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Experimental and Numerical Study of Thermal Process in Friction Stir Welding

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CTC Concurrent Technologies Corporation

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Background

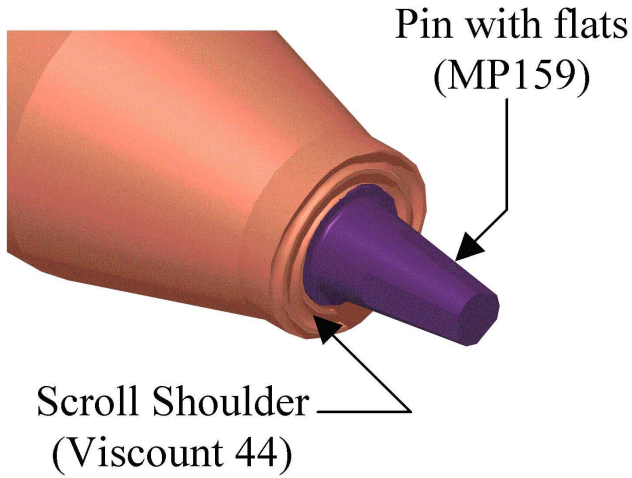
Features of the manufacturing of the combat vehicle structures and their impact on the FSW process

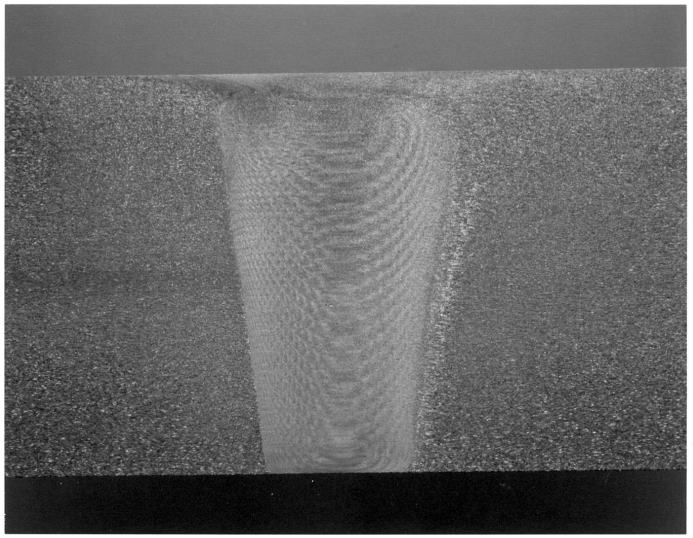
- The joining of thick (one inch and above) gauge workpieces–temperature gradient through the workpiece thickness that may affect the weld quality
- The varying thermal insulation conditions due to different types of welds–influence of the heat loss on the selection of the FSW process parameters such as welding tool advancing speed and others

Background

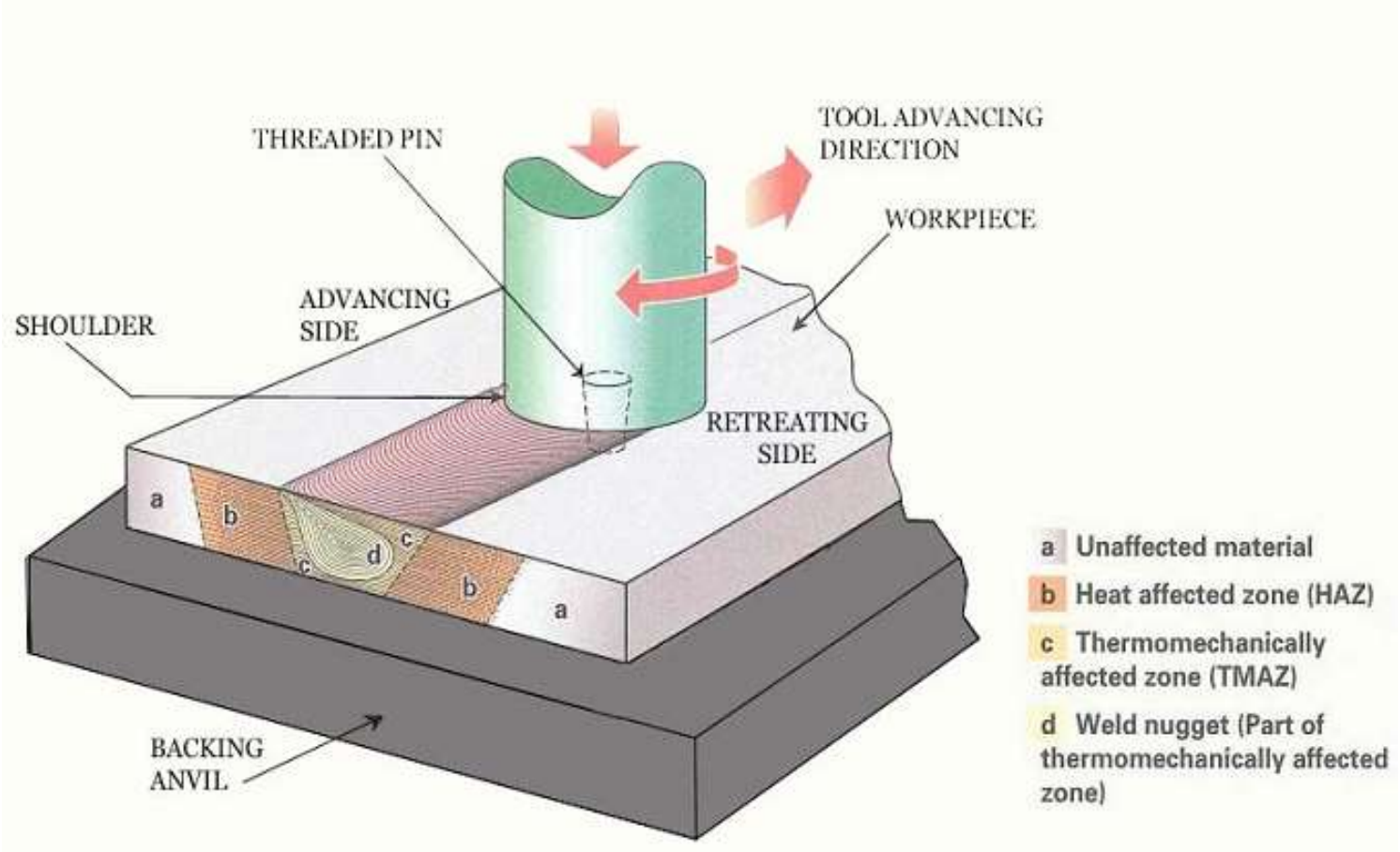
New FSW Tool Design

- Based on TWI tool design
- Frustum pin profile with flats
- Zero tilt angle
- Weld stir zone coinciding with the profile of the pin
- No sizable TMAZ
- No “vertical mixing”





Schematic of Friction Stir Welding Process



Large FSW System at *CTC*

- Large working envelope:
  - 26-ft vertical
  - 13-ft horizontal
- High force capability:
  - 25,000-lb plunge force
  - 450 ft-lb torque
  - 2-in thick Al weldments
- Data acquisition system:
  - Torque
  - Temperature (12 ports)
  - Longitudinal force
  - Transverse force

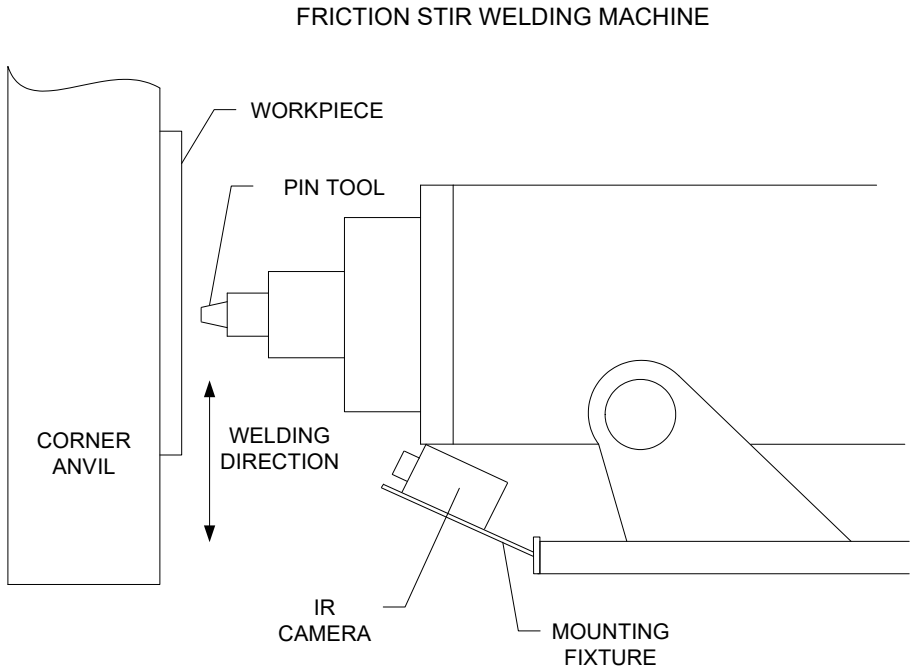
Objectives

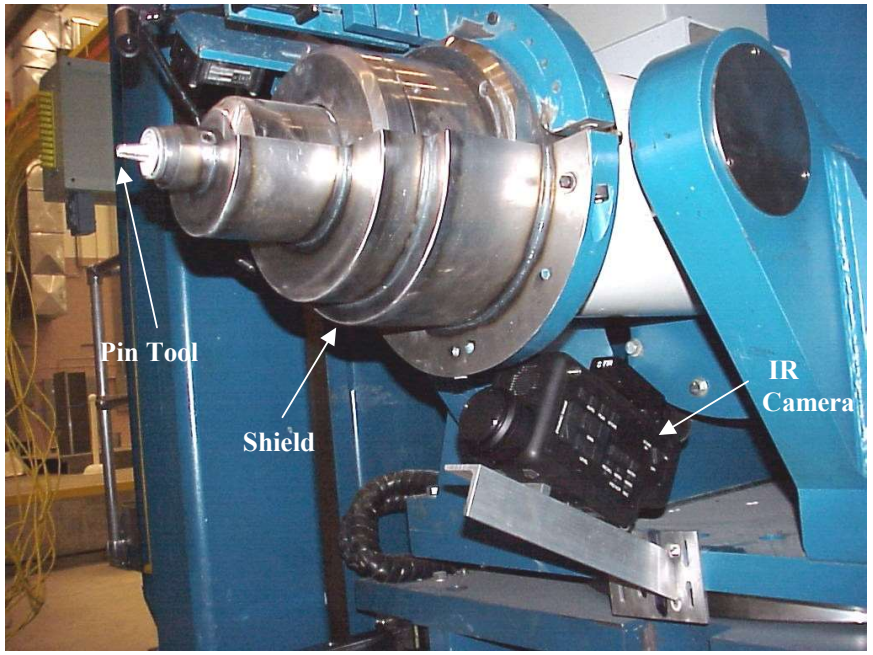
- Measure in-situ development of temperature field on the surface and in the interior of the workpiece
- Investigate the influence of the tool shoulder diameter and tool advancing speed on the heat generation in the workpiece
- Determine the heat generation due to tool shoulder and pin
- Determine the heat loss through the tool and anvil
- Predict the temperature history of the weld stir zone

Bead-on-Plate Welding Tests

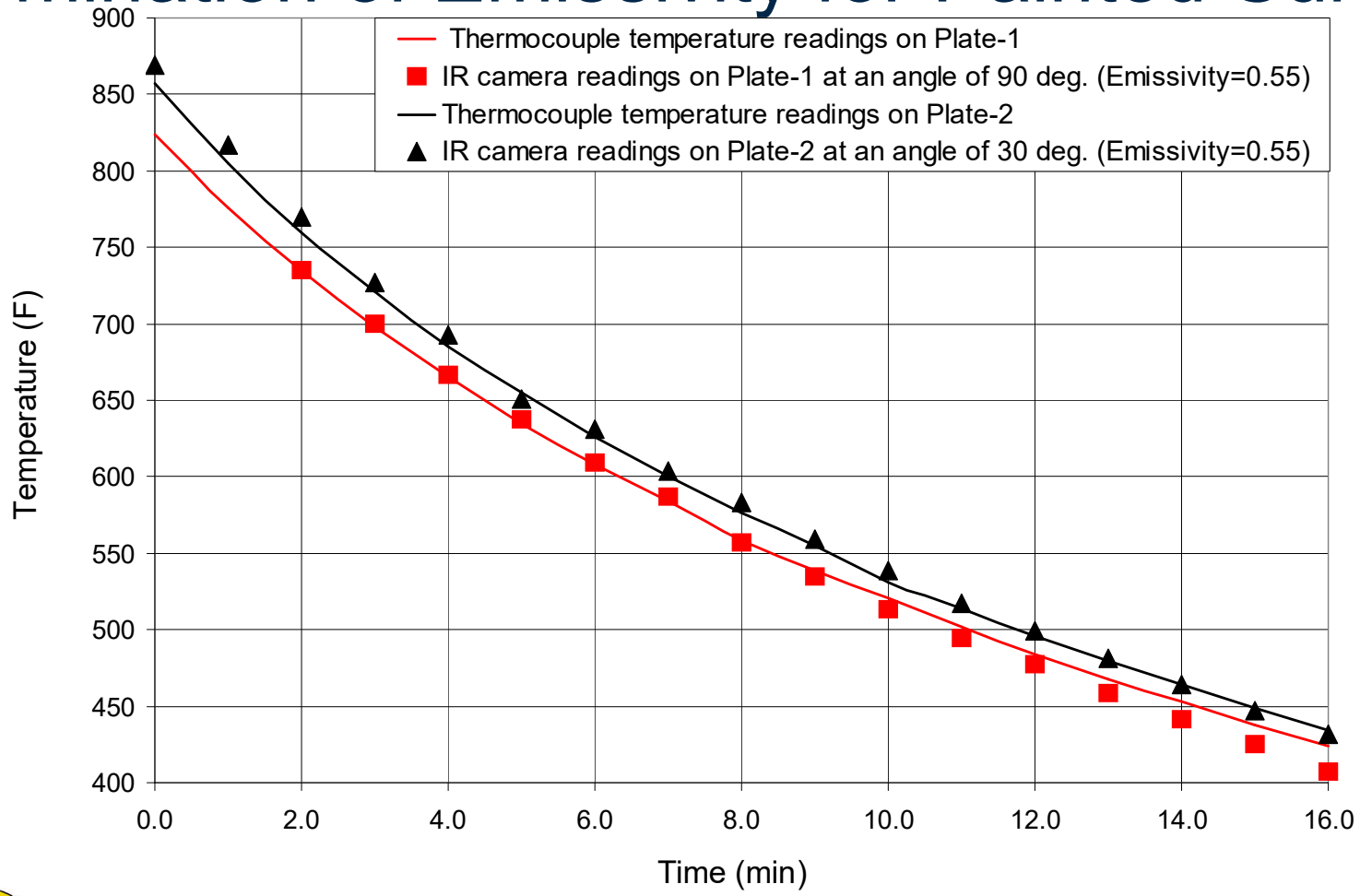
- Material: 1-in thick aluminum alloy 5083-H116 plate
- Dimensions of welded plate: 30-in (L) by 8-in (T)
- Welding tool
  - Pin root diameter: 0.6 in
  - Pin tip diameter: 0.35 in
  - Thread pitch: 1/18 in
  - Number of flats: 4
  - Tool shoulder diameter: 1.65 in and 1.2 in
- Thermal insulation conditions
  - Mica used to insulate the plate from the anvil
  - Plate directly fixed on the anvil

Infrared Imaging of Temperature Field



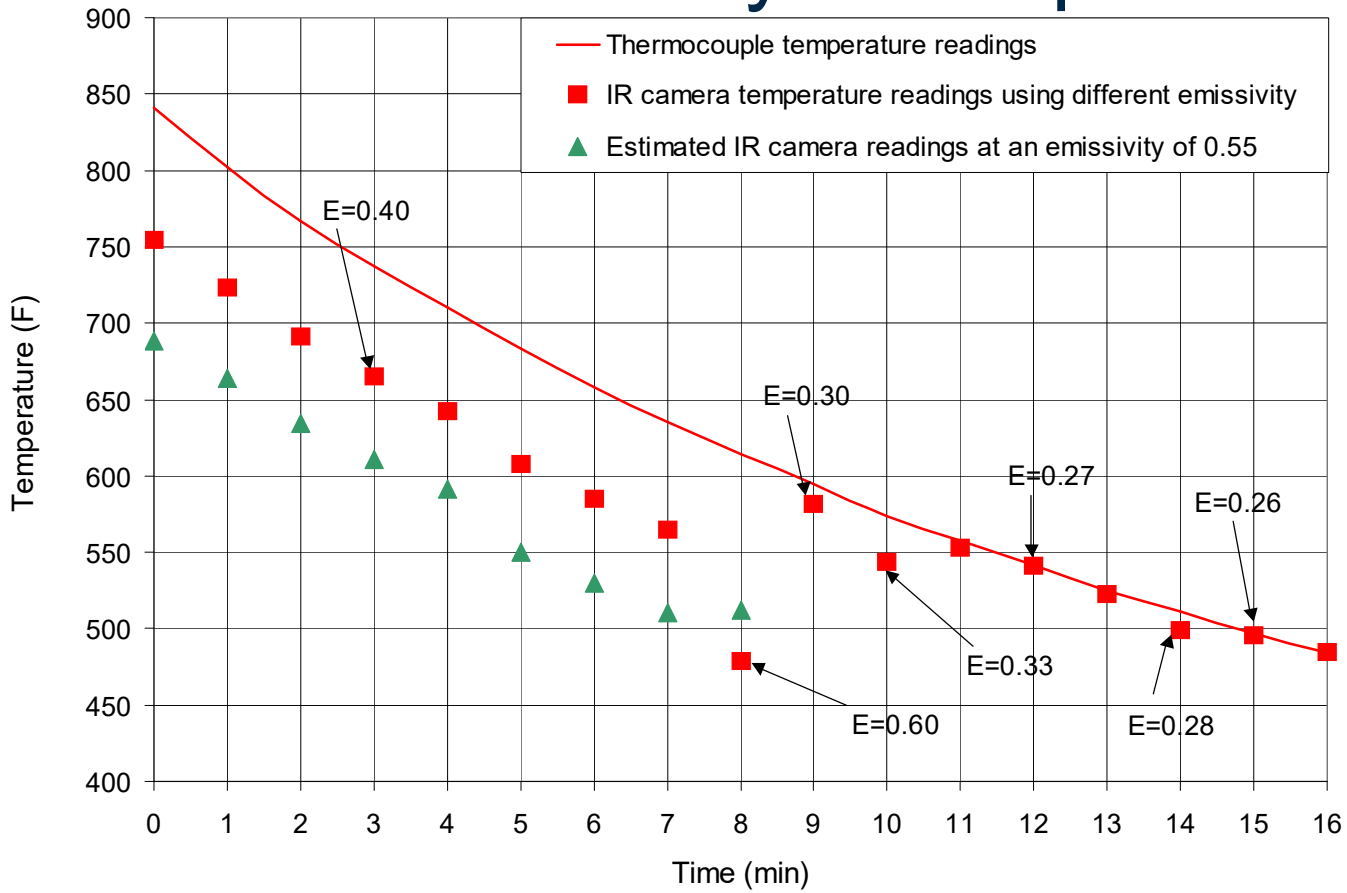


Determination of Emissivity for Painted Surface



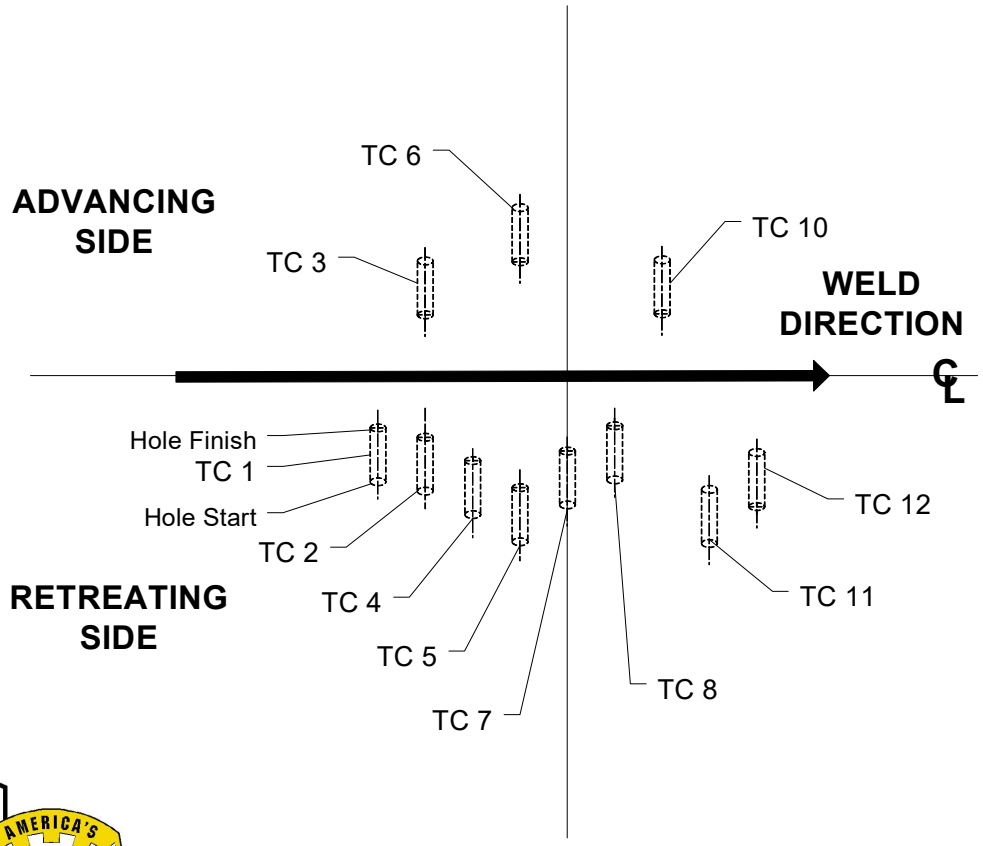
- For painted surface, emissivity=0.55
- Emissivity is independent of IR camera orientation

Determination of Emissivity for Unpainted Surface



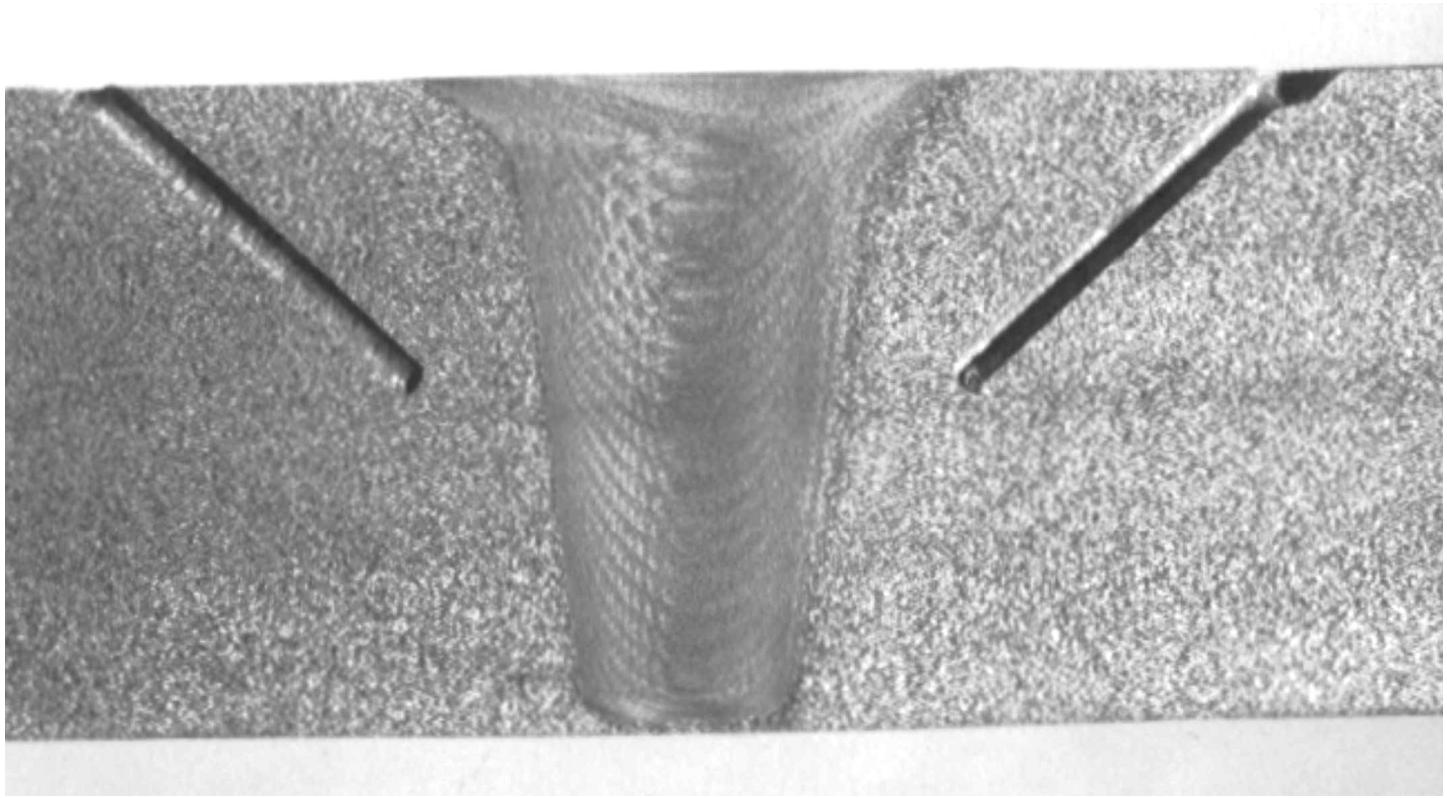
- For unpainted surface, emissivity=0.26
- An emissivity of 0.55 for the unpainted surface underestimates the temperature by ~150 °F

Temperature Measurements Using Thermocouples



TC	Distance from Centerline (in)	TC Tip Depth (in)
1	0.24	0.25
2	0.27	0.50
3	0.27	0.50
4	0.45	0.50
5	0.70	0.50
6	0.70	0.50
7	0.30	0.75
8	0.24	0.25
10	0.27	0.50
11	0.70	0.50
12	0.30	0.75

Thermocouple Hole Configuration



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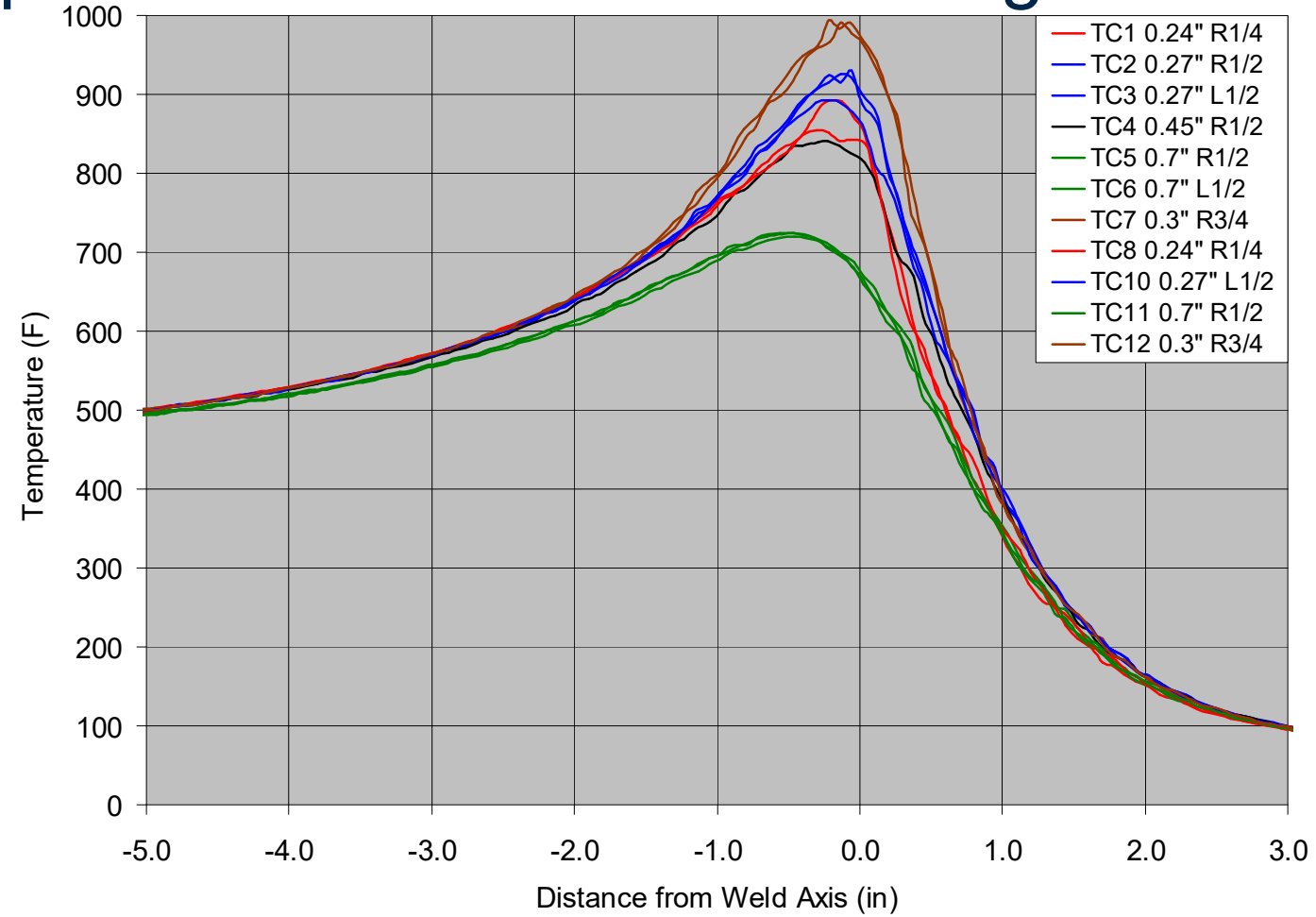
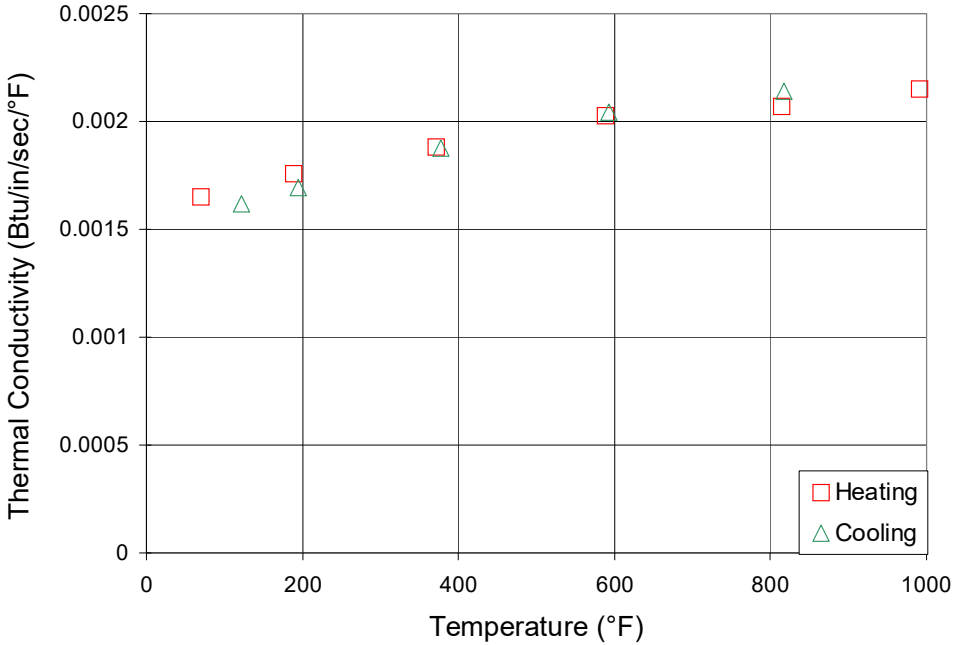
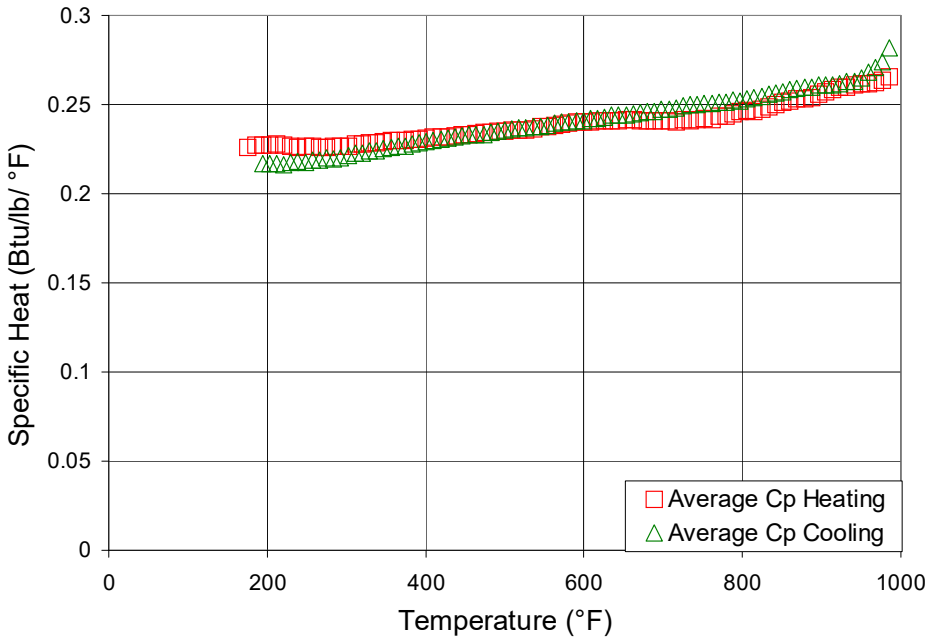


Temperature profiles in Plate 02 (shoulder diameter 1.65 in, tool advancing speed 5 in/min, and mica used to insulate from the anvil)

Thermophysical Properties of Aluminum Alloy 5083

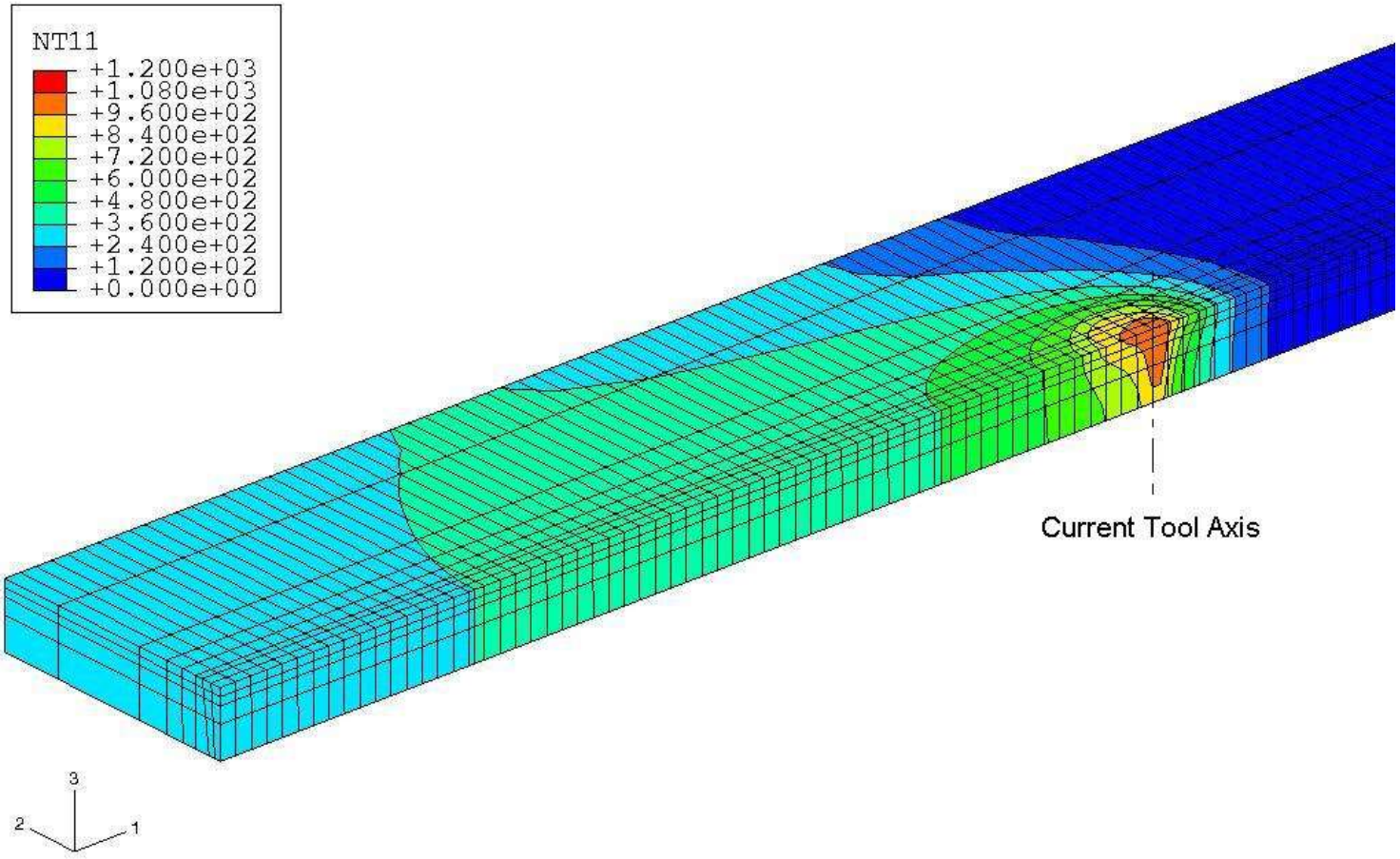




Finite Element Simulation

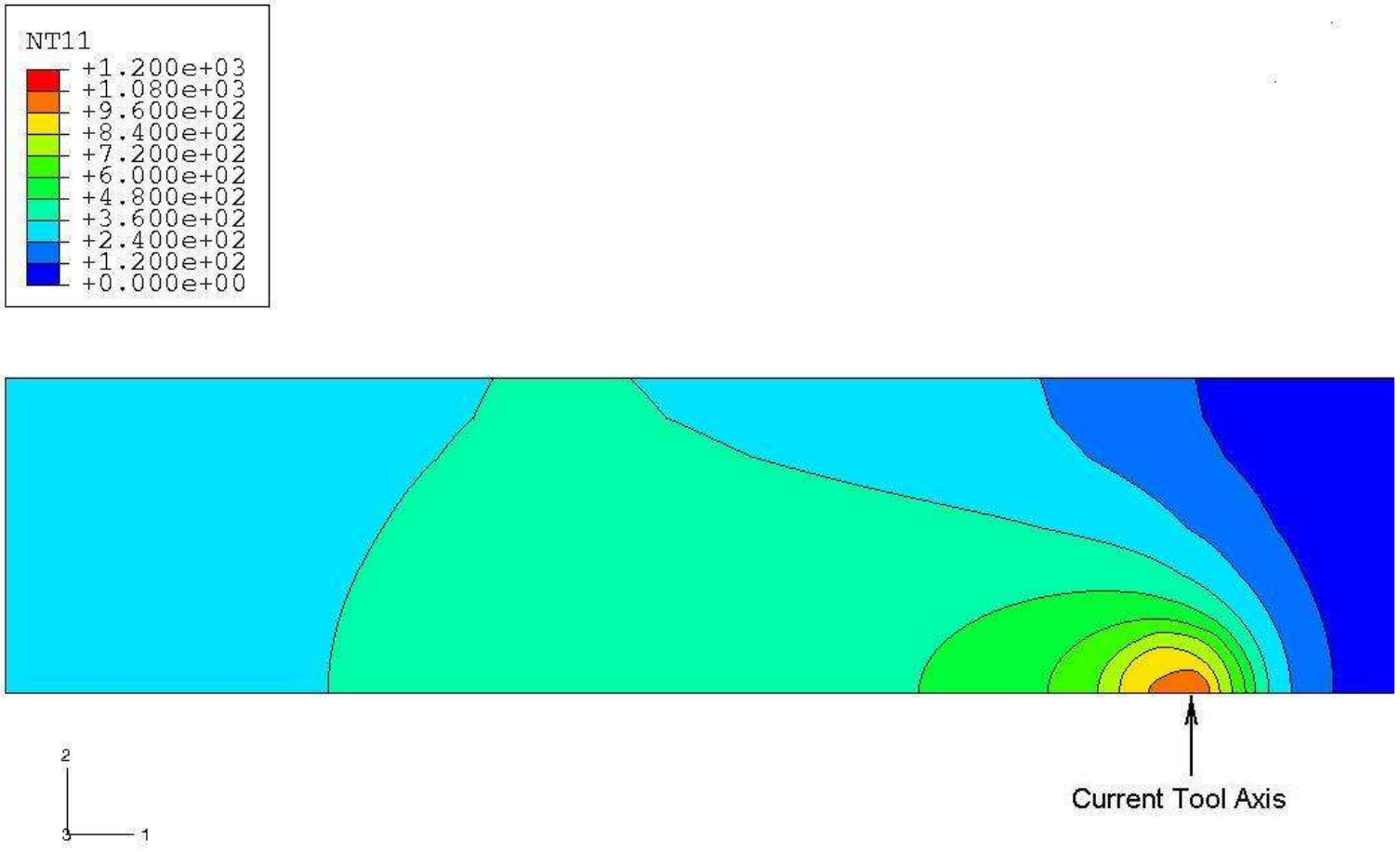
- Non-linear commercial package ABAQUS/Standard
  - Thermal analysis
  - 20-node quadratic 3D elements
- Heat generation (user-coded subroutine DFLUX)
  - Power input to workpiece
  - Heat generated due to shoulder-workpiece interaction
  - Heat generated due to pin-workpiece interaction
- Heat loss (film coefficients)
  - Heat loss through ambient air
  - Heat loss through back anvil

Results of Finite Element Simulation



Isometric view of the temperature field (in °F) of Plate 02

Results of Finite Element Simulation



Top view of the temperature field (in °F) of Plate 02

Comparison between Measurement and Simulation-Temperature Field

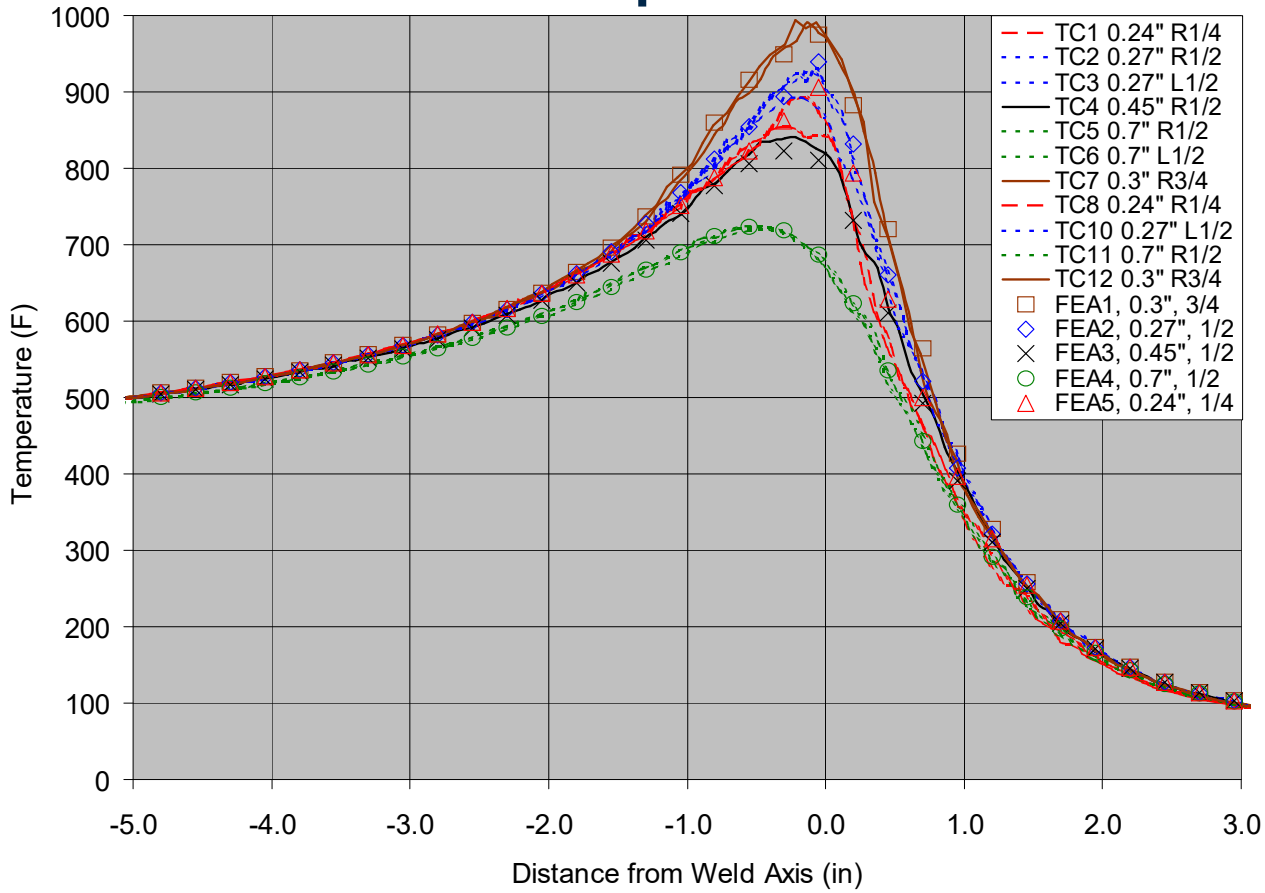
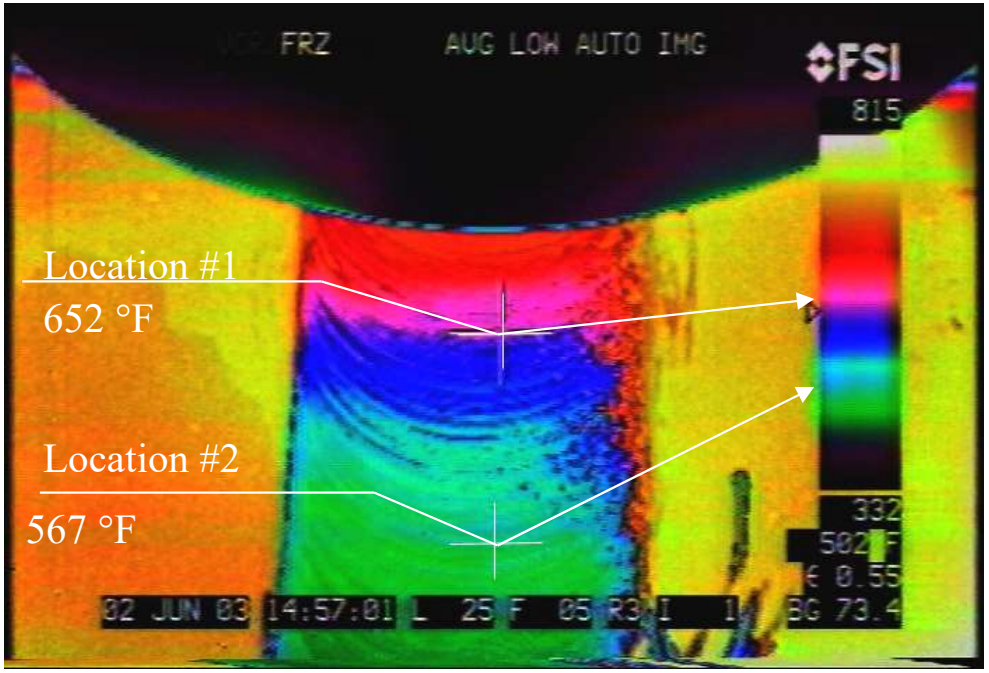


Plate 02 (shoulder diameter 1.65 in, tool advancing speed 5 in/min, and mica used to insulate from the anvil; power input to workpiece: 5.9 Btu/s)

Comparison between IR Measurement and Simulation-Temperature Field



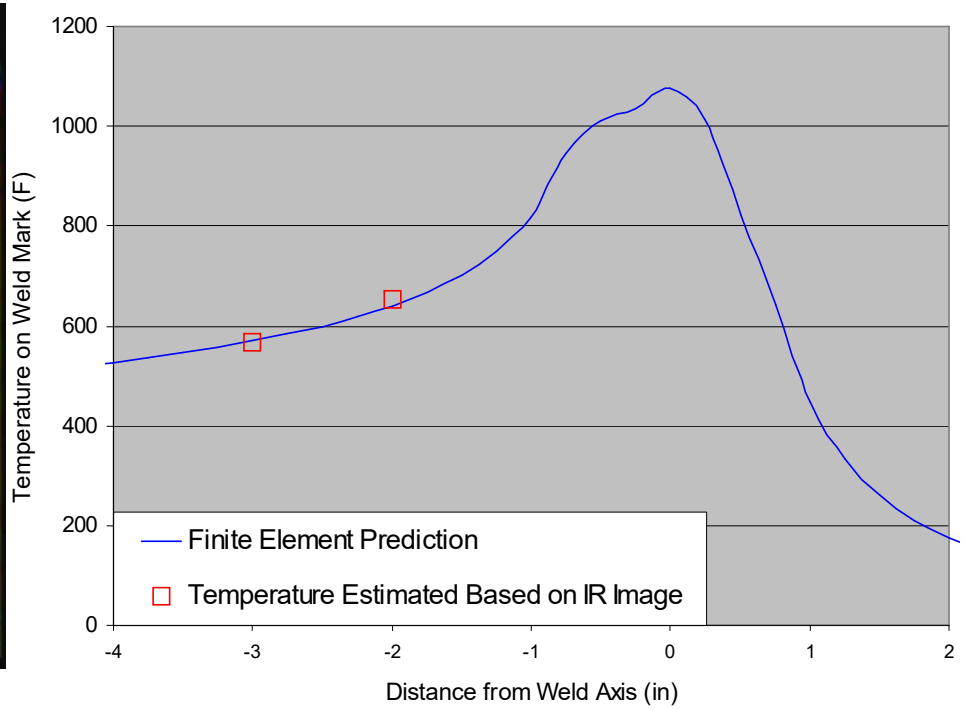


Plate 02 (shoulder diameter 1.65 in, tool advancing speed 5 in/min, and mica used to insulated from the anvil; power input to workpiece: 5.9 Btu/s)

Comparison between Measurement and Simulation-Temperature Field

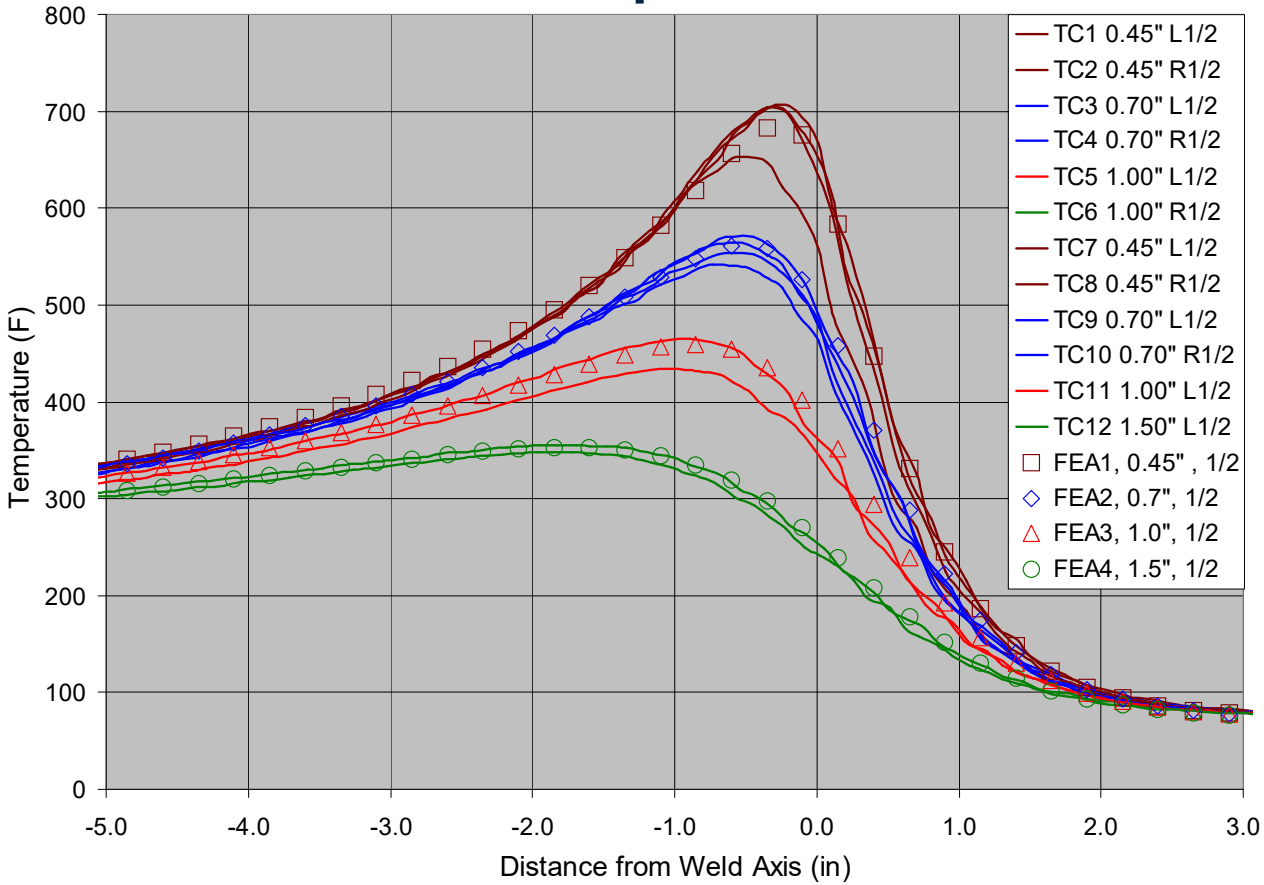


Plate 09 (shoulder diameter 1.2 in, tool advancing speed 7 in/min, and Plate directly fixed on the anvil; power input to workpiece: 5.6 Btu/s)

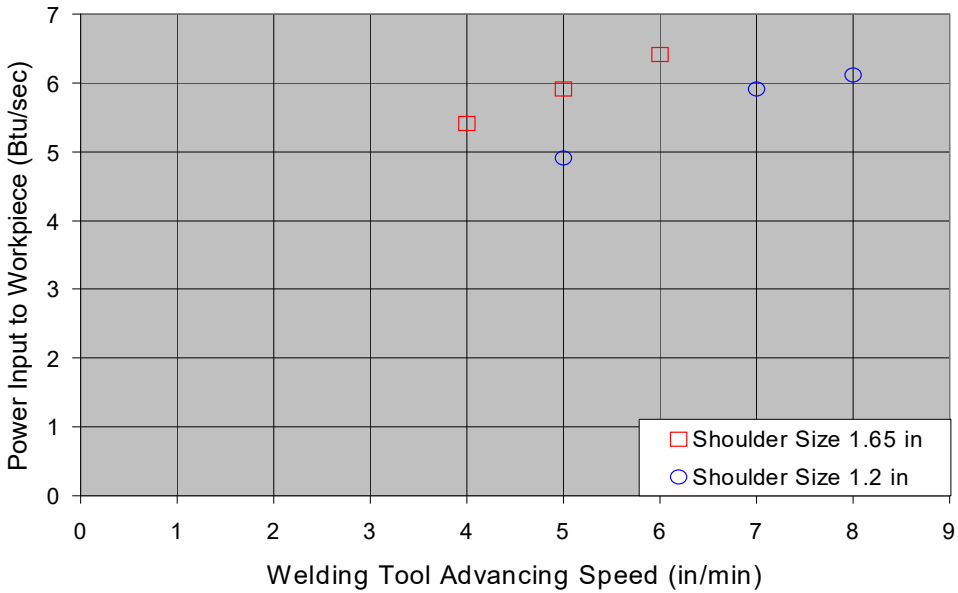
Summary of Simulation Results

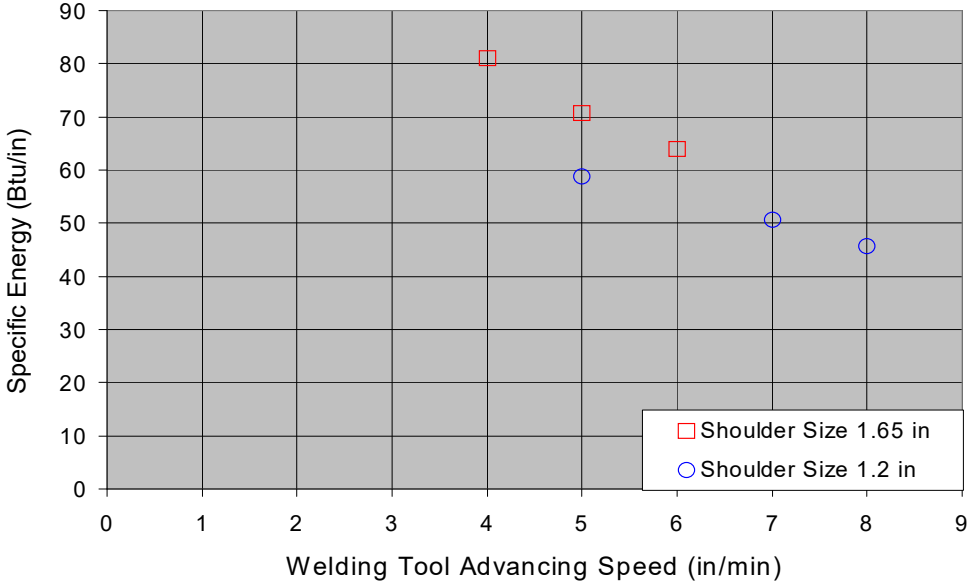
Plate Number	Shoulder Size (in)	Advancing Speed (in/min)	Insulation Conditions	Machine Power Consumption (Btu/sec)	Power Input to Workpiece (Btu/sec)	Percentage Heat Generation due to Shoulder : Pin
Plate04	1.65	4	with mica	7.3	5.4	60% : 40%
Plate02	1.65	5	with mica	8.1	5.9	50% : 50%
Plate05	1.65	6	with mica	8.9	6.4	40% : 60%
Plate08	1.65	5	no mica	9.1	5.8	30% : 70%
Plate03	1.2	5	with mica	6.5	4.9	50% : 50%
Plate06	1.2	7	with mica	7.9	5.9	50% : 50%
Plate07	1.2	8	with mica	7.7	6.1	40% : 60%
Plate09	1.2	7	no mica	8.8	5.6	30% : 70%

Observations from Experiment and Simulation Results

- Increasing the tool shoulder diameter increases the heat generated in unit time
- Increasing the tool advancing speed increases the heat generated in unit time
- Increasing the tool advancing speed increases the heat loss through the welding tool in unit time
- Increasing the tool advancing speed increases the percentage of heat generation due to the pin
- Heat loss through the backing anvil increases the percentage of heat generation due to the pin

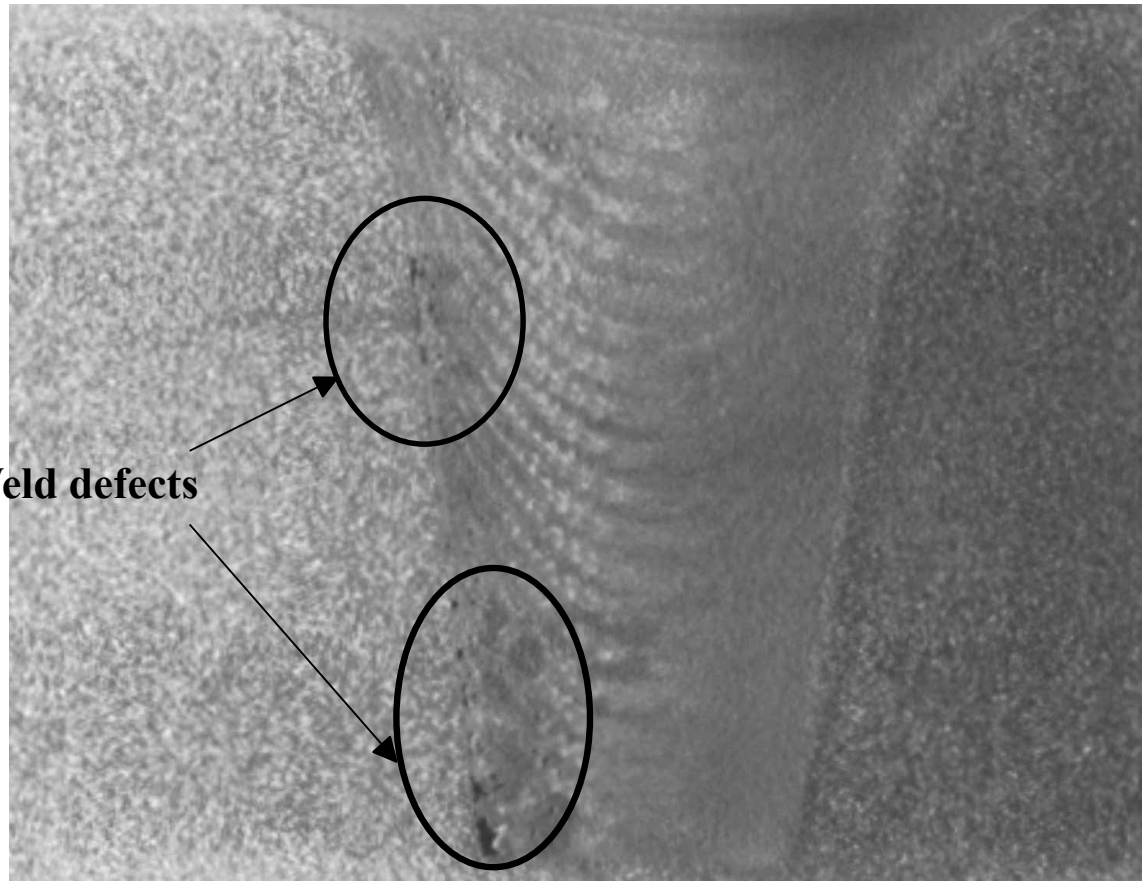
Observations from Experiment and Simulation Results





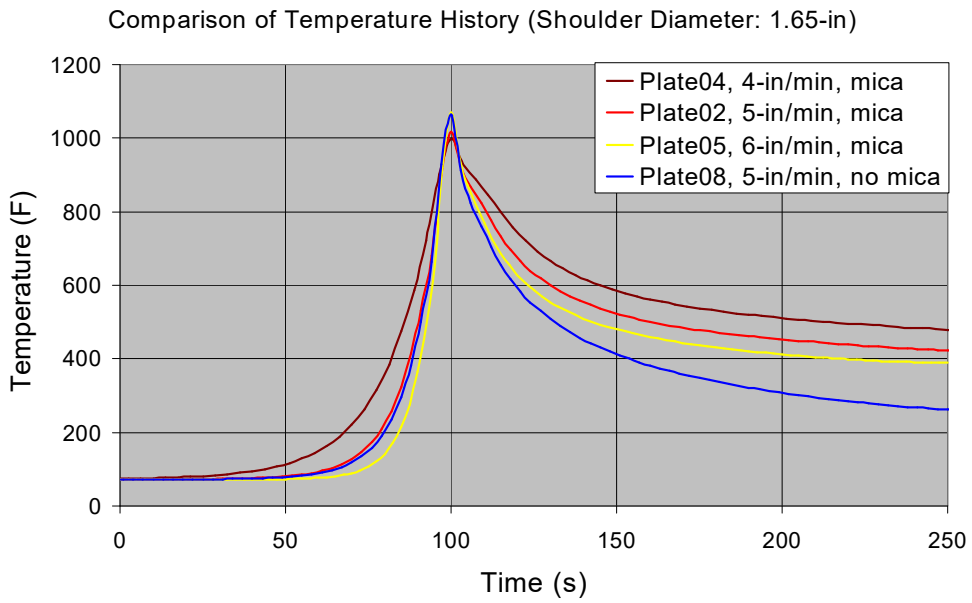
- Specific energy: heat generated per unit weld length
- For the same tool shoulder diameter, specific energy decreases with increasing tool advancing speed
- For the same advancing speed, specific energy increases with increasing tool shoulder diameter

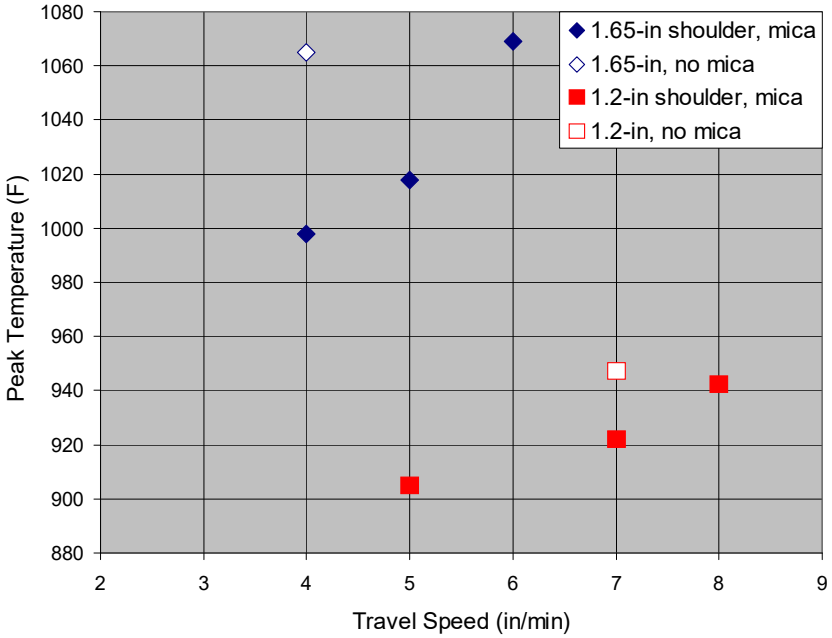
Weld Defect and Low Specific Energy



Transverse section of Plate 07 (shoulder diameter 1.2 in, advancing speed 8 in/min, and mica used to insulate from the anvil)

Prediction of Temperature in Weld Stir Zone





- Increasing the tool advancing speed reduces the time duration for the material to experience elevated temperature but increases the peak temperature in the stir zone
- For the same advancing speed, the “no mica” condition yields a higher peak temperature in the stir zone, although the temperature drops faster than when mica is used to minimize heat loss

Concluding Remarks

- Both the tool shoulder and the pin contribute significantly to the heat generation in the FSW process. The shoulder : pin contribution ranges from 60% : 40% to 30% : 70%, depending on the process conditions
- Welding tool with a larger shoulder diameter generates more heat in the workpiece and consumes more machine power than the tool with a smaller shoulder diameter
- Increasing the tool advancing speed or the heat loss through the backing anvil
  - Increases the fractional heat generation due to the pin
  - Increases the peak temperature in the weld stir zone
  - Reduces the time duration for the base material to experience elevated temperature