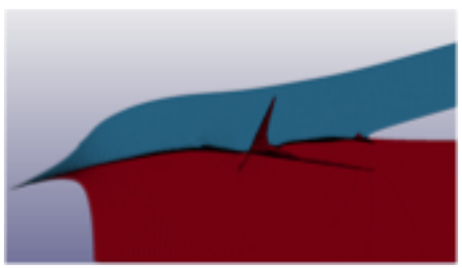
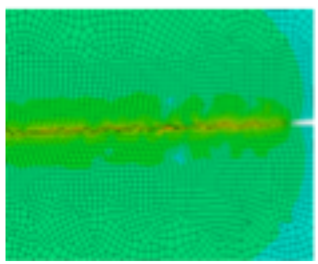
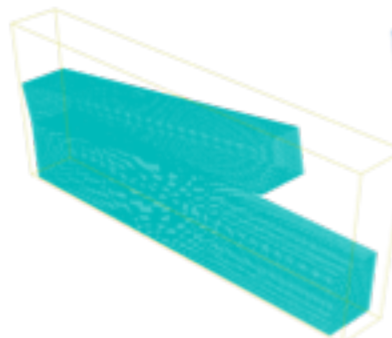
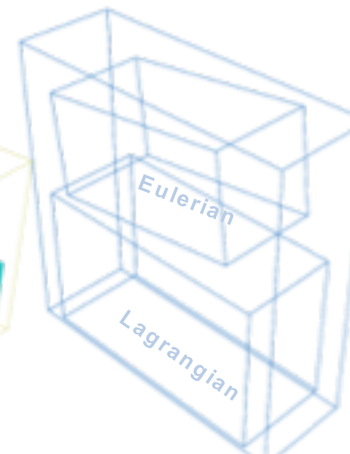
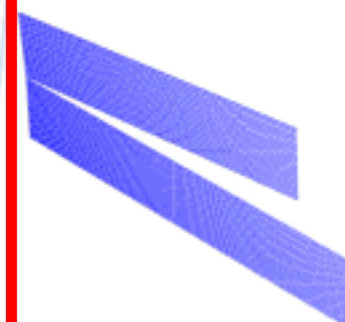
$$C = \frac{c_d . \Delta t_{max}}{\Delta x} \le 1$$

$$c_d = \sqrt{\frac{E}{\rho}}$$

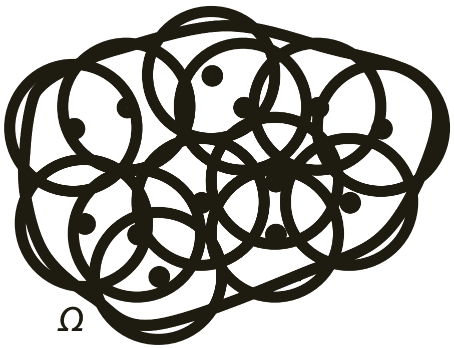
c_d dilatational wave

E elastic modulus

ρ density

	Method 1	Method 2	Method 3	NEW Method
				
Pure Lagrangian	Adaptive technique (ALE)	Pure Eulerian	Coupled Eulerian Lagrangian (CEL)	Meshfree method

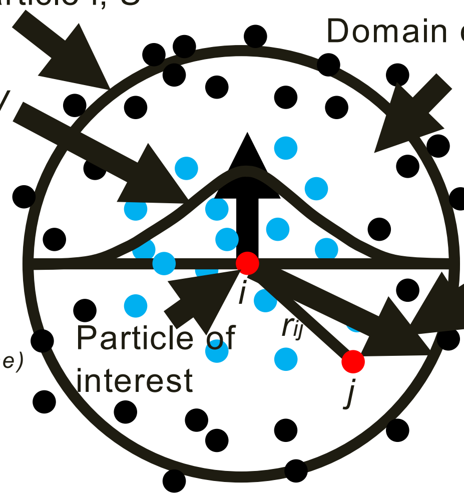
MESHFREE METHOD (SPH)



No element!
No node!

$$f(r) \cong \sum_j \frac{m_j}{\rho_j} f_j W\left(\left|r - r_j\right|, h\right)$$

f(r): field variable
r: location of the particles
m_j: associate mas
ρ_j: associate density
h: smoothing length (or radius of influence)
W: Kernel function



Governing Equations

Continuity:
$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j \left(v_i^\beta - v_j^\beta\right)\frac{\partial W_{i,j}}{\partial x_i}$$

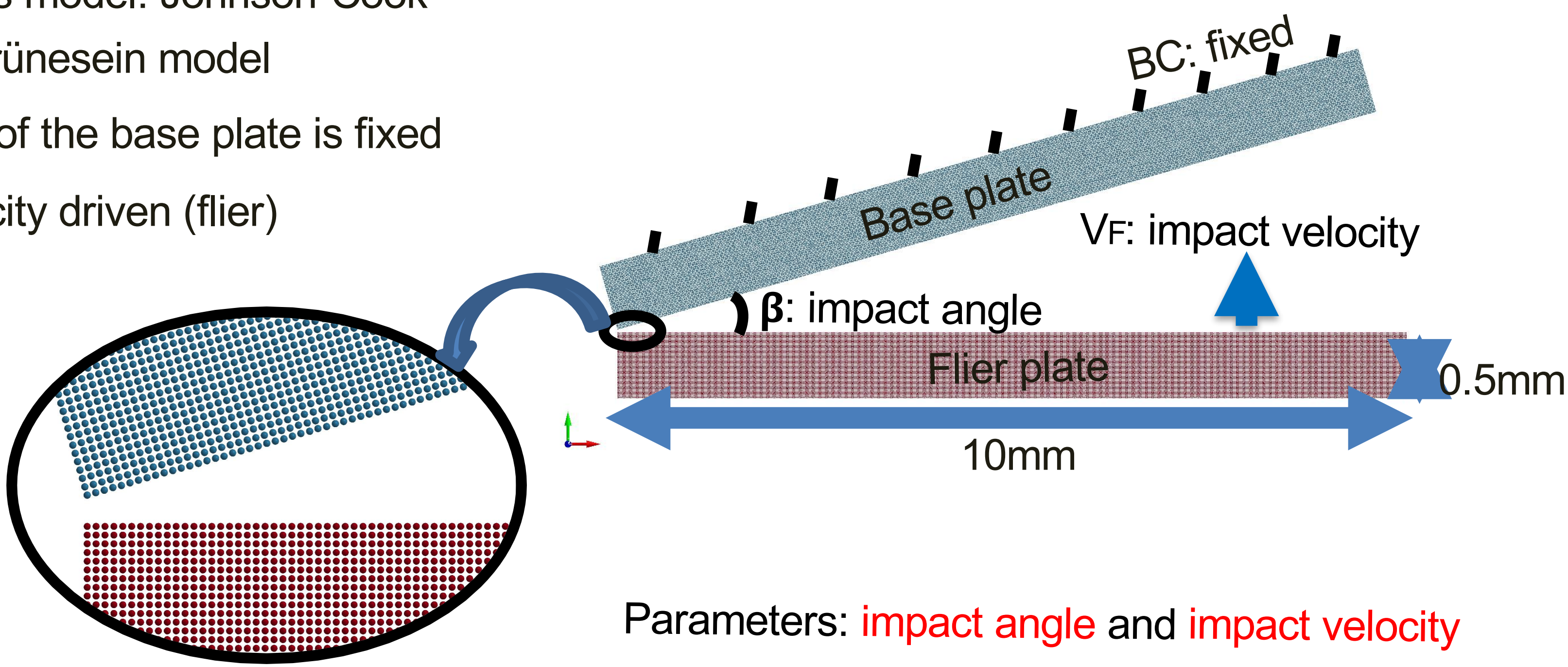
Momentum:
$$\frac{Dv_i^\alpha}{Dt} = -\sum_{j=1}^{N} m_j \left(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_j^{\alpha\beta}}{\rho_j^2} + \pi_{i,j}\right)\frac{\partial W_{i,j}}{\partial x_i}$$

Energy:
$$\frac{De_i}{Dt} = \frac{1}{2}\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \pi_{i,j}\right)\left(v_i^\beta - v_j^\beta\right)\frac{\partial W_{i,j}}{\partial x_i} + \frac{1}{\rho_i}\tau_i^{\alpha\beta}\varepsilon_i^{\alpha\beta} + H_i$$

α, β: *space indices*
$\pi_{i,j}$ *: artificial viscosity*
H_i*: artificial heating (in this study is zero)*

NUMERICAL MODEL SETUP

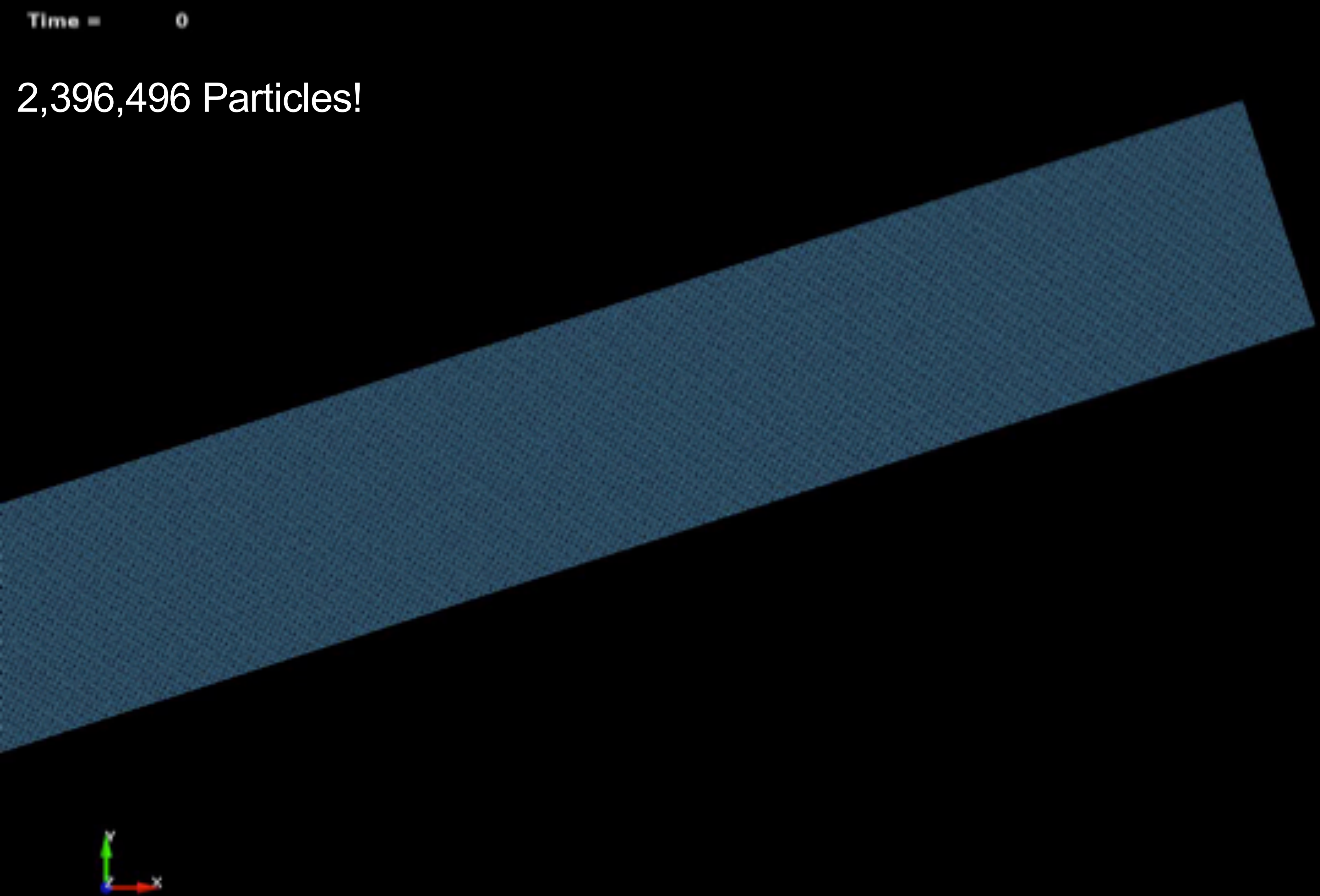
- Coupled thermo-mechanical model
- Particle size: 2-5μm
- Total number of particles: 2,396,496
- Materials model: Johnson-Cook
- EOS: Grünesein model
- BC: top of the base plate is fixed
- IC: velocity driven (flier)



Parameters: impact angle and impact velocity

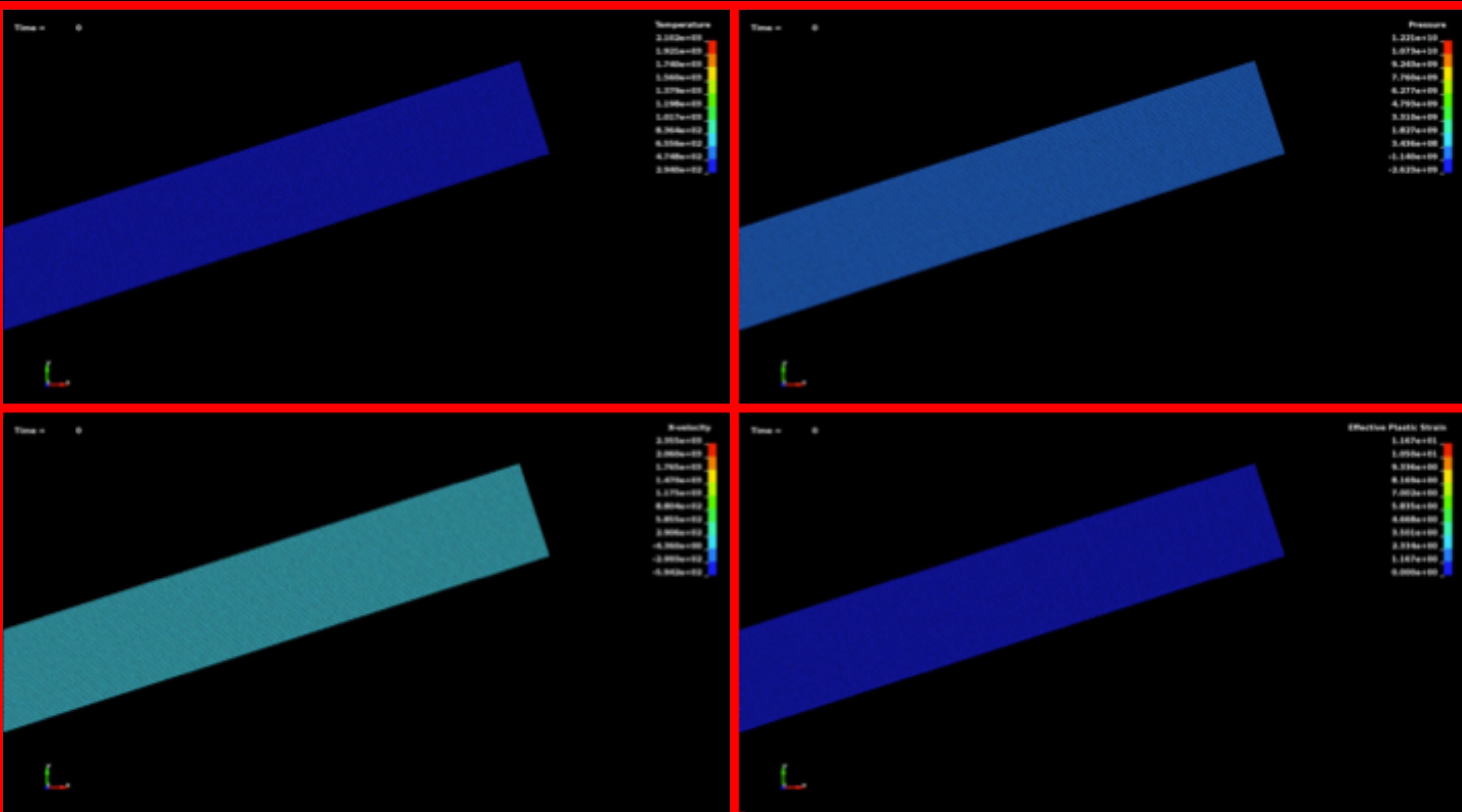
COPPER/TITANIUM IMPACT

2,396,496 Particles!



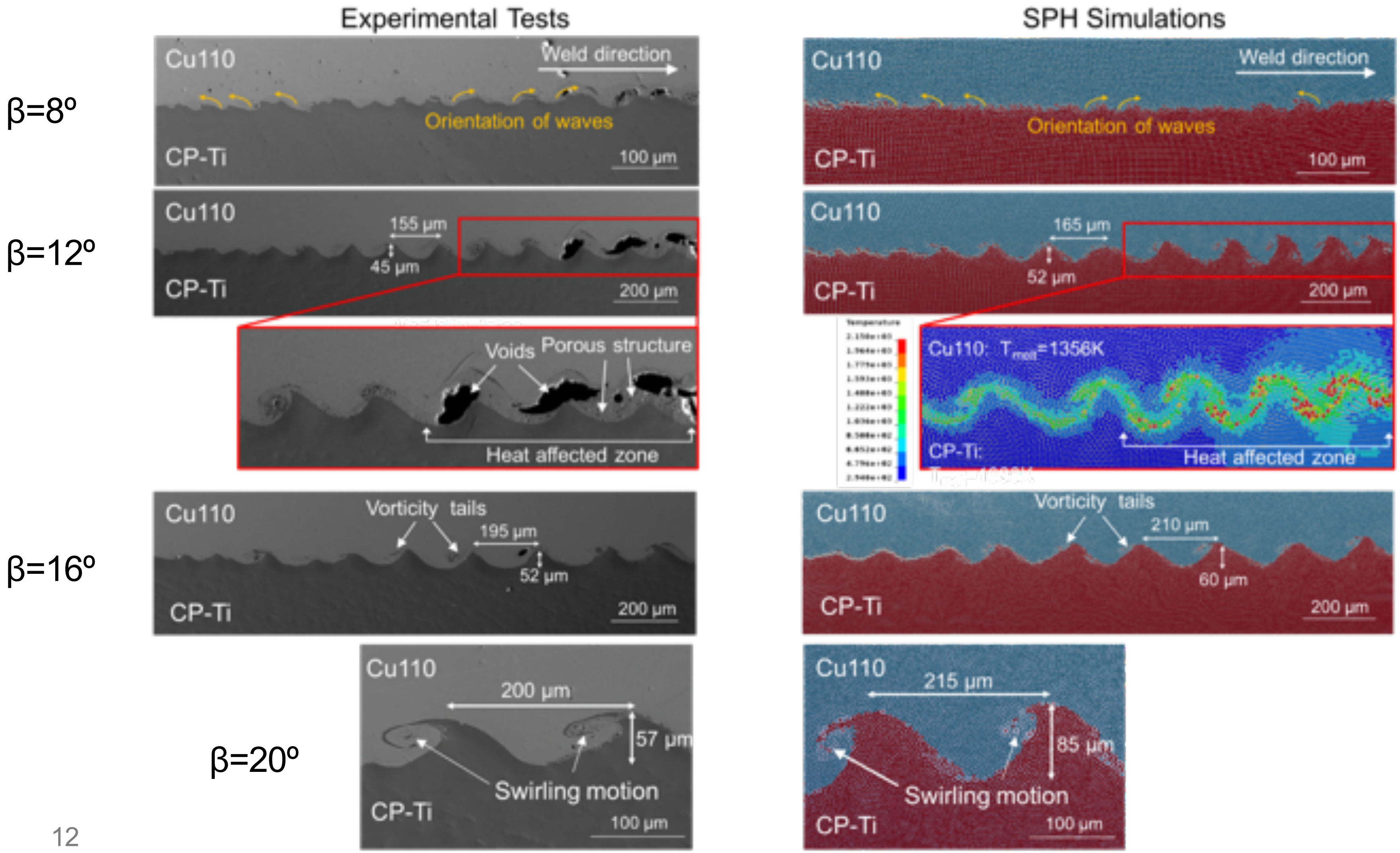
Experimental test

COPPER/TITANIUM IMPACT

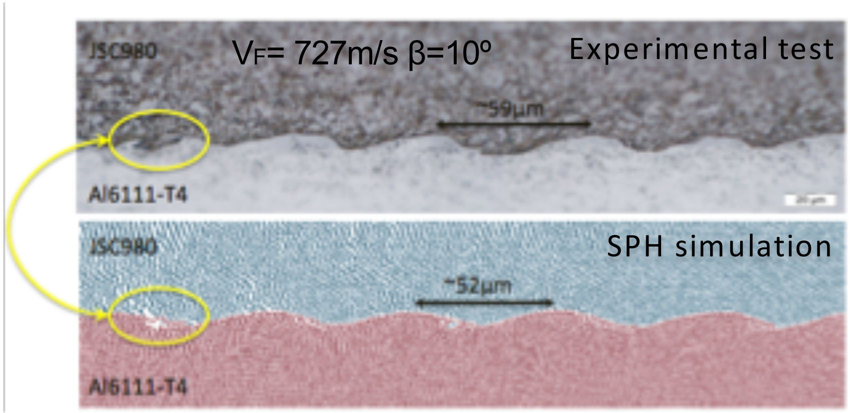


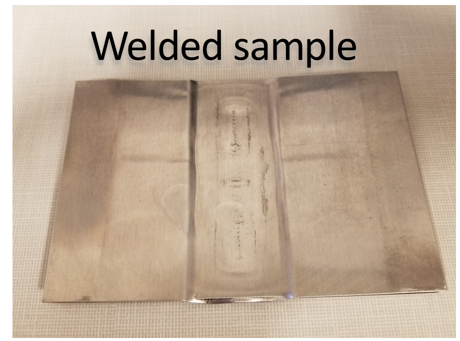
Impact velocity: 670m/s

COPPER/TITANIUM IMPACT

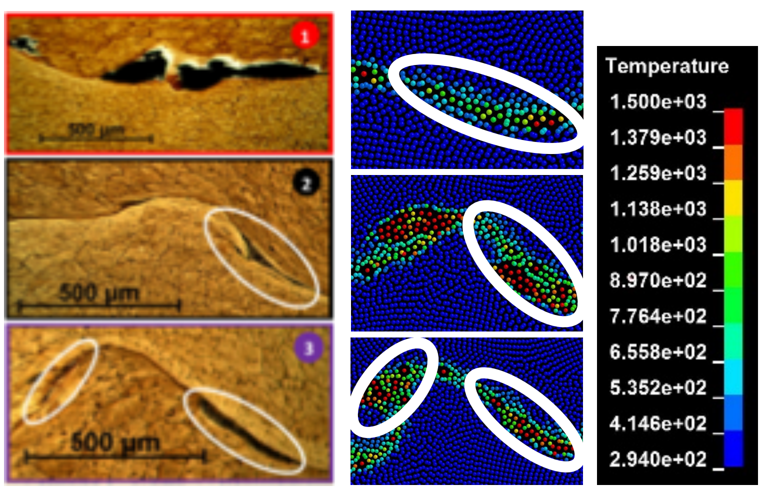


DIFFERENT METAL PAIRS



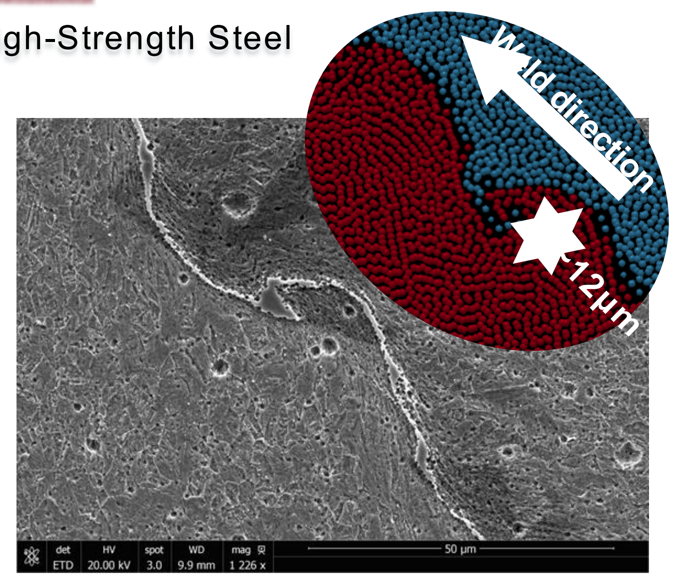


Al6111-T4/High-Strength Steel



Al6060-T5/ Al6060-T5

Experimental tests (Sapanathan et al., 2016)

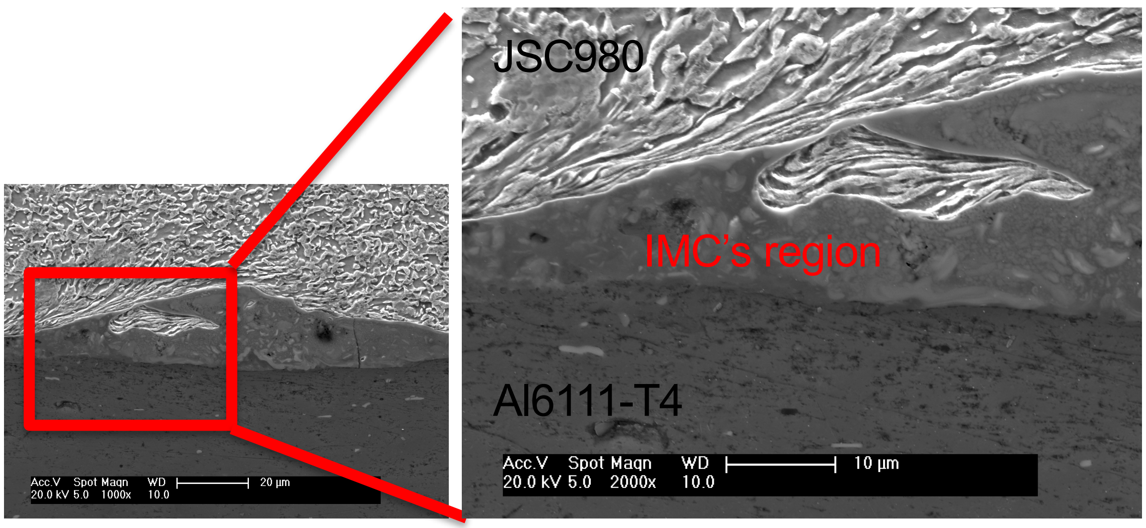


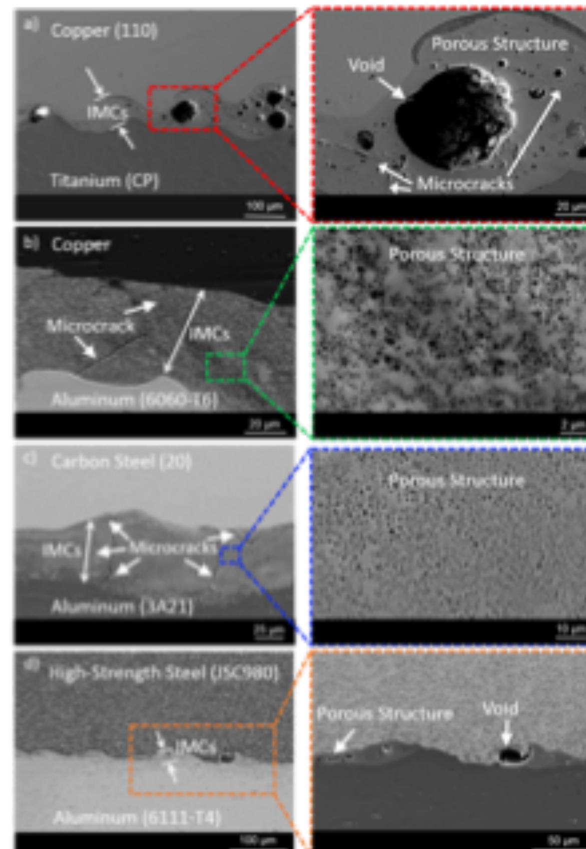
AM steel/AM steel

Experimental test (courtesy of Bert Liu, AFRL)

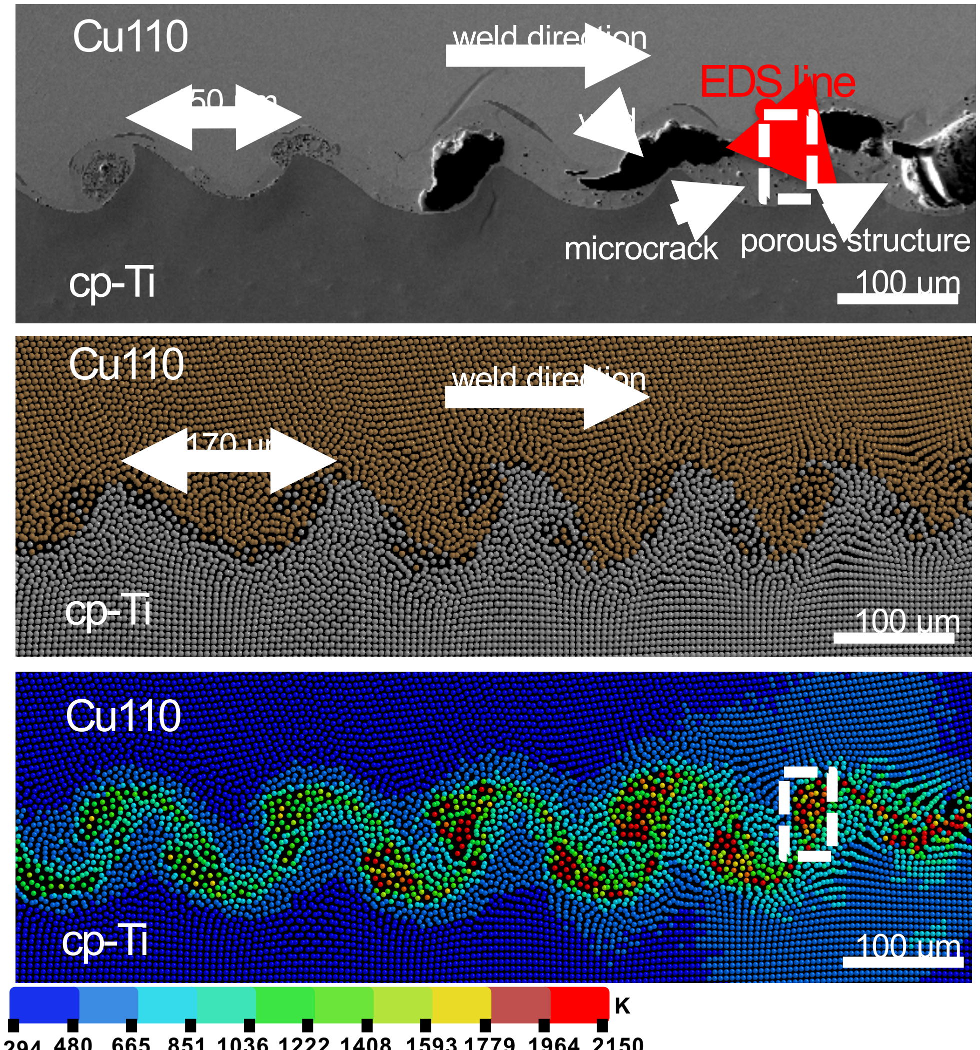
MODEL CALIBRATION

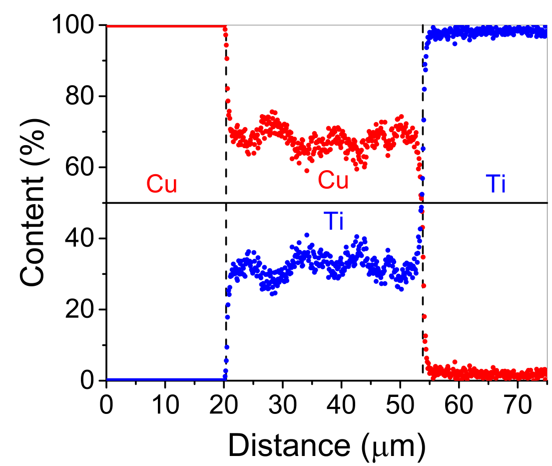
- Leveraging advanced characterization to calibrate the numerical simulations
- Foil was created using Focused Ion Beam (FIB)
- Transmission Kikuchi Diffraction (TKD) analysis was conducted

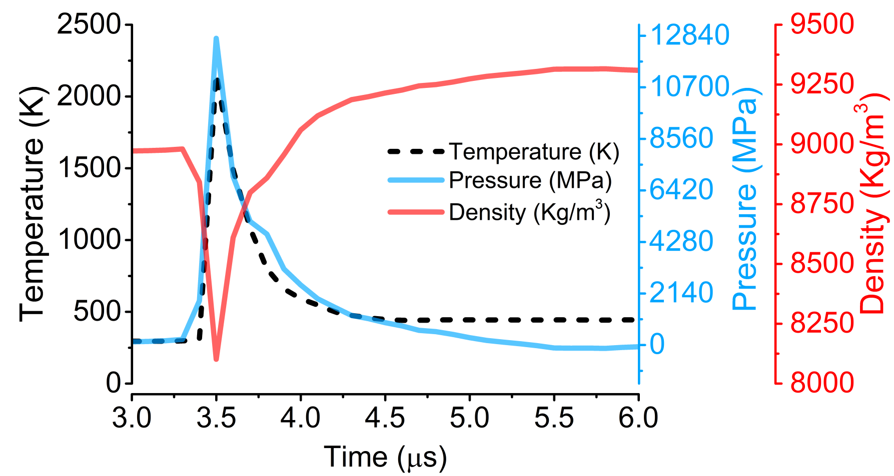




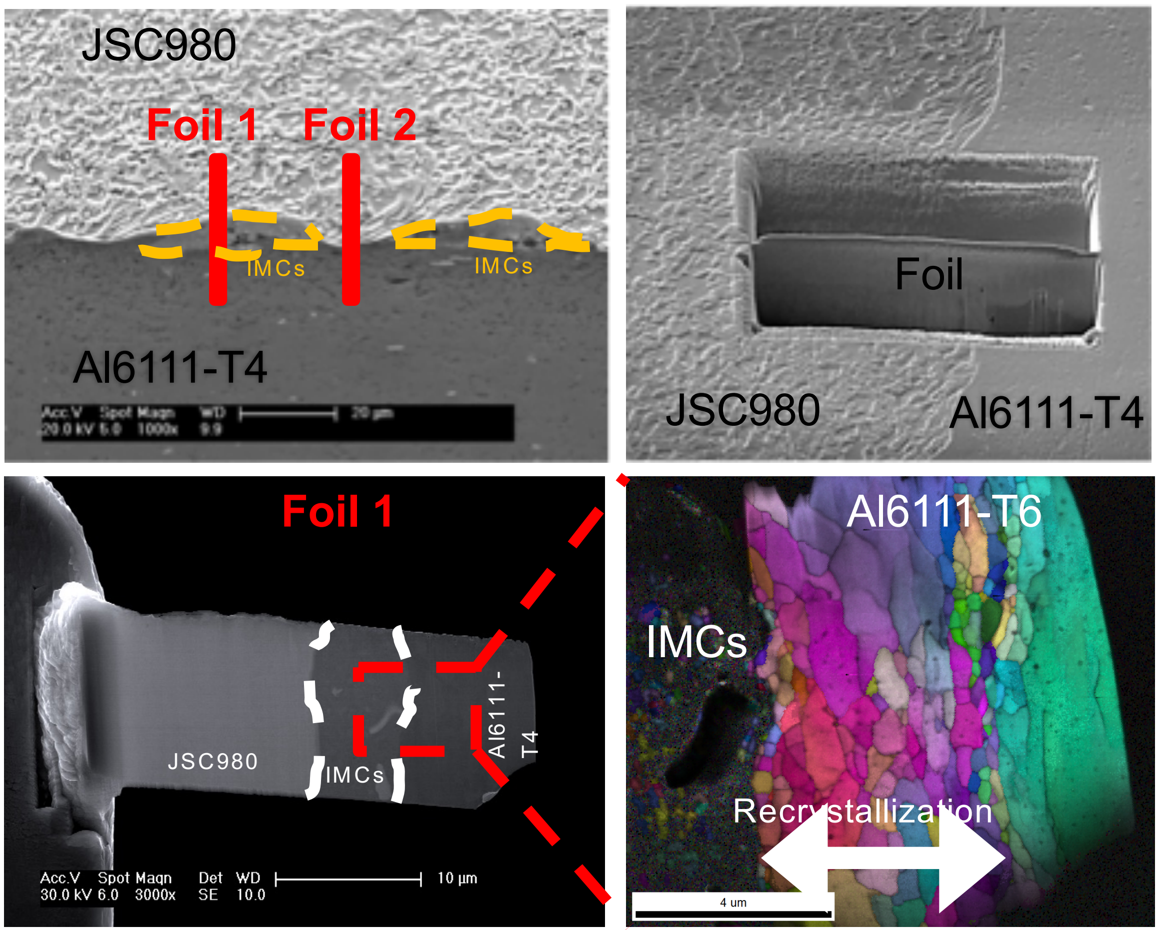
COPPER/TITANIUM IMPACT



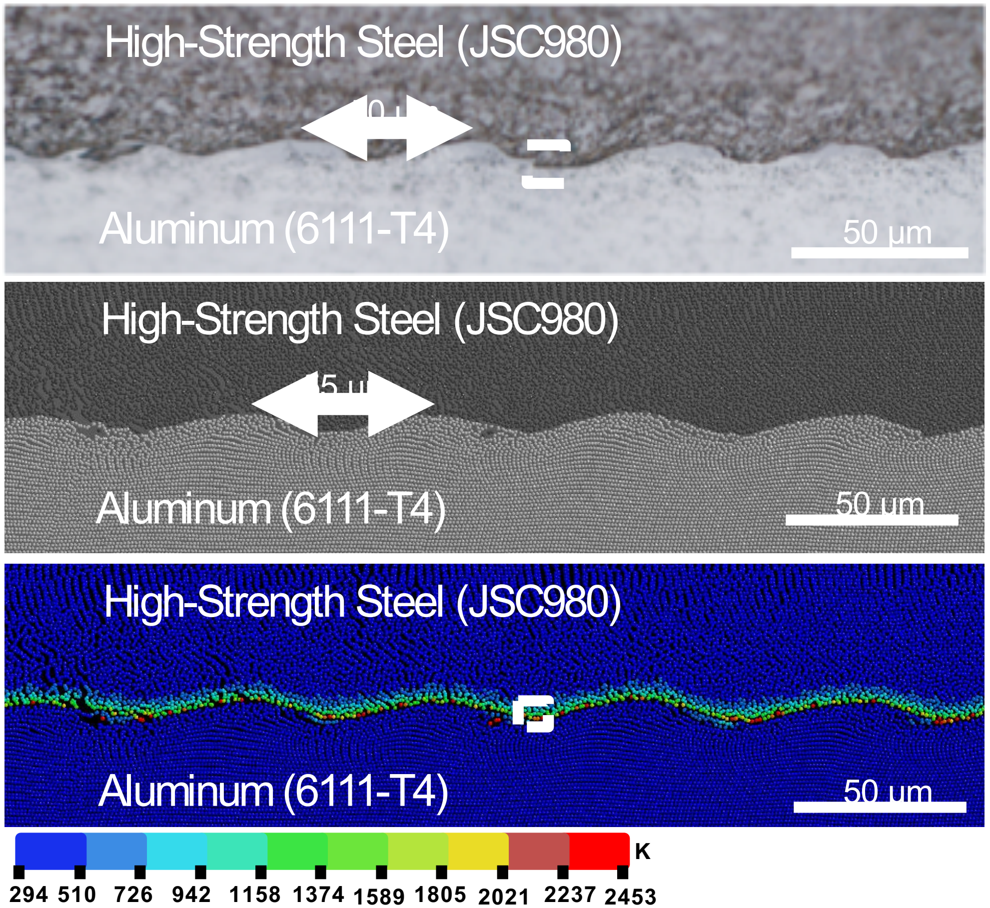


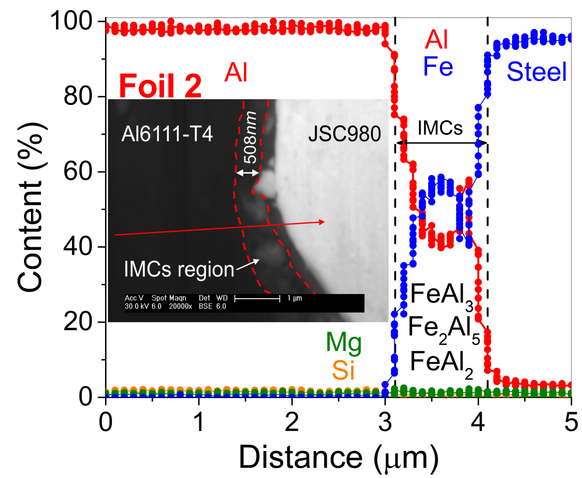


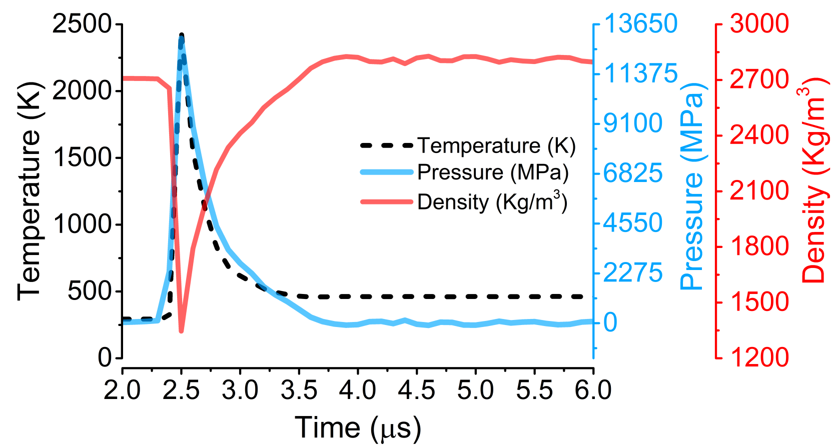
ALUMINUM/STEEL IMPACT



ALUMINUM/STEEL IMPACT

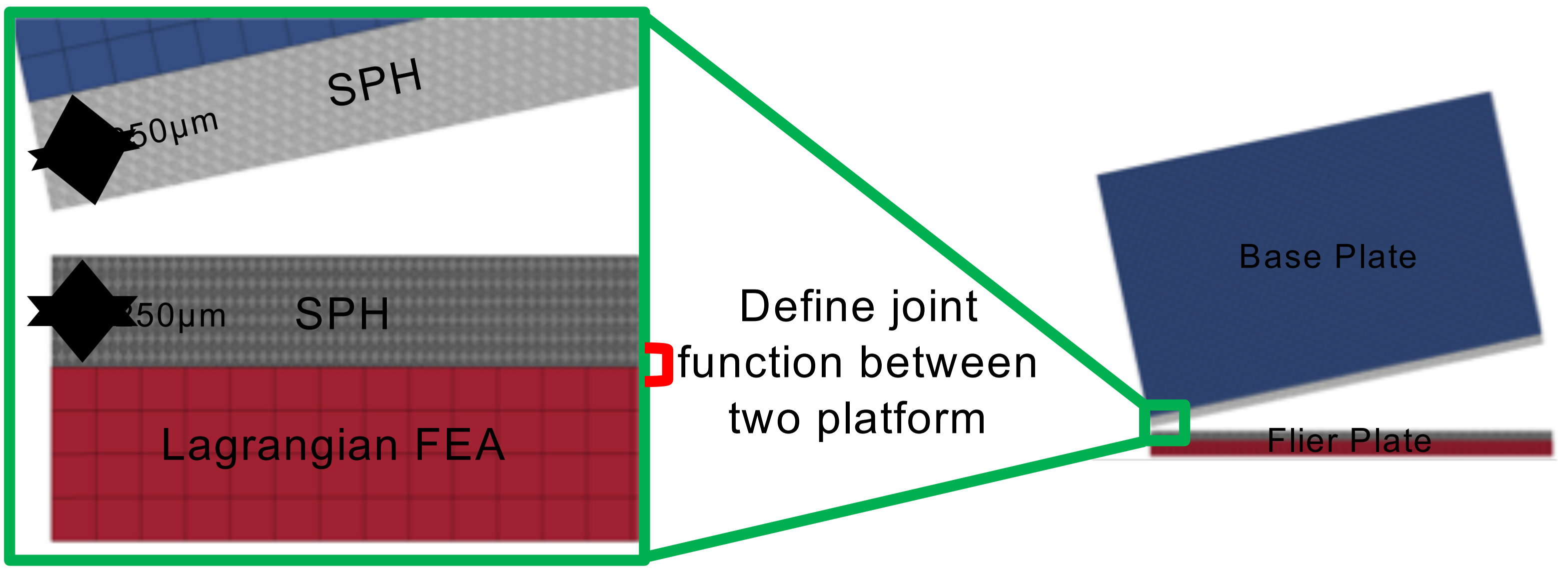




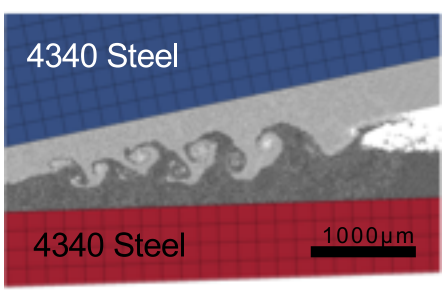


HYBRID PLATFORM

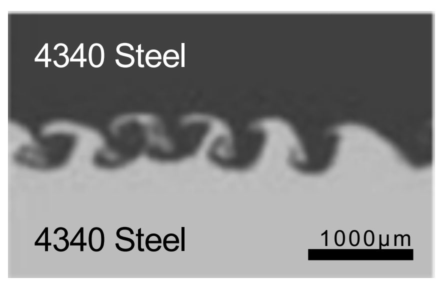
- To save computational time, a hybrid platform was created by defining joint function
- Submicron Scale Particles! → instead of 2M particles, less than 80,000 particles were generated



Reduced the computational time to ¼ !

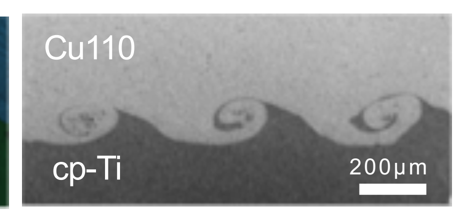


SPH Simulation

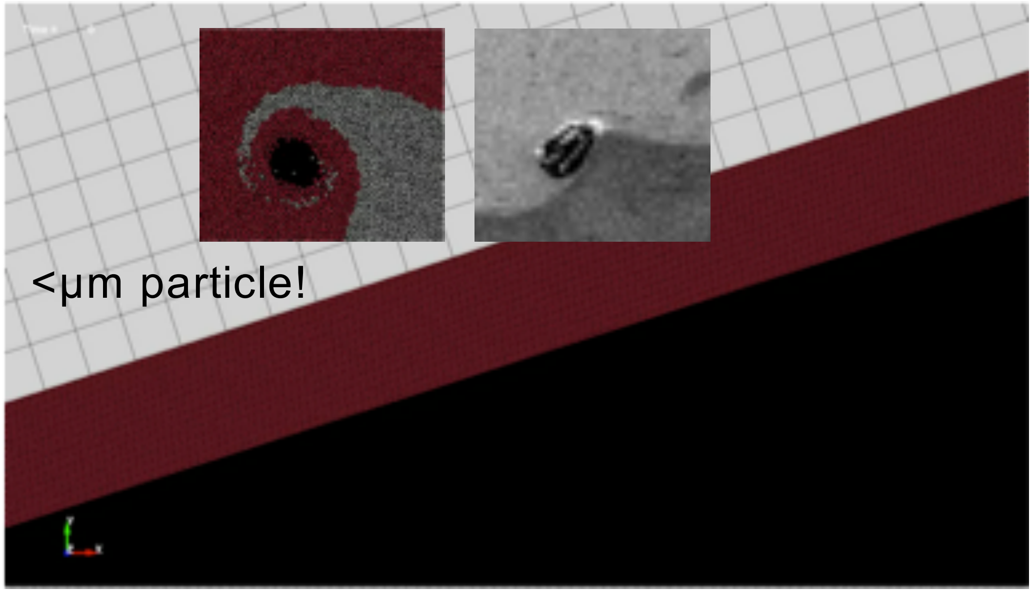


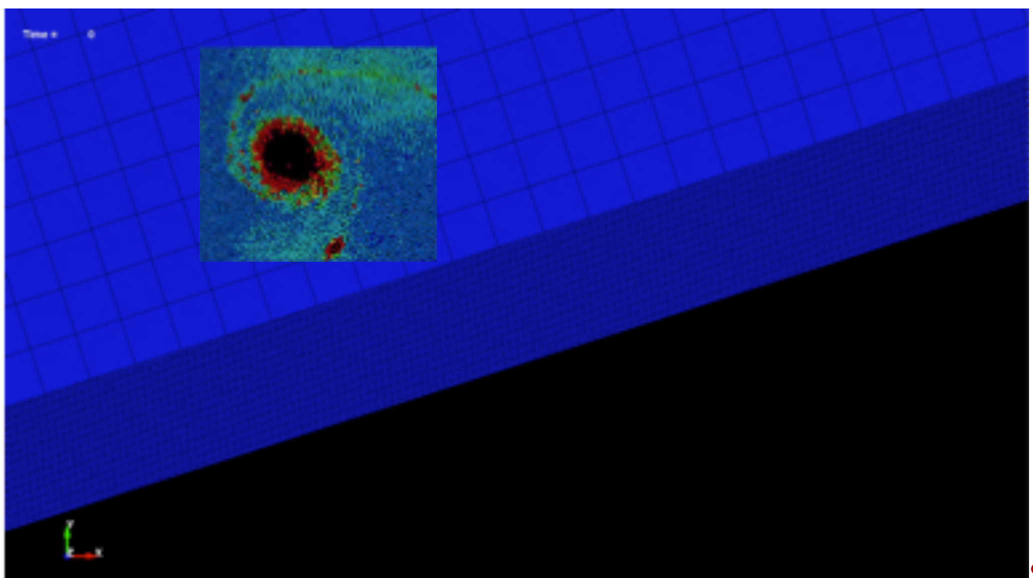
Result from EXW (Li at al. 2012)

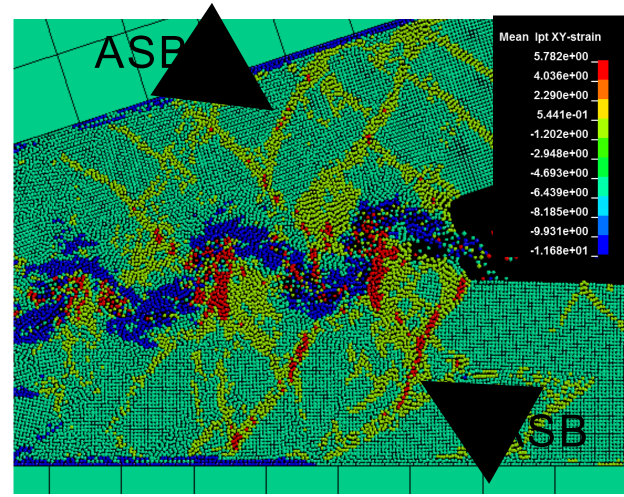
SPH Simulation

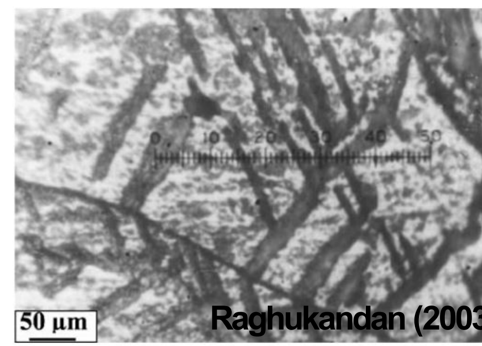


Result from VFAW


<μm particle!



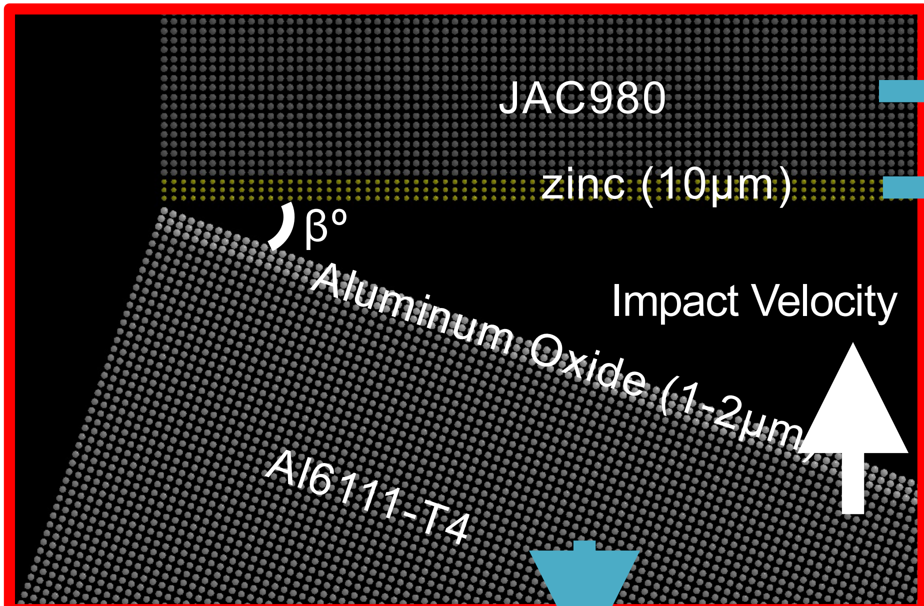

ASB
Mean Ipt XY-strain
5.782e+00
4.036e+00
2.290e+00
5.441e-01
-1.202e+00
-2.948e+00
-4.693e+00
-6.439e+00
-8.185e+00
-9.931e+00
-1.168e+01
ASB


50 μm
Raghukandan (2003)


Melt
7075
Melt
Interface
AZ31B
Adiabatic shear band
Yan et al. (2010)
Jet direction
500μm

HYBRID PLATFORM

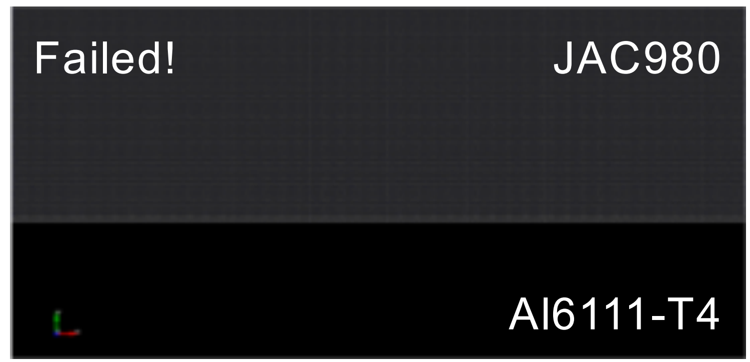
- Coating, surface oxides, impurities, and etc. can be added to the structure



Johnson-Cook

Johnson-Cook Failure

Johnson-Cook

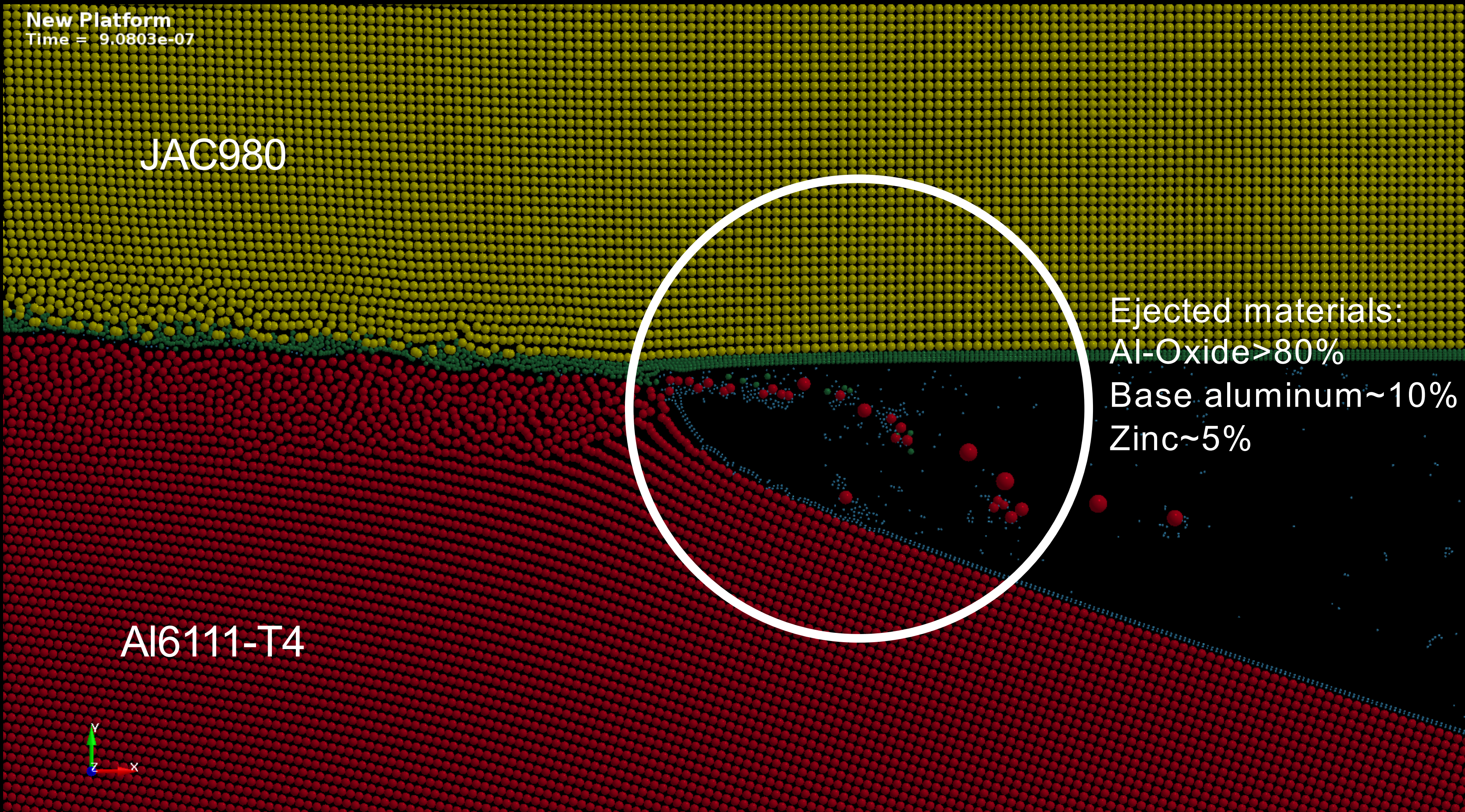


Each Layer → Different Material

Different Thermo-Mechanical Property

HYBRID PLATFORM

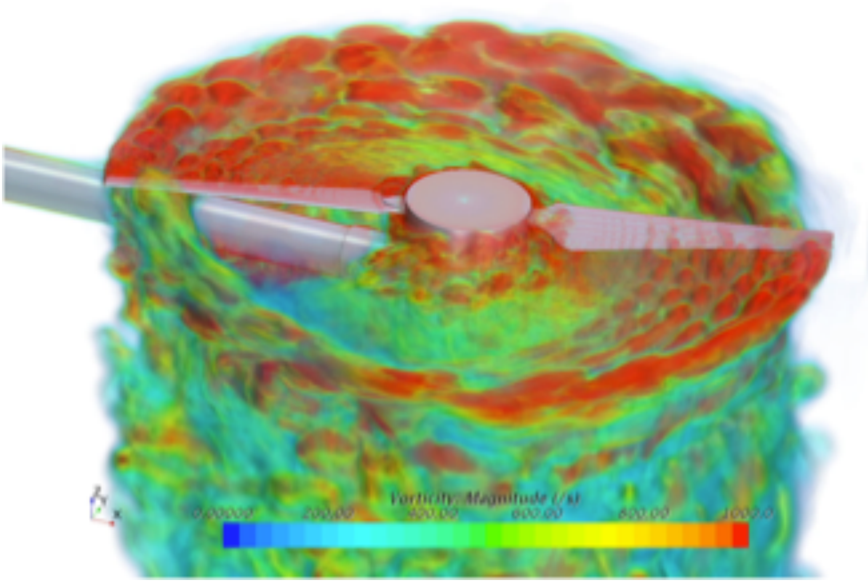
Impact velocity, V_F=900m/s



CONCLUSIONS

- SPH platform is developed to simulate the HVIW
- The model predicts key process parameters such as collision velocity, shear stress, pressure, temperature, etc.
- SPH method is able to accurately simulate both the wavy morphology and the jetted materials
- The emergence of significant grain refinement could be associated to melting and subsequent recrystallization due to the ultra-fast heating and cooling rate of the high pressure impact process.
- Hybrid Platform is created to save computational time as well as to capture the effects of different coating layers

Simulation Innovation and Modeling Center



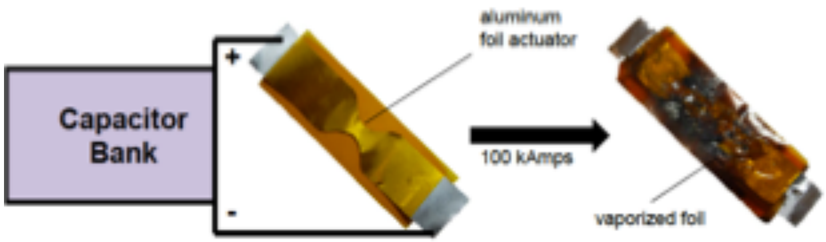
- Computational Solid and Structural Mechanics
- Computational Fluid Mechanics
- Multiphysics Simulations
- Optimization and CAE Automation
- System Modeling, Integration, and Control

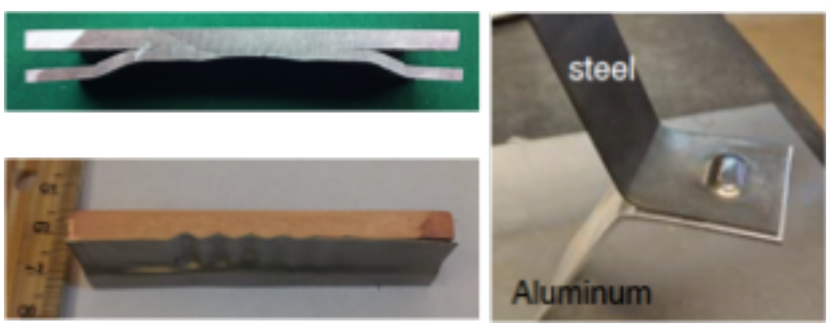
Questions?

EXTRA SLIDES

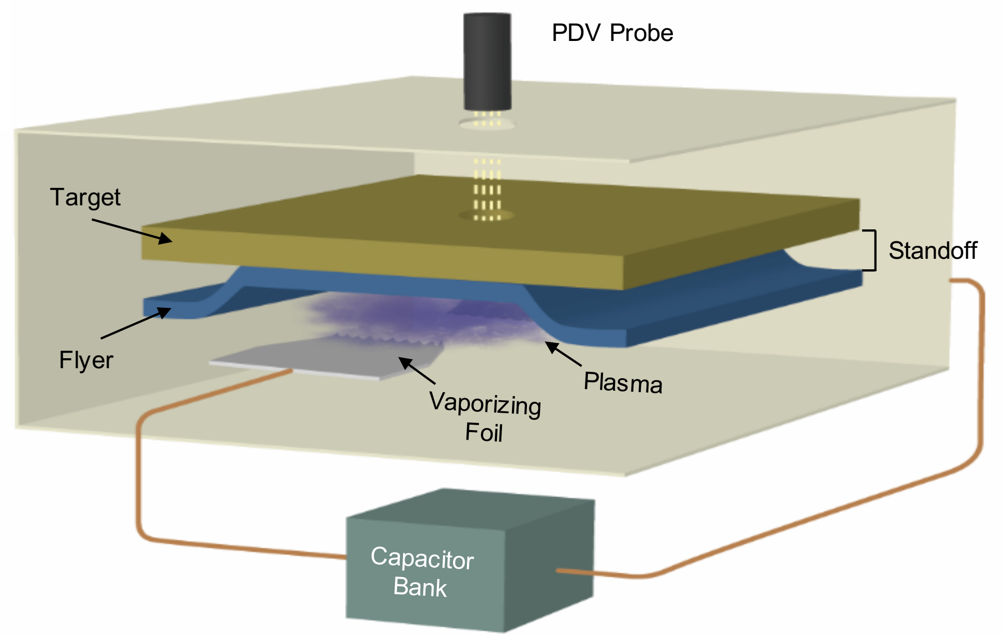
EXPERIMENTAL TEST (VFAW)

- Vaporizing Foil Actuator Welding (VFAW) invented at the Ohio State University
- Advantages: conductivity NOT required, more efficient than Magnetic Pulse Welding





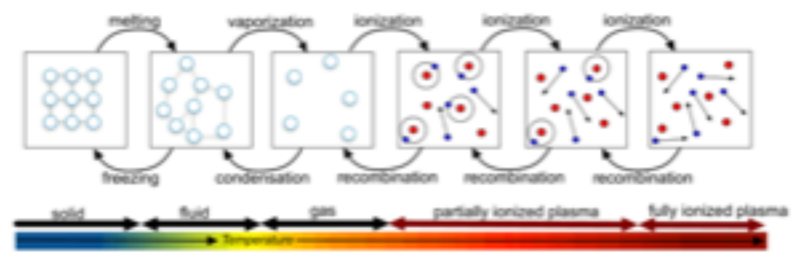
Typical welded Samples

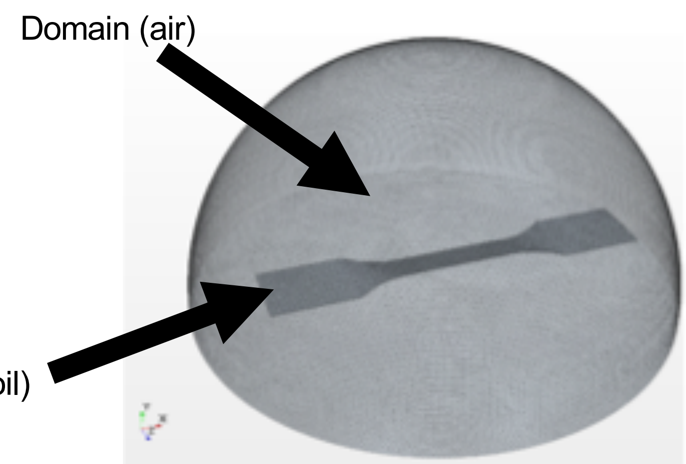


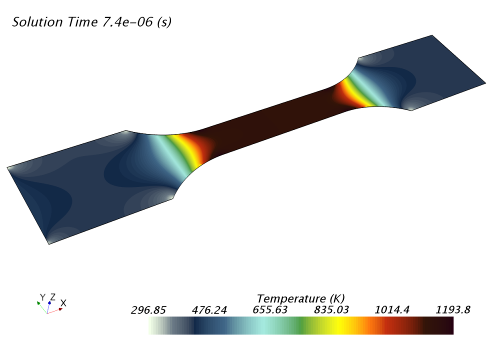
Schematic of the VFAW process (https://iml.osu.edu/)

MULTIPHYSICS MODELING OF FOIL VAPORIZATION

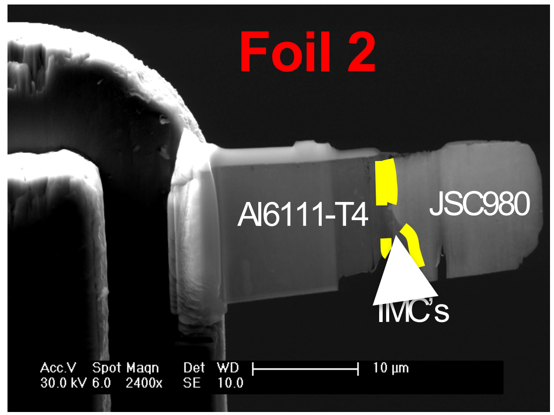
- The proposed multiphysics model would have the below interfaces:
  a) Joule heating
  b) Heat transfer in solid
  c) Structural analysis in solid
  d) Convection heat transfer to domain
  e) Radiation heat transfer to domain
  f) Mass Transfer due to vaporization
  g) Plasma formation
  h) Aeroacoustic



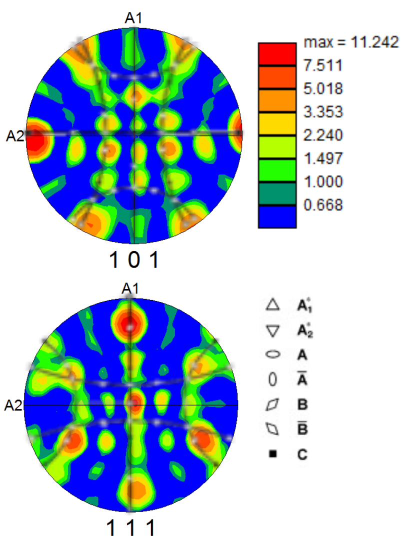


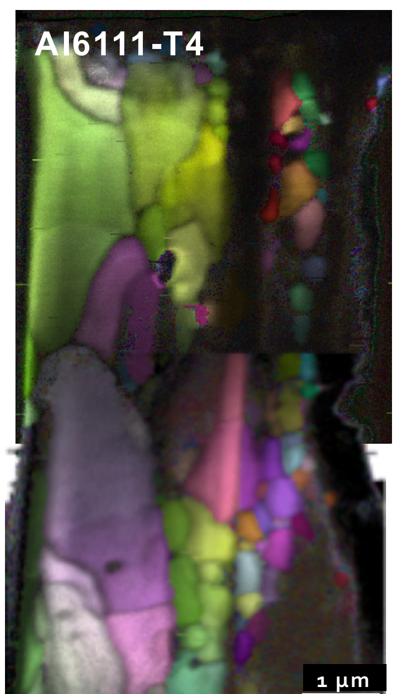


TKD ANALYSIS

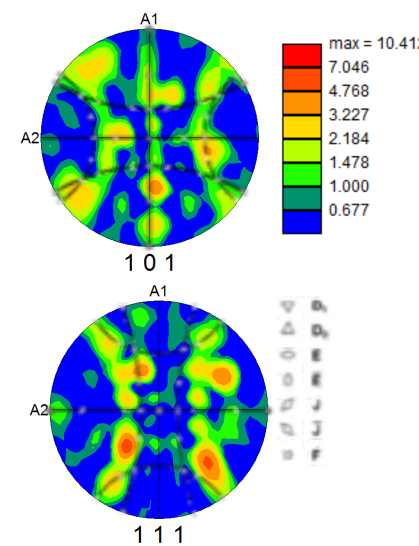


- Strong B/-B {112}<110> texture, commonly seen in literature for Al alloy in shear
- May be weak A{111}<112> shear components present





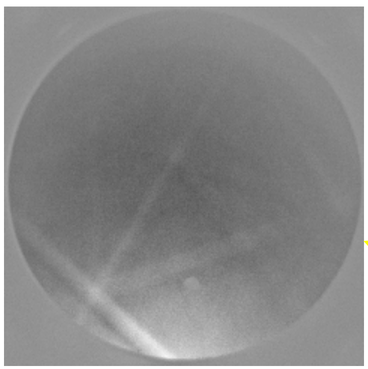
- May be slightly rotated – usually pole figures will not match up exactly to ideal shear components.
- D {112}<111> shear is typically observed in steels

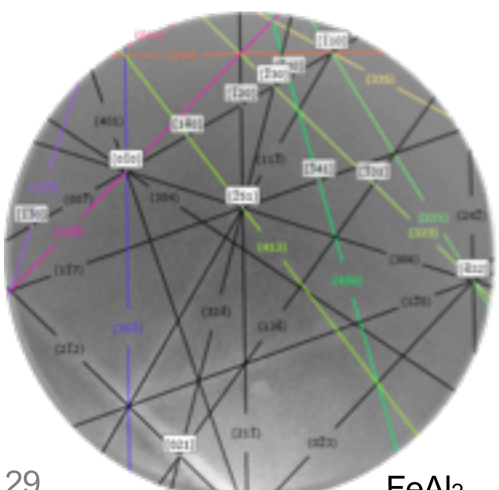


EDS, TKD ANALYSIS

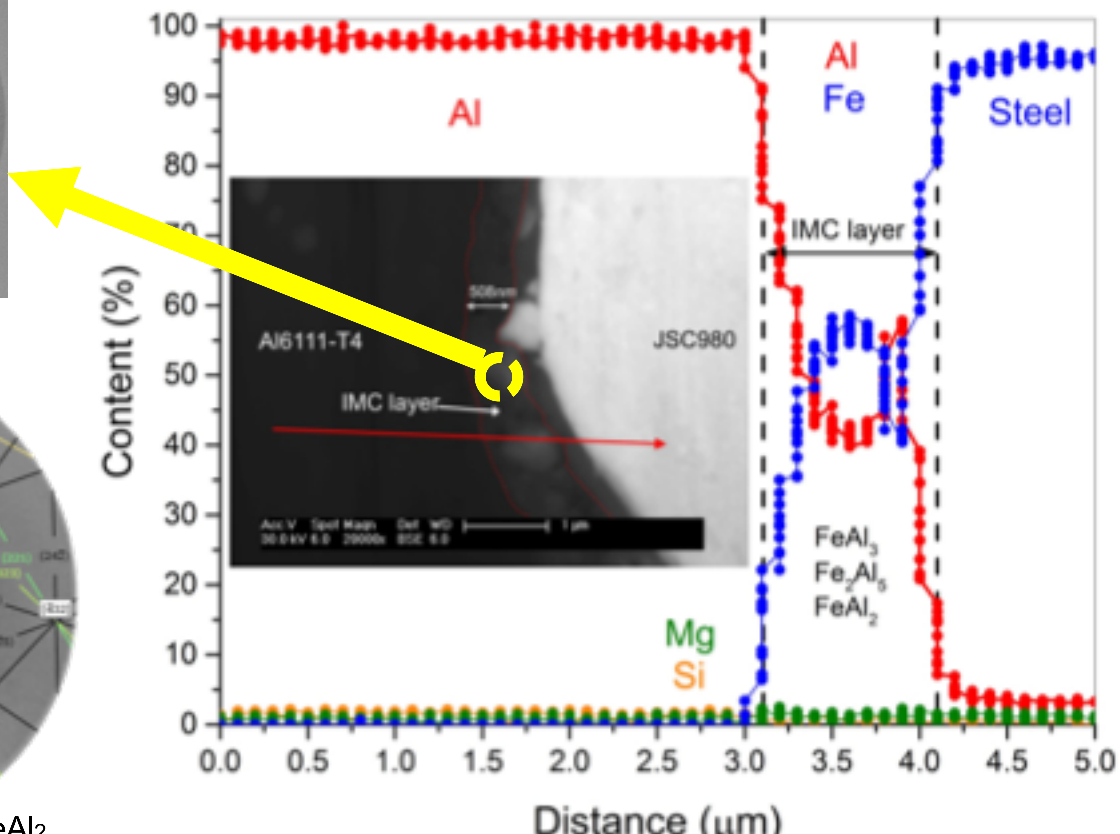
- For chemical characterization of the sample Energy Dispersive Spectroscopy (EDS)
- Three IMCs were identified: $FeAl_2$, Fe_2Al_5, $FeAl_3$

Foil 2



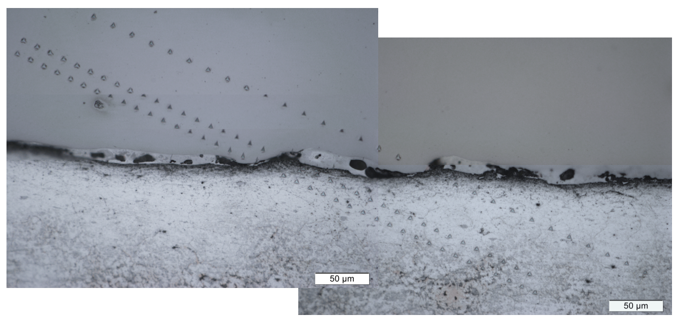


FeAl2

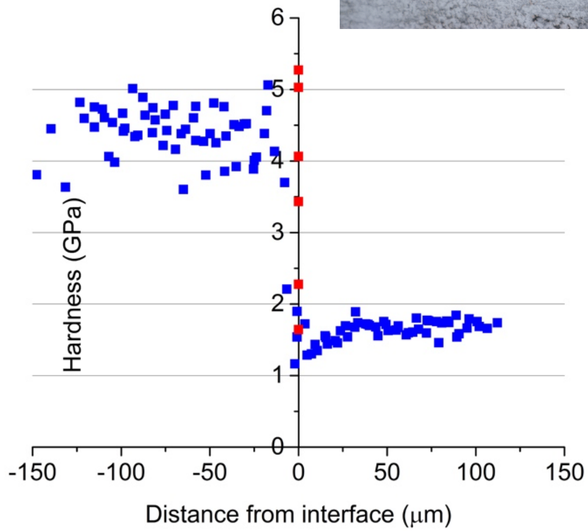


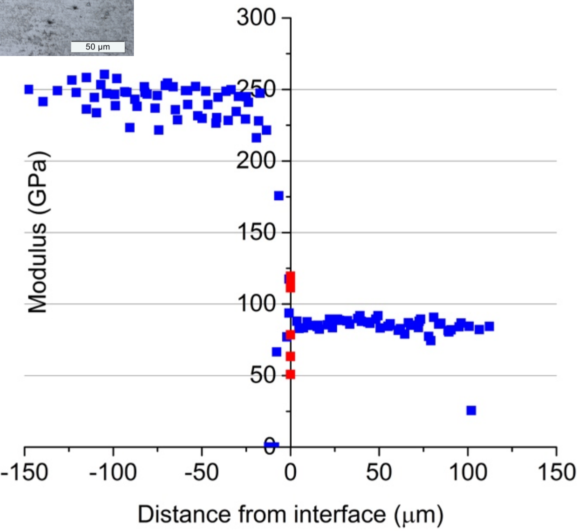
NANINDENTATION TEST

- Frequency distribution shows 2 different modulus and hardness values corresponds to the aluminum and steel values
- Steel: 242.1 GPa modulus; 4.4 GPa hardness
- Aluminum: 85.0 GPa modulus; 1.7 GPa hardness

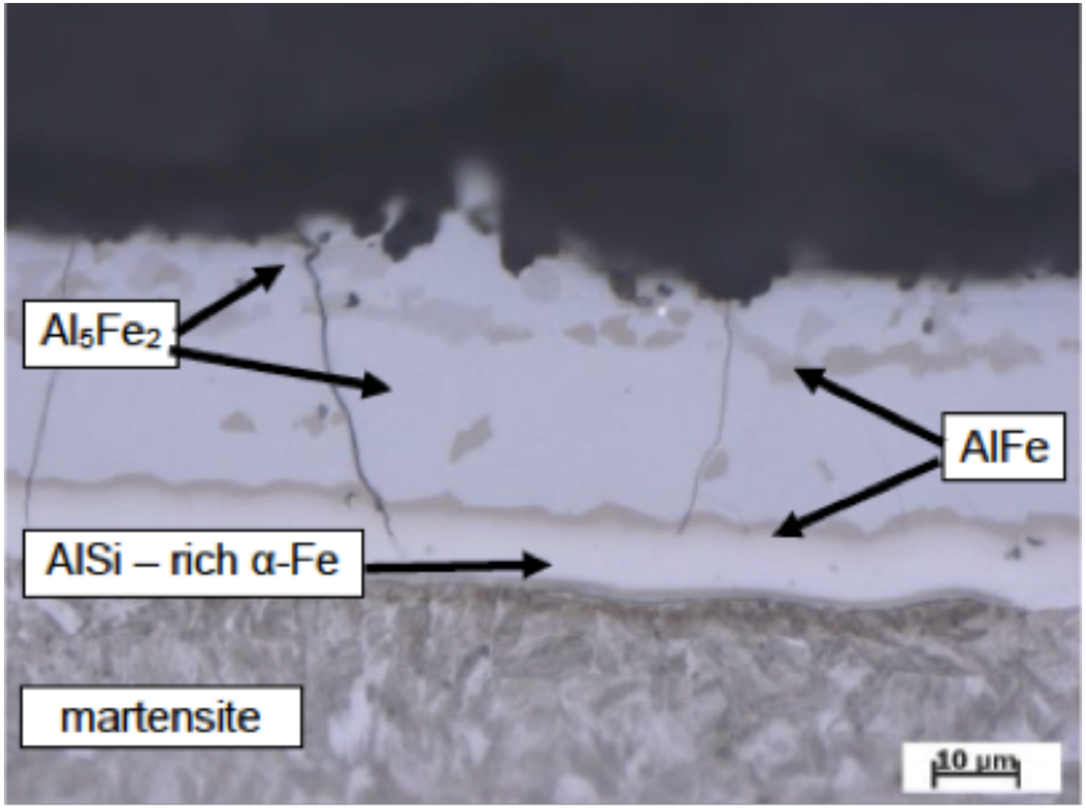


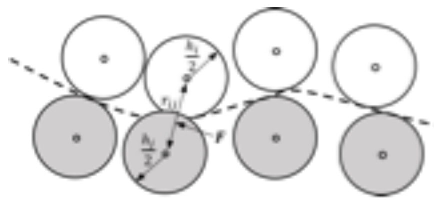
IMCs may not associated with melting!





COATING





$$pe = \frac{h_i + h_j}{2r_{ij}} \geq 1$$

$$F = \begin{cases} p(pe^{n_1} - pe^{n_1}), & pe \geq 1 \\ 0, & pe < 1 \end{cases}$$