Modeling of Transport Phenomena in Gas Tungsten Arc Welding of Ni to 304 Stainless Steel

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Motivation

- Joining of dissimilar metals / alloys by using arc welding has been a challenge in several industries such as power plants and offshore piping.

- Challenging physics behind the welding of dissimilar alloys is not yet well understood, because of differences in the thermo-physical, mechanical, and metallurgical properties.

For this reason to produce quality dissimilar welds, it is necessary to perform mathematical / numerical modeling of transport phenomena in the weld pool during melting & solidification.

Not only does modeling of the dissimilar welds provide a better understanding of the physics behind it, but also is a more cost effective process to produce high quality welds.
Gas Tungsten Arc (GTA) welding

- An arc is established between a tungsten electrode and the base metal.
- Tungsten electrode is not a consumable.
- An inert shielding gas protects the weld from the atmosphere.

(Welding Metallurgy; S. Kou; 2003)
Transport phenomena

- Physics involved in the welding process
  - Electromagnetics
  - Fluid flow
  - Heat transfer

- Dissimilar welding
  - Different properties
  - Three dimensional modeling
  - Mass transfer

- Weld zone shape and penetration
- Dilution
- Cooling rate (Thermal cycle)
- Heat affected zone geometry / width
- Thermal stress residues
- Defect formation
Convective Forces

- Buoyancy force
- Lorentz Force
- Marangoni effect depends on $d\gamma/dT$

(Welding Metallurgy; S. Kou; 2003)
Mathematical Formulations

Classic transport equations are solved for the domain

Momentum equation:

\[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = \nabla \left[ -p \mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2\mu}{3} (\nabla \cdot \mathbf{u}) \mathbf{I} \right] + \mathbf{F}_d + \mathbf{F}_b \]

\[ \mathbf{F}_b = \mathbf{J} \times \mathbf{B} + \rho_0 (1 - \beta (T - T_s)) \mathbf{g} \]

\[ \mathbf{F}_d = \frac{(1 - f_l)^2}{f_l^3 + \varepsilon} A_{mush} \mathbf{u} \]
Mathematical Formulations

Marangoni effect:

\[ \mu \frac{\partial u}{\partial z} = f_l \frac{dy}{dT} \frac{\partial T}{\partial x} \]
\[ \mu \frac{\partial v}{\partial y} = f_l \frac{dy}{dT} \frac{\partial T}{\partial y} \]
\[ \mu \frac{\partial z}{\partial y} = f_l \frac{dt}{dT} \frac{\partial y}{\partial y} \]

Energy equation:

\[ \rho C_p' \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + Q_e \]
\[ C_p' = C_p + \delta(T) \Delta H_f \]
Material properties

- Solution properties:

\[
\mathbf{A} = \sum x_i \mathbf{A}_i
\]

For \( \rho, \mu, \beta, k, C_p \) and \( \sigma \)

- Surface tension:

\[
\gamma = \gamma_m - A_\gamma (T - T_l) - RT \Gamma_s \ln \left[ 1 + k_1 a_s \exp \left( \frac{-\Delta H_0}{RT} \right) \right]
\]

\[
\frac{d\gamma}{dT} = -A_\gamma - R \Gamma_s \ln (1 + K a_s) - \frac{K a_s}{1 + K a_s} \frac{\Gamma_s \Delta H_0}{T}
\]

\[
K = k_1 \exp \left( \frac{-\Delta H_0}{RT} \right)
\]
For $a_s = 0.012$ wt%
Numerical Method

- Software: COMSOL Multi-Physics
- Physics: Electromagnetic Field, Fluid Flow and Heat Transfer
- Mesh: Tetrahedral, 0.08 mm at Fluid and 1 mm at Solid Domain
Numerical vs Experimental Results

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston
Top View of the FZ

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston
Side View of the FZ

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston
Temperature Distribution

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Conclusion

• Weld profile is asymmetric due to different melting points.
• Higher Lorentz force in the Ni side pushes the fluid towards the steel side.
• At the top surface flow is under Marangoni effect.
• Conductive heat transfer is higher in the Ni side; therefore its temperature grows higher.
Thank You