FINITE ELEMENT ANALYSIS OF FRICTION STIR WELDING OF AL ALLOY AND INCONEL 718

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AGENDA

- Motivation
- Scope
- Methodology
- Results
- Conclusion

MOTIVATION

- Most of the advanced manufacturing processes utilize heating and/or generate heat during the production.
- Heat directly affects the dimensional accuracy of the parts, their microstructure (porosity, anisotropy, …), their mechanical properties, and their surface quality.
- In this study we will address one of the main manufacturing processes, friction stir welding (FSW)

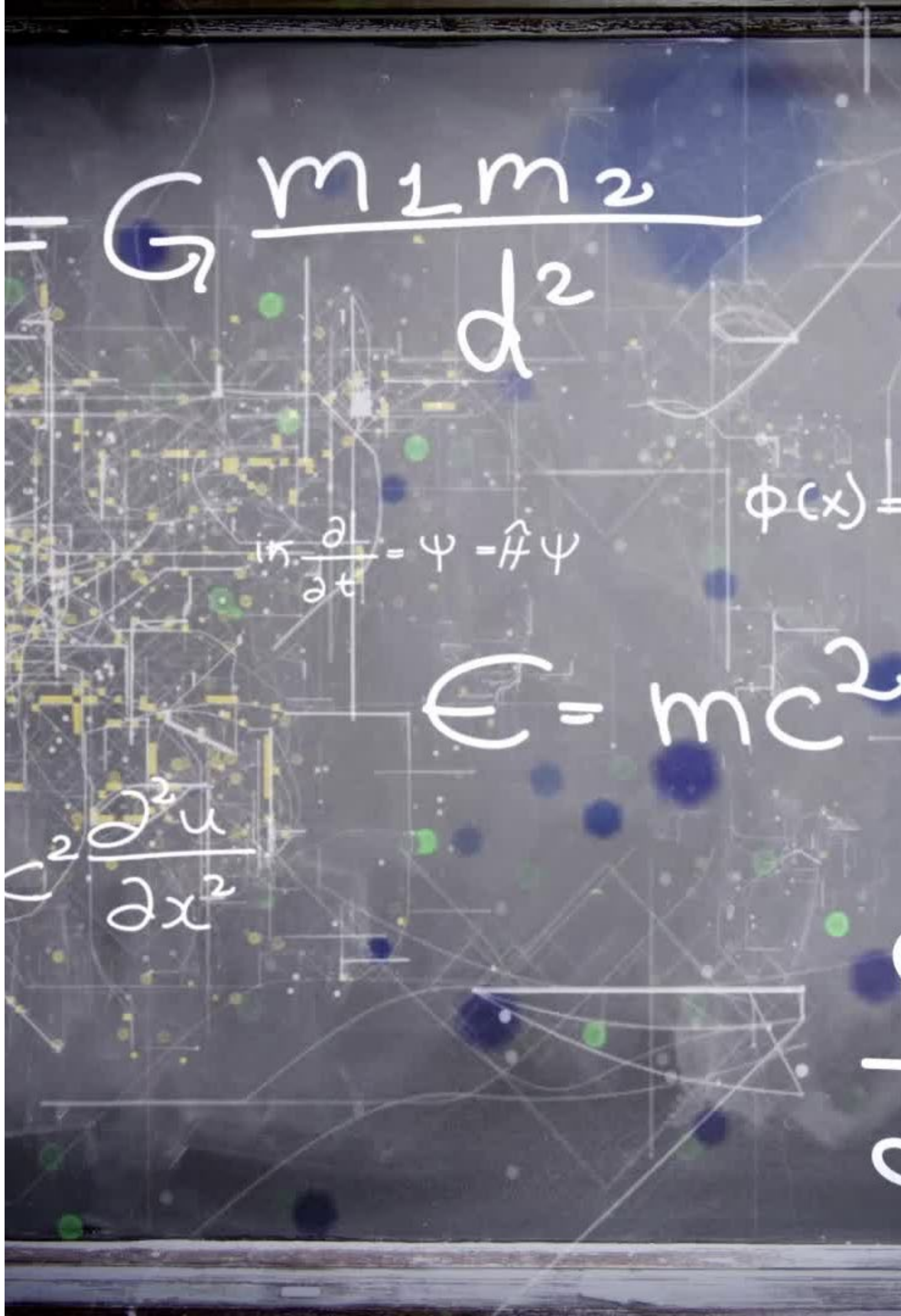
Advancing Additive Manufacturing in Aerospace

MOTIVATION

- New welding technology is often commercialized before a fundamental science emphasizing the underlying physics and chemistry can be developed''.

  by Prof. Thomas W. Eagar, MIT

- Considering the high workpiece material and experimentation cost, modelling and simulation of machining processes has become a key factor in the machinability assessment.



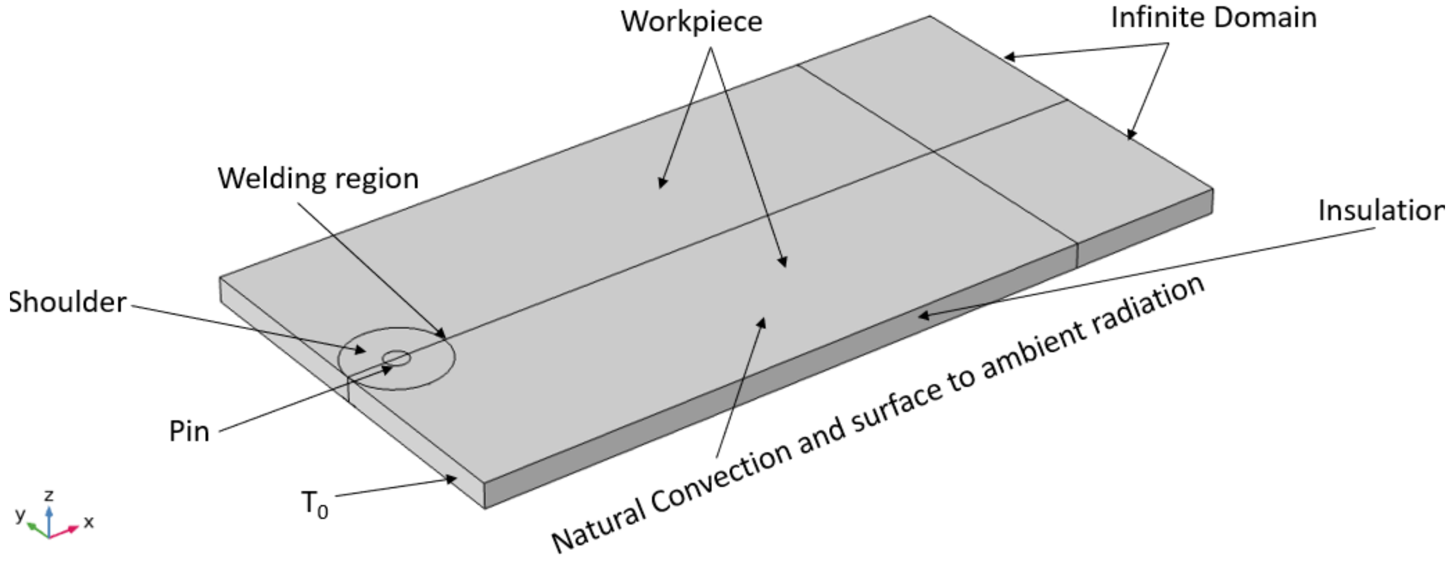
SCOPE

- A validated FEM model aims to correctly predicts the relationships between the process parameters and properties of the material.
- FSW of Al alloy
- FSW of Inconel-718
- Optimizing the process for desired microstructures and properties

METHODOLOGY

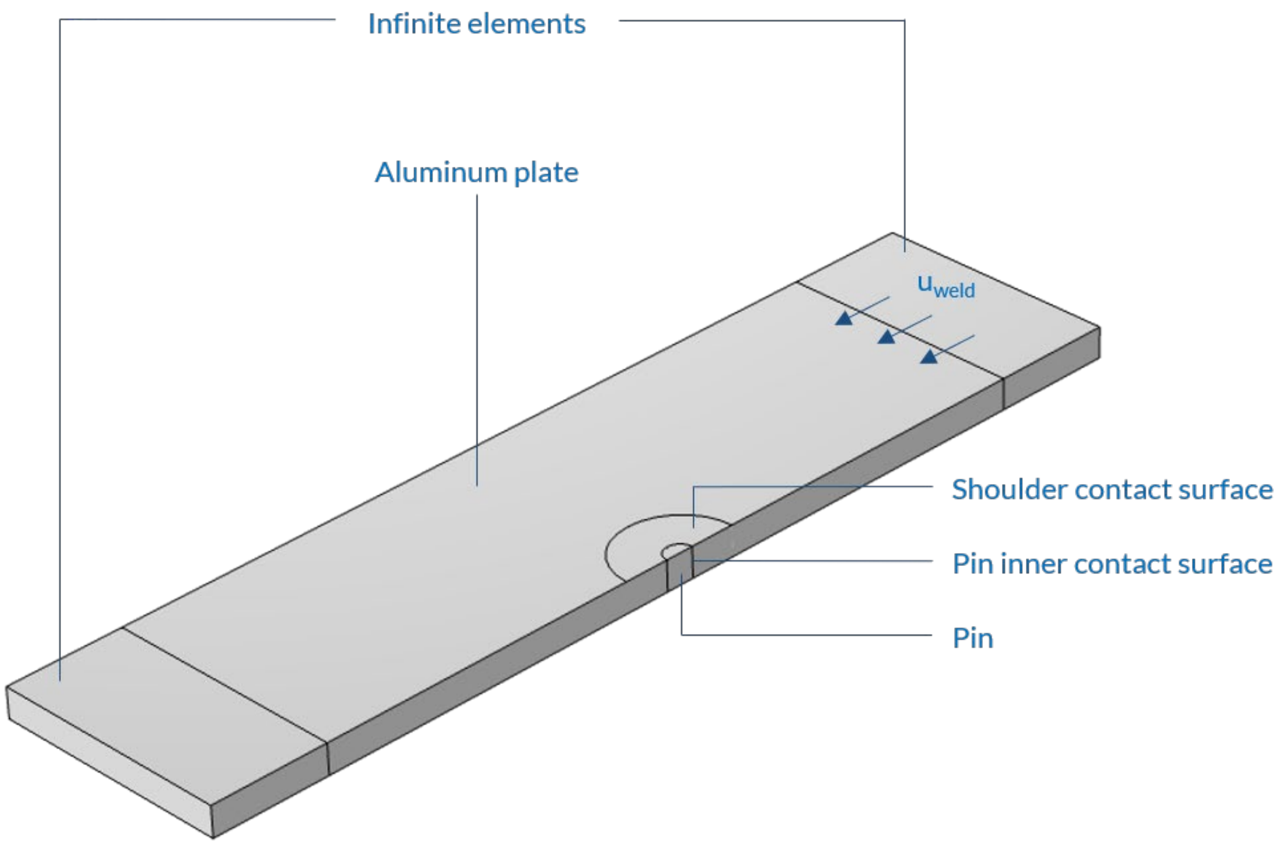
FSW of Al alloy and Inconel 718 by numerical modeling.

- A 3D thermo-mechanical model
- The plate dimensions are 400-by-102-by-12.7 mm.



METHODOLOGY

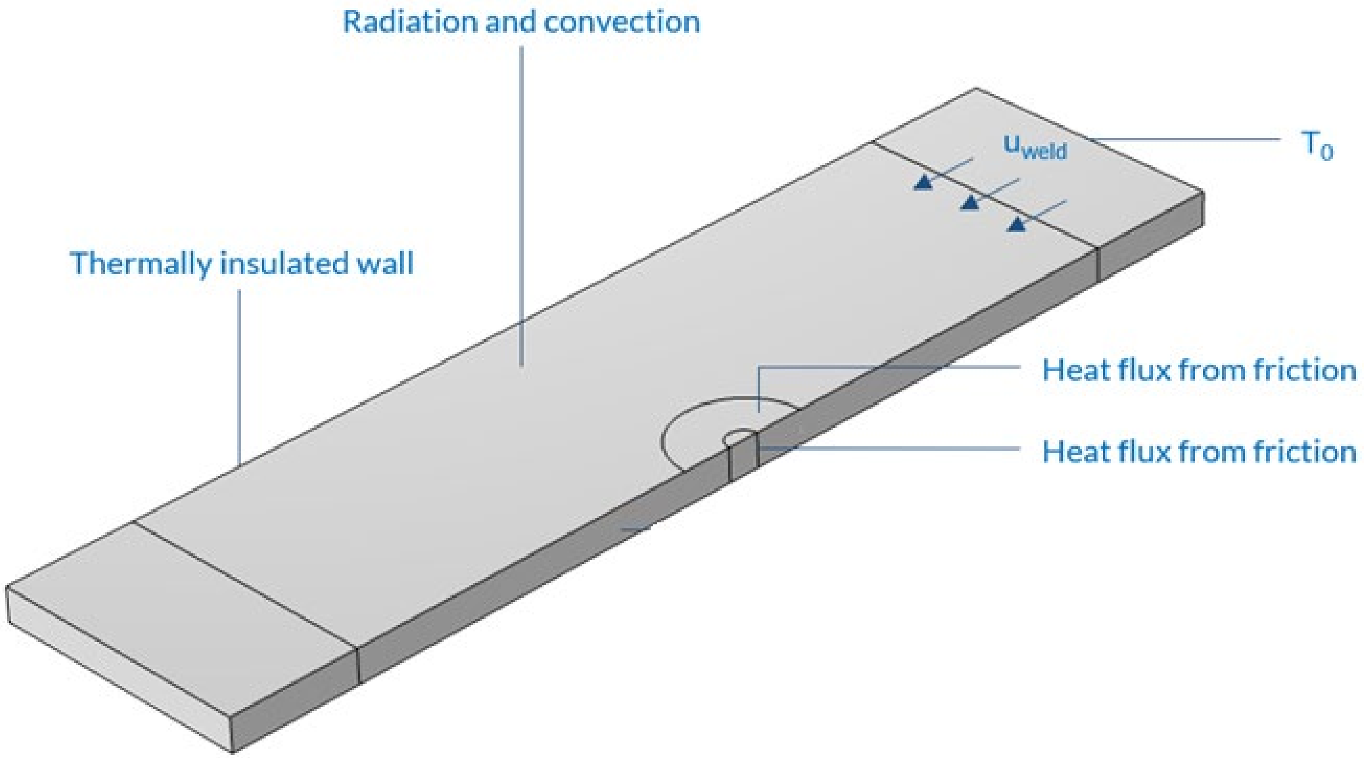
- Instead of modeling the tool as a moving heat source, a moving coordinate system fixed to the tool axis is used
- Two infinite element domains , before and after the welding zone, are used to model an infinitely long plate.
- The rotating tool is divided into two parts: a pin with an inner contact, and a shoulder with a contact surface on the plate.
- The shoulder itself is not represented



Model geometry

METHODOLOGY

- Heat fluxes from friction with the rotating tool are considered on both contact surfaces. They account for the rotating speed and the normal force
- The heat fluxes from friction are set to 0 if the temperature exceeds the melting temperature
- Surface-to-ambient radiation as well as convection are considered on the plate
- The right side of the infinite plate, which corresponds to the supply side, is set to ambient temperature



Model boundary conditions

METHODOLOGY

- Heat transfer by conduction + convection

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q$$

- Heat generated in the interface

$$q_{\text{pin}}(T) = \frac{\mu}{\sqrt{3(1+\mu^2)}} r_{\text{p}} \omega \overline{Y}(T)$$

- Heat generated at the interface between the tool's shoulder and the workpiece

$$q_{\text{shoulder}}(r, T) = \begin{cases} (\mu F_{\text{n}}/A_{\text{s}})\omega r & \text{if } T < T_{\text{melt}} \\ 0 & \text{if } T \geq T_{\text{melt}} \end{cases}$$

- Natural convection and surface-to-ambient radiation

$$q_{\text{u}} = h_{\text{u}}(T_0 - T) + \varepsilon\sigma(T_{\text{amb}}^4 - T^4)$$

$$q_{\text{d}} = h_{\text{d}}(T_0 - T) + \varepsilon\sigma(T_{\text{amb}}^4 - T^4)$$

- Zener–Hollomon parameter for microstructure change

$$Z = \dot{\epsilon}_e \exp\left(\frac{Q}{RT}\right)$$

- Average grain size

$$\ln(d) = 9 - 0.27 \ln(Z)$$

- Hall–Petch relationship for microhardness estimation

$$H_v = 40 + 72d^{-1/2}$$

- Johnson-Cook model for flow stress behavior

$$\sigma_{JC} = [A + B\varepsilon^n] \cdot \left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$$

- Thermal softening (for Inconel 718), modified JC

		T_0	m
Modified JC model TS term, σ_T	< 700 °C	21	2
	≥700 °C	700	0.0016*T+2.0031

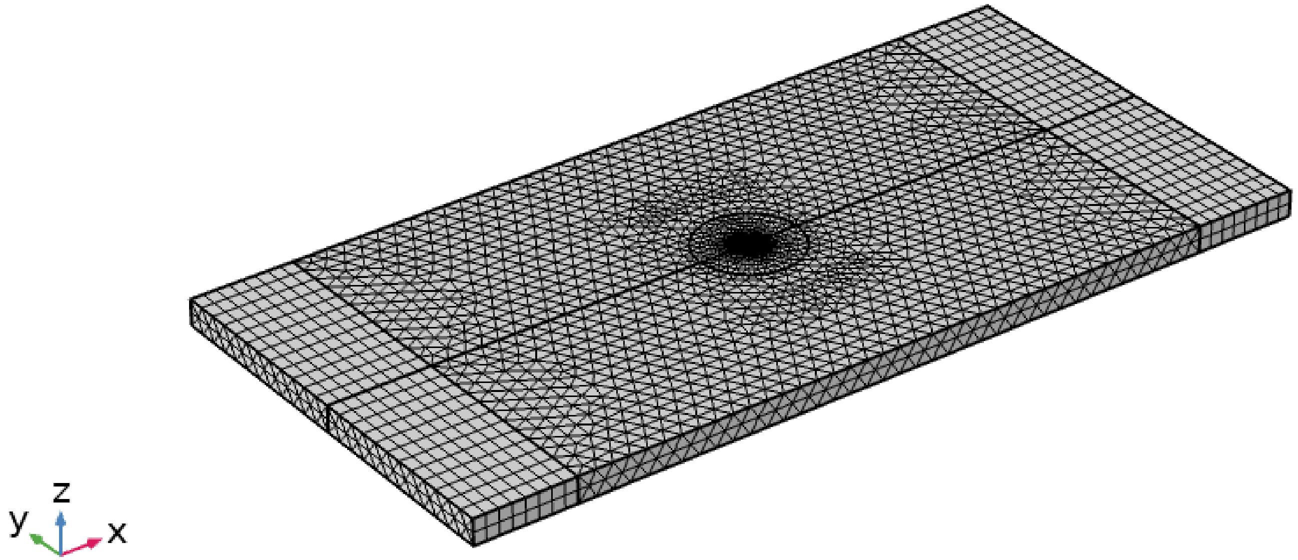
METHODOLOGY

- Material properties are temperature dependent.

Parameter	Unit	Al-T6	Ni-Inconel 718
Workpiece melting temperature	ºC	660	1300
Welding speed	mm/s	1.59	1.65
Rotation Speed	RPM	637	400
Normal Force	kN	25	12.6
Activation energy of lattics diffusion	kJ/mol	140	320
Initial yield stress, sigmags	MPa	324	1350
Strength coefficient, k_jcook	MPa	114	1139
Hardening exponent, n_jcook	-	0.42	0.6522
Strain rate strength coefficient, C_jcook	-	0.002	0.0134
Reference strain rate, ε_jcook	S^{-1}	1	1
Temperature exponent,m_jcook	-	1.34	Fn(T)

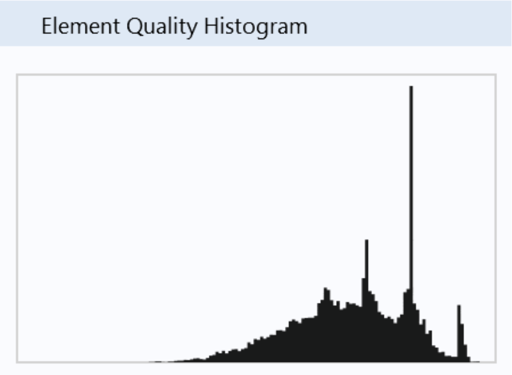
METHODOLOGY

- Using a mix of tetrahedral, prisms, triangles, and quads with total of **86,000 elements** and **0.78** average element quality.
- The solver settings at **10^{-5}** tolerance.



Complete mesh

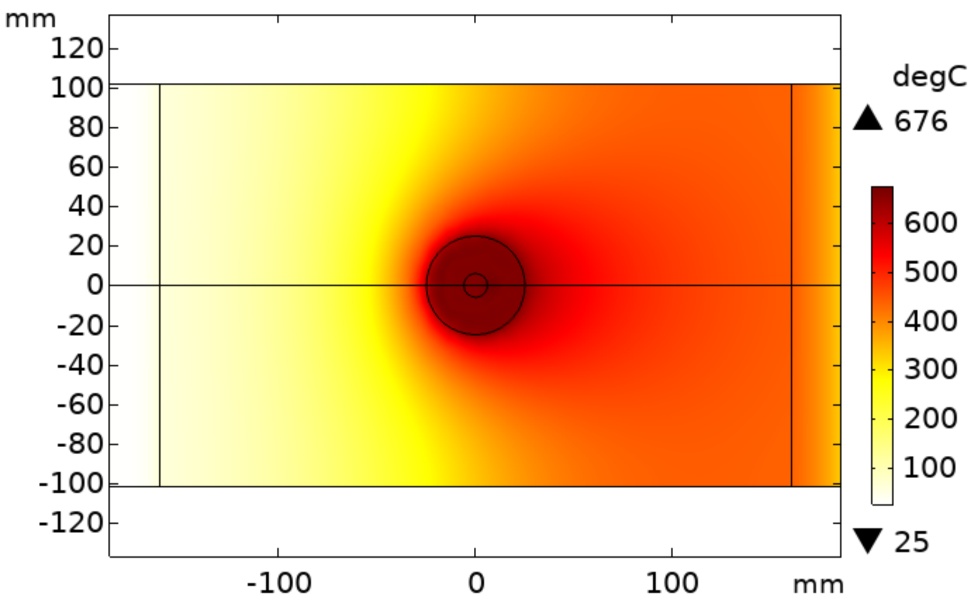
Mesh vertices:	8699
Element type:	All elements
Tetrahedra:	34674
Prisms:	1600
Triangles:	8214
Quads:	864
Edge elements:	752
Vertex elements:	40
Domain element statistics	
Number of elements:	36274

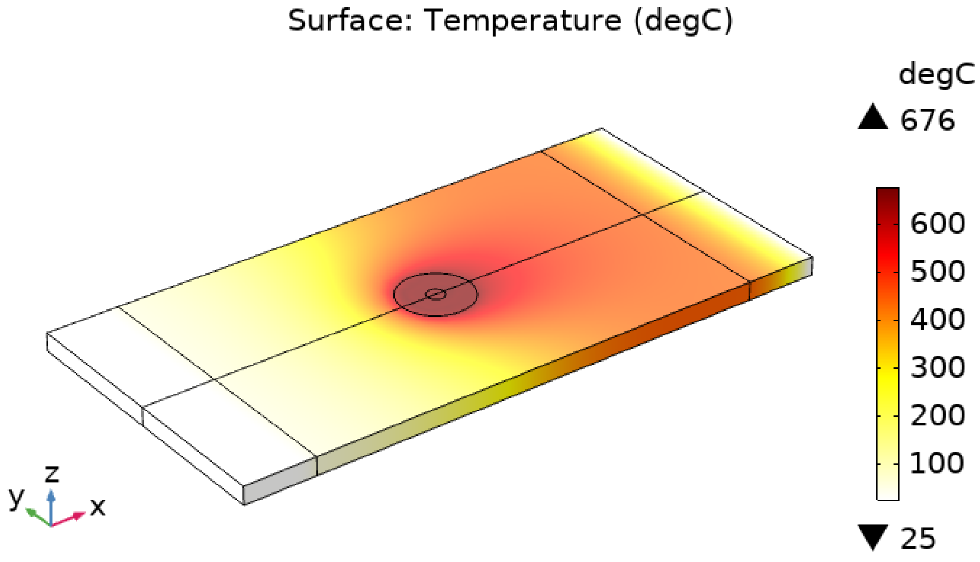


RESULTS

Al Workpiece

- 3D and 2D surface temperature profile for Al Workpiece.
- Peak temperature showed 676 °C at the welding joint.

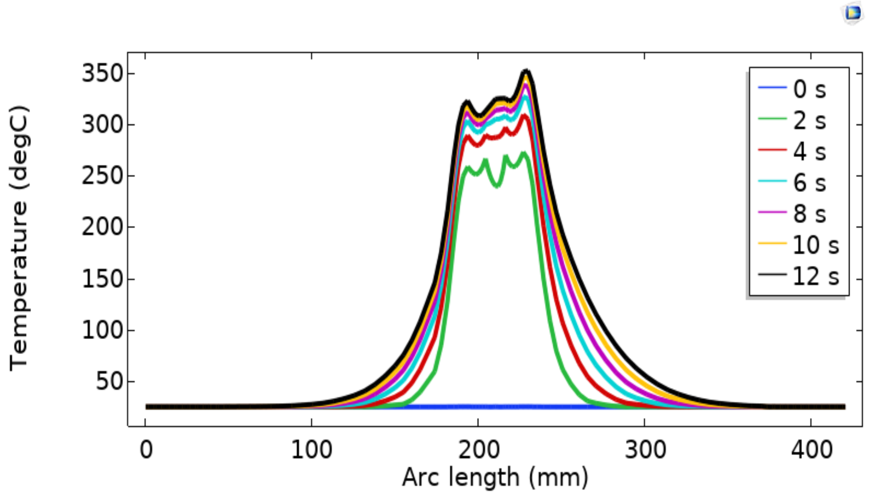




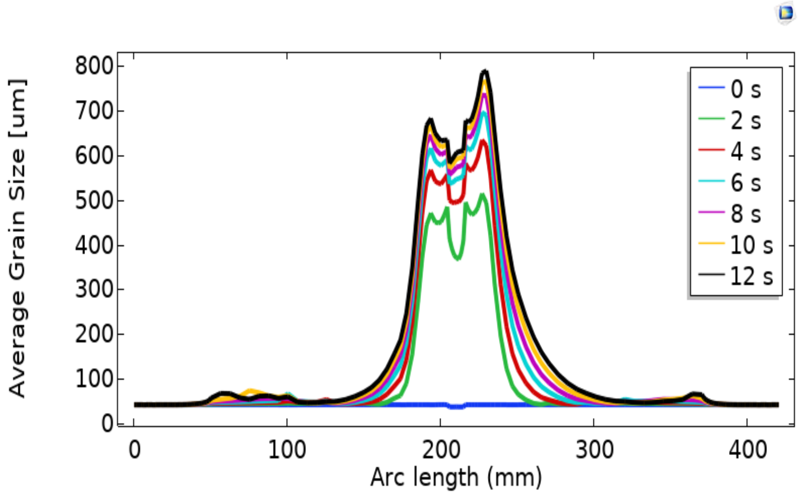
- 2D cross section showed a heat dissipation across the aluminum plates in the range of 200 up to 600 °C.

RESULTS

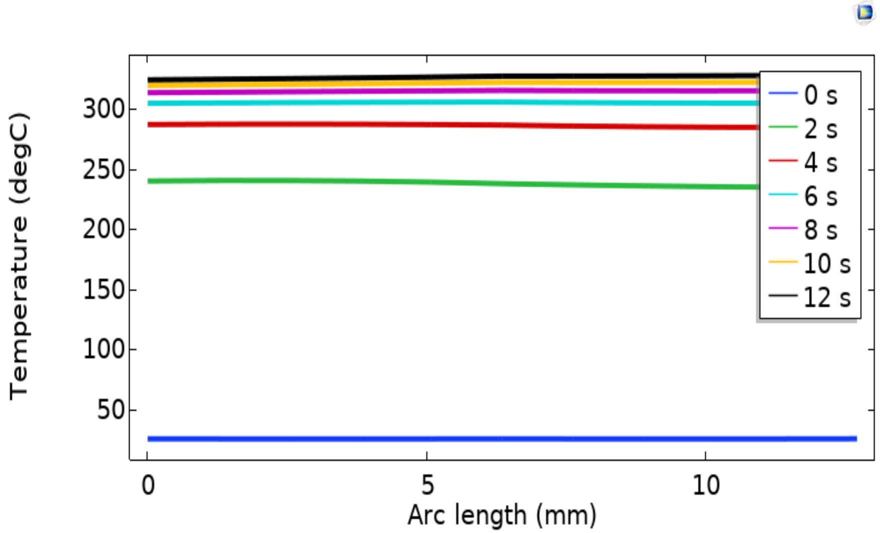
Al Workpiece



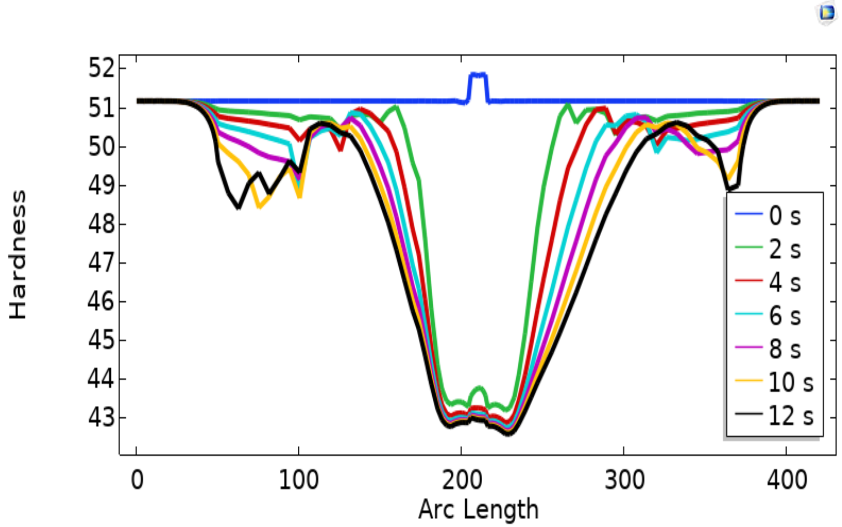
1D Temperature profile for Al workpiece across welding centerline



Average grain size for Al workpiece



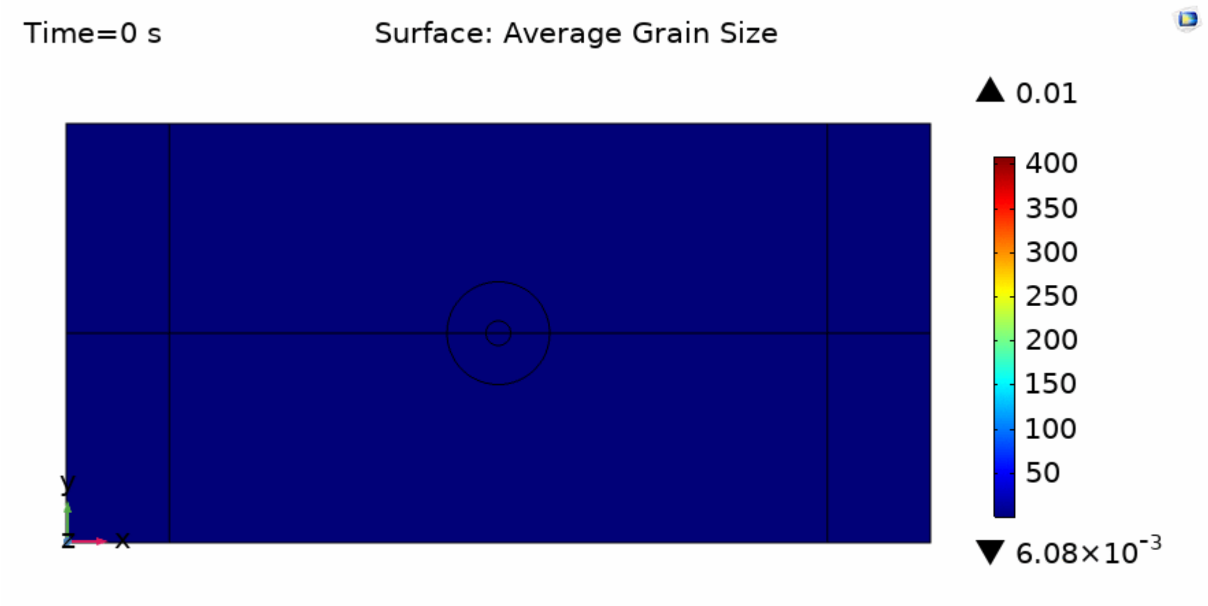
1D Temperature profile for Al workpiece across plate thickness

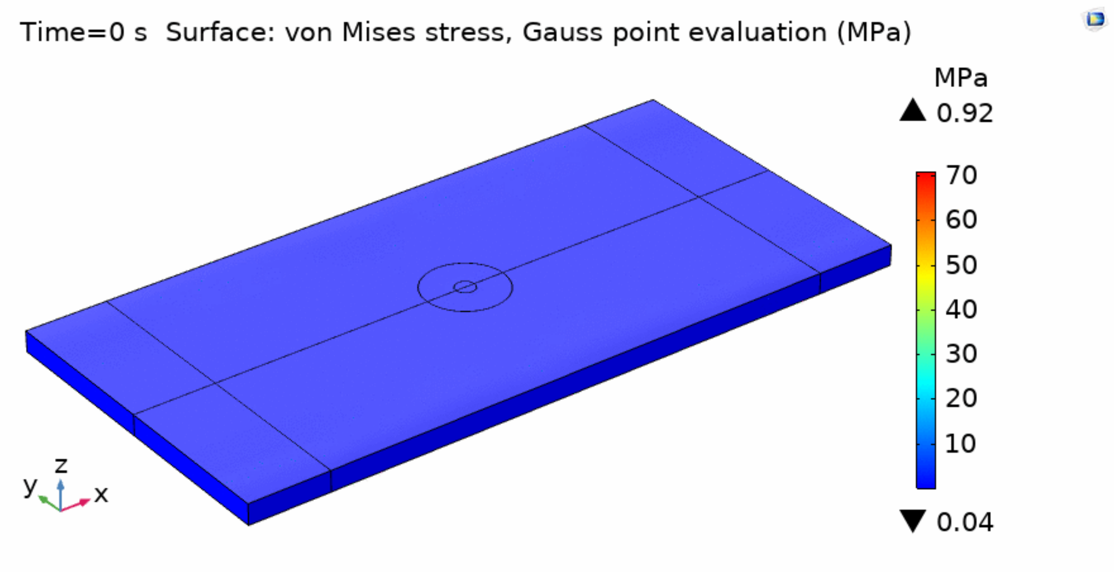


Microhardness for Al workpiece

RESULTS

FSW Animation

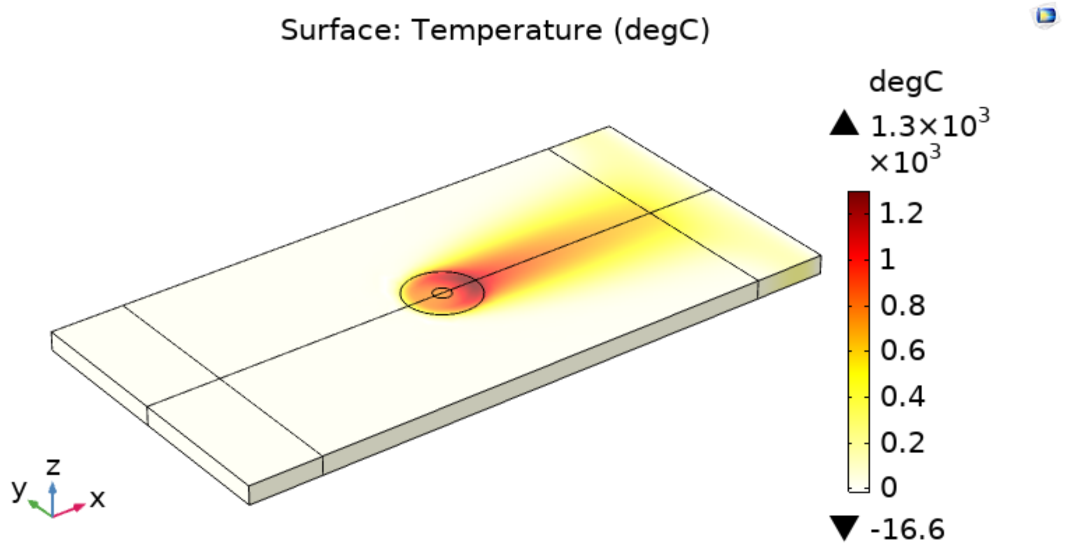


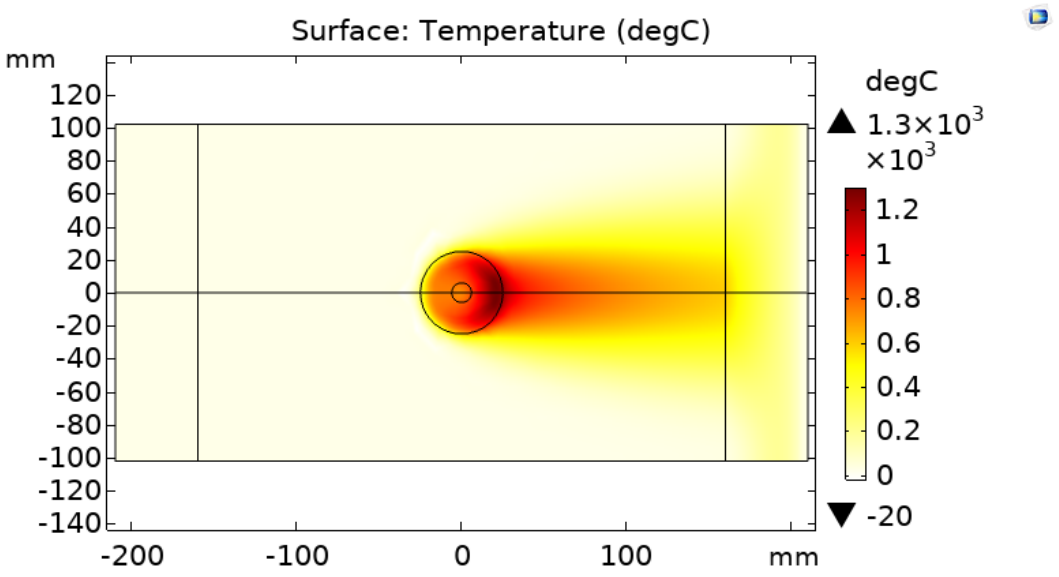


RESULTS

Inconel 718 Workpiece

- 3D and 2D surface temperature profile for Inconel 718 Workpiece.
- Peak temperature recorded around 1300 °C.

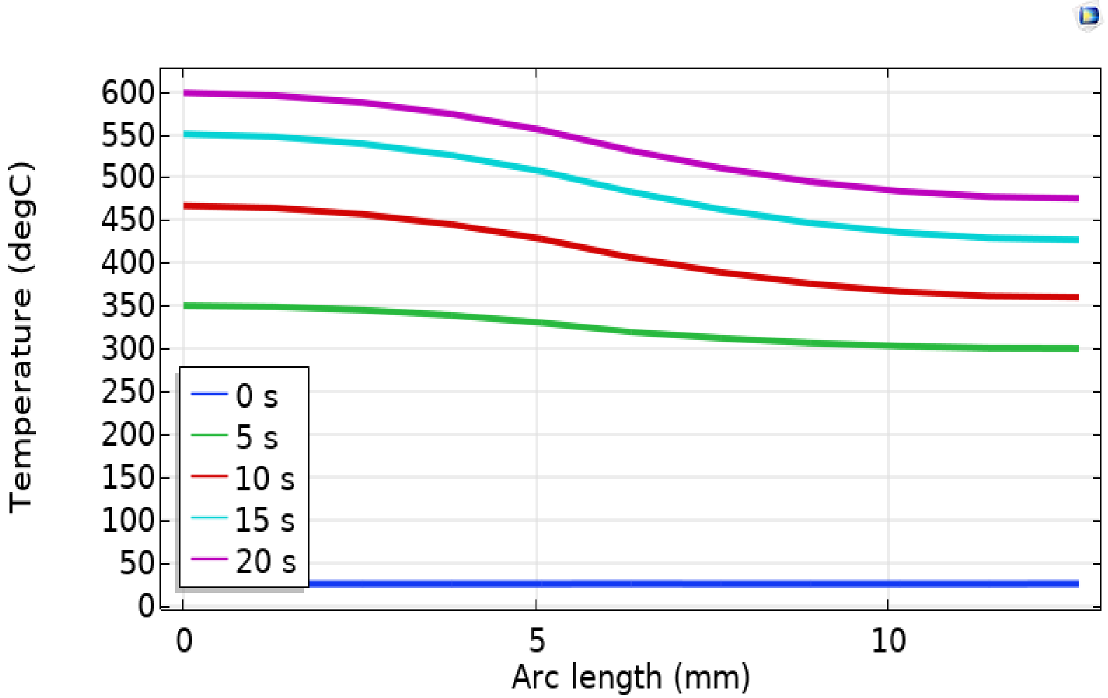




- 2D cross section clearly shows the temperature distribution across the plates, where the maximum was focused around the welding regions only with almost uniform distribution in the x-direction.

RESULTS

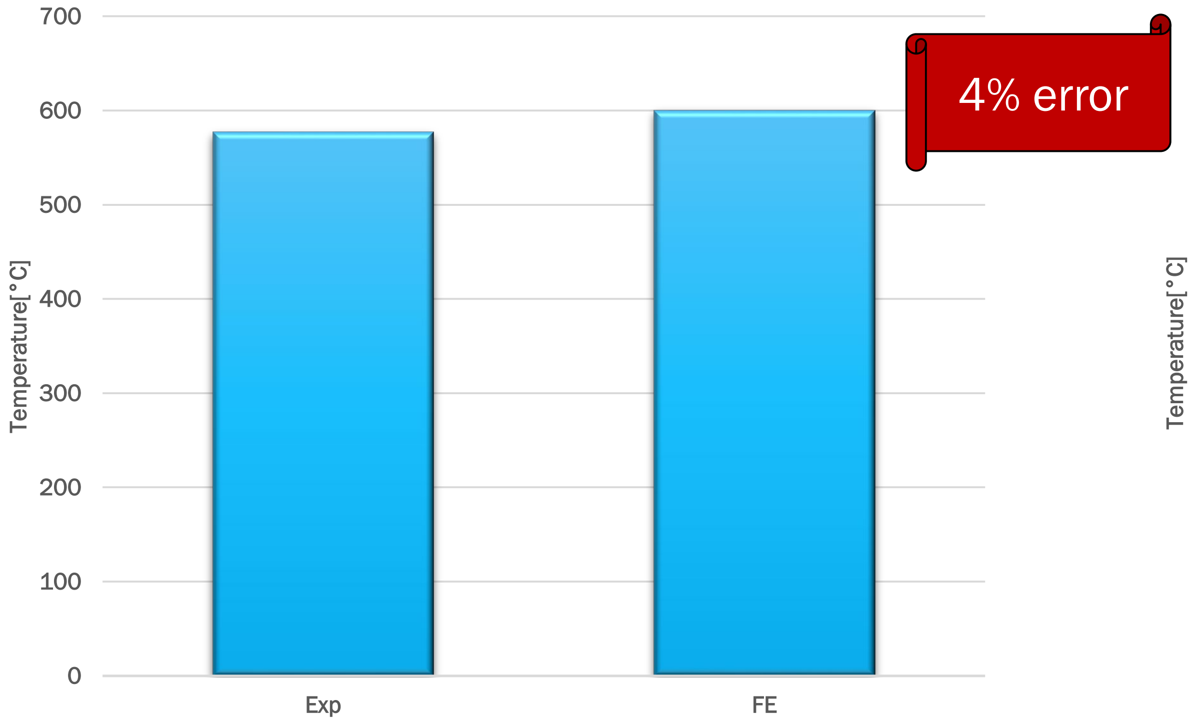
Inconel 718 Workpiece



1D Temperature profile for Inconel-718 workpiece across plate thickness

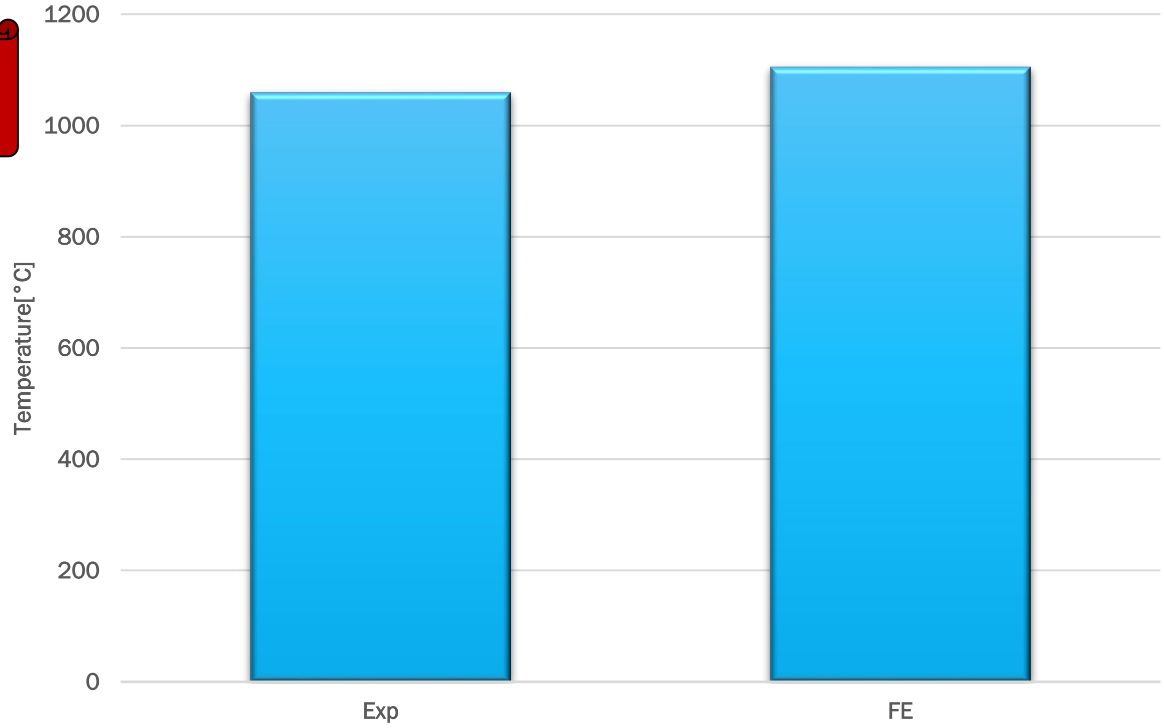
MODEL VALIDATION

- Aluminum plates, 5 mm from the welding nugget zone.



Ref: https://doi.org/10.1016/j.ijmecsci.2022.107827

- Inconel 718 plates, 2 mm from the welding nugget zone.



Ref: https://doi.org/10.1016/j.ijpvp.2022.104731

CONCLUSION

1. A transient non-isothermal 3D FEM model was built using COMSOL Multiphysics for FSW process.

2. The model was checked against an Al Workpiece and Inconel 718 plates.

3. The model was built for welding dissimilar materials.

4. Model has been validated against published experimental data


Q & A