Basic models, animations and unsolved problems in welding

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• A basic heat conduction model - benefits and limitations
• Applications of heat transfer and fluid flow models
  Unusual weld pool shapes
  Weld surface profiles
  Effect of surface active elements
  Welding two plates with different sulfur contents
  Uphill, downhill, tilted, L and V configurations
  Weld metal composition change
  Why Sievert’s Law cannot be directly applied in welding
• Tailoring weld geometry

Basic models in welding

Models the essential physical processes

“Essential” => of interest to many for meaningful understanding of the process and the weld metal

• Heat transfer and melting
• Evaporation of elements & dissolution of gases
• Flow of liquid metal
• Solidification & structural changes
• Properties
Rosenthal model for heat conduction in welding - a most widely used basic model

“For an engineer in search of a theory, the simpler the better”
(paraphrased)

Professor D. Brian Spalding
picture from http://www.cham.co.uk/about.php

Rosenthal model for heat conduction in welding

- Analytical solution to calculate temperature fields, cooling rates and weld geometry
- Widely used - simple, phenomenological and insightful
- But ignores convection which is the main mechanism of heat transfer in many cases
Four main difficulties of heat conduction models

"Everything should be made as simple as possible, but not simpler."

— Albert Einstein

From: http://rescomp.stanford.edu/~cheshire/EinsteinQuotes.html
Problem 1: diversity of weld shapes cannot be predicted from heat conduction equation

All these shapes have been explained considering convective heat transfer
Problem 2: weld orientation effect cannot be explained

This effect has been explained considering convective heat transfer
Problem 3: The effects of minor alloying elements cannot be explained ignoring convection.

The effects of oxygen and sulfur has been explained considering convective heat transfer.

20 ppm sulfur

150 ppm sulfur

* Minor changes in composition => major changes in geometry
* Does not always happen!
Problem 4: Heat conduction equations overpredict cooling rates

“...the heat conduction equation has been found to be inadequate in representing experimental cooling curves” SVENSSON, GRETOFT and BHADESHIA, An analysis of cooling curves from the fusion zone of steel weld deposits, Scand. J. Metallurgy, vol. 15, pp. 97-103, 1986.

They recommended use of empirical correlations.

The heat conduction equations predict high temperature gradients and cooling rates because mixing of hot and cold liquids is ignored.

Convective heat transfer calculations do not have any such problems.
Heat and fluid flow models and their diverse applications
GTA weld pool with deformed free surface
Heat and fluid flow models - diverse applications

**Welding Processes**
Gas tungsten arc (GTA), Gas metal arc (GMA), Laser (conduction & keyhole), Electron beam, GTA-Laser hybrid, Friction stir welding

**The Main Engine**
Transient, three dimensional, heat, mass and momentum transfer numerical model

**Output**
- Solidification parameters, solidification growth rates, temperature gradients etc.
- Transient temperature and velocity fields, mixing of consumables, heating and cooling rates, weld geometry
- Deformed free surface, loss of alloying elements, composition change etc.

**Applications**
- Phase transformation in the fusion and heat affected zone
- Grain growth in the heat affected zone
- Inclusion type, size and distribution
- Pore structure, gas dissolution etc.
Many more applications

1. Fusion zone (FZ) and heat affect zone (HAZ) geometries
2. Grain size and topological features in the HAZ
3. Evolution of inclusion composition and size distribution
4. Evolution of microstructure in both FZ and HAZ
5. Control of cooling rates
6. Composition change owing to selective vaporization of alloying elements
7. Control of hydrogen and nitrogen in steel weldments
8. Joining of dissimilar materials including steels of different surface active elements such as sulfur and oxygen
9. Prevention of macro-porosity in laser welding
10. Enhancing fatigue property through improved surface finishing
1. Understanding unusual weld pool shapes
Wavy weld pool boundary

Hemispherical boundary
Arc welding of Al 5182
Zhao, DebRoy, Met. Trans B, 2001

Concave at the center
Laser melting of NaNO3
Limmaneevichitr, Kou, Welding Journal, 2000

Convex at the center
Arc welding of steel
Elmer, Palmer, Zhang, DebRoy, STWJ, 2008

Arora, Roy, and DebRoy, Scripta Materialia, 2009
High Marangoni number, $Ma$, leads to formation of wavy weld pool boundary.

The Marangoni number, $Ma$, is defined as:

$$Ma = \frac{\text{Surface tension force}}{\text{Viscous force}} = \frac{L \Delta T (d\gamma/dT)}{\alpha \mu}$$

- $L$: Characteristic length
- $\Delta T$: Temperature difference
- $d\gamma/dT$: First derivative of surface tension wrt temperature
- $\alpha$: Thermal diffusivity
- $\mu$: Viscosity

Source: Arora, Roy, and DebRoy, Scripta Materialia, 2009
Origin of wavy weld pool boundary

Marangoni (Ma) and Prandtl (Pr) numbers can be used to predict the shape of the wavy weld pool boundary.

\[ \text{Ma} = \frac{\text{Surface tension force}}{\text{Viscous force}} \]

\[ \text{Pr} = \frac{\text{Viscous diffusion rate}}{\text{Thermal diffusion rate}} \]

Arora, Roy, and DebRoy, Scripta Materialia, 2009
2. Surface profiles
Why study surface profile?

Improper parameters ⇒ poor mechanical properties ⇒ defects ⇒ failure

$\theta$ - weld toe angle

$h$ - weld reinforcement height

- Stress range vs. Cycles to crack initiation
  - Increasing $\theta$

- Stress range vs. Cycles to crack initiation
  - Increasing $h$
Development of bead profile in GMA welds

W. Zhang and T. DebRoy
The Pennsylvania State University

Phase Transformations & Complex Properties Research Group, Cambridge University, 19 August 2011
Calculated and experimental GMA bead shape

Experimental data from Kim and Na, *Welding J.*, 1995 (5) 141s
Effect of welding parameters on the solidified surface profile

<table>
<thead>
<tr>
<th>Test case A</th>
<th>Test case B</th>
<th>Test case C</th>
</tr>
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<tbody>
<tr>
<td>Bead width (mm) - W</td>
<td>11.20</td>
<td>11.32</td>
</tr>
<tr>
<td>Bead Height (mm) - h</td>
<td>3.02</td>
<td>3.12</td>
</tr>
<tr>
<td>Penetration (mm) - P</td>
<td>5.00</td>
<td>5.05</td>
</tr>
<tr>
<td>Toe angle - θ</td>
<td>59°</td>
<td>53°</td>
</tr>
</tbody>
</table>
3. Effect of surface active elements
Convection in Fe and Fe-S Melts

\[ \tau = \frac{d\sigma}{dx} = \frac{d\sigma}{dT} \cdot \frac{dT}{dx} \]

Negative or positive

Negative

\[ \mu \frac{\partial u}{\partial z} = f_L \left( \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial x} + \frac{\partial \gamma}{\partial C} \frac{\partial C}{\partial x} \right) \]
High power welding - sulfur affects penetration

Minor changes in composition \(\rightarrow\) major changes in geometry
Low power welding - sulfur does not influence penetration

Minor change in composition $\rightarrow$
Insignificant change in geometry

20 ppm sulfur
1900 W
Pe $<< 1$
150 ppm sulfur
2.0 cm/s
Variable penetration - summary

Experiments

- *reveal what happens: sometimes the depth changes with % S*
- but do not reveal why

Modeling

- *surface active elements improve penetration only when convection is important (high Pe)*

*Modeling is a path to understand the science of welding*
4. Welding two plates with different sulfur contents
Identifying factors affecting weld pool geometry

Distribution of sulfur on the top surface

The arc shifts towards the low sulfur side

$I = 150 \, A, \, V = 10.5 \, V, \, \text{Welding speed} = 1.7 \, \text{mm/s}$

$S = 0.003 \, \text{wt}\%$

$S = 0.293 \, \text{wt}\%$

$I = 101 \, A, \, V = 9.6 \, V, \, \text{Welding speed} = 1.7 \, \text{mm/s}$

$S = 0.024 \, \text{wt}\%$

$S = 0.003 \, \text{wt}\%$

$S$ gradient
Sulfur distribution in the weld

EPMA results

**Welding conditions:** 150 A, 10.8 V, welding speed is 1.7 mm/s

- No significant sulfur concentration gradient
- Not much influence on weld bead shift
Reason for arc shift

- Sulfur covers more surface on high sulfur side => less metal sites on the surface.
- Sulfur has strong interaction with low ionization potential metals like Mn. Higher the sulfur the more it prevents ionization.
Incorporating arc shift

Maximum penetration occurs approximately below the arc location

Amount of arc shift is approximated by length AB

Empirical relation for amount of arc shift

\[ 0.19 \times \left| C_L - C_R \right|^{0.24} \times \left( \frac{I \times V}{U} \right)^{0.42}, (\text{wt\%})^{0.24} - (\text{J/mm})^{0.42} \]
Temperature and velocity fields & Sulfur distribution

Welding conditions: 150 A, 10.8 V, welding speed is 1.7 mm/s

No significant sulfur gradient except very close to the edges

Fair agreement between the calculated and experimental weld pool geometry
5. Uphill, downhill, tilt, L and V configurations
Effect of tilt angle

Welding Conditions
I = 362 A
V = 33 V
U_w = 4.2 mm/s
CTWD = 22.2 mm
w_f = 211.7 mm/s

Temperatures: in Kelvin
Weld pool boundary: 1745 K

Pe = \frac{u L}{\alpha} = 120
u: Liquid velocity
L: Weld pool width
\alpha: Thermal diffusivity
Effect of lift angle
**Weld bead geometry**

- **Weld bead is depressed in the center during downhill welding**
- **Hump formation during uphill welding**
- **More penetration during uphill welding**

![Diagram showing weld bead geometry](image)

- **I = 362 A, V = 33 V, U = 4.2 mm/s, w_f = 211.7 mm/s**
- **I = 250 A, V = 29 V, U = 7.0 mm/s, w_f = 150.0 mm/s**
- **I = 362 A, V = 33 V, U = 6.4 mm/s, w_f = 211.7 mm/s**
- **I = 322.6 A, V = 32 V, U = 5.3 mm/s, w_f = 190.5 mm/s**

**Weld bead geometry**

- **V-shape, Horizontal**
- **V-shape, 10° Downhill**
- **V-shape, 10° Uphill**

**Images showing weld bead geometry in different stages:**

- **Tilt angle = 0°, Welding direction**: V-shape, 0 = 45°
- **Tilt angle = 0°, Welding direction**: L-shape
- **Tilt angle = 0°, Welding direction**: V-shape, 0 = 45°, Downhill welding
- **Tilt angle = 0°, Welding direction**: V-shape, 0 = 45°, Uphill welding
6. Composition change
Pronounced weld metal composition change

Temperature field and weld pool size are important factors.
Composition change is more pronounced at low powers - why?
Why is the composition change more pronounced at low powers?

- Most of the evaporation takes place under the beam.
- Pool size increases strongly with increase in power – alloying element loss is spread over a larger volume.
Temperature from Vapor Composition

\[
\frac{\text{Vaporization rate of } A}{\text{Vaporization rate of } B} = \frac{J_A}{J_B} = \frac{p_A}{p_B} \sqrt{\frac{M_B}{M_A}} = f(T)
\]
Temperature from Vapor Composition

\[
\frac{J_A}{J_B} = \frac{p_A}{p_B} \sqrt{\left( \frac{M_B}{M_A} \right)}
\]

Vaporization rate of A

Vaporization rate of B

Graph showing the relationship between \( J_{Fe}/J_{Mn} \) and temperature (K). The graph indicates that at 3125 K, the value of \( J_{Fe}/J_{Mn} \) is 10.8.
## Temperature from Vapor Composition

<table>
<thead>
<tr>
<th>Power and pulse</th>
<th>Spot radius (mm)</th>
<th>Peak temperature from numerical heat transfer (K)</th>
<th>Temperature from $J_{Fe}/ J_{Mn}$ (K)</th>
<th>Temperature from $J_{Cr}/ J_{Mn}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1067 W, 3.0 ms pulse</td>
<td>0.260</td>
<td>3270</td>
<td>3125</td>
<td>3110</td>
</tr>
<tr>
<td></td>
<td>0.325</td>
<td>2879</td>
<td>3005</td>
<td>2865</td>
</tr>
<tr>
<td>530 W, 4.0 ms pulse</td>
<td>0.210</td>
<td>2761</td>
<td>3090</td>
<td>3060</td>
</tr>
<tr>
<td></td>
<td>0.313</td>
<td>2308</td>
<td>2435</td>
<td>2485</td>
</tr>
</tbody>
</table>
Model Validation

Experimental and Calculated Weld Pool Cross Sections


(a) beam radius: 0.43 mm

(b) beam radius: 0.57 mm
Iron and chromium were the dominant species in the vapor.
Weld Metal Composition Change

Initial concentrations:
Mn: 1 wt%, Cr: 18.1 wt%,
Ni: 8.6 wt%, Fe: 72.3 wt%

Final weight percent of element i:

\[
(\% \ i) = \frac{V \rho (% \ i)^0 - \Delta m_i}{V \rho - \sum_{i=1}^{n} \Delta m_i} \times 100\%
\]

V: volume of weld pool
\( \rho \): density of liquid metal
\( \Delta m_i \): weight loss of element i
n: number of vapor species

Assumption: uniform weld pool composition resulting from strong recirculating flow
Change of Composition of Weld Pool

Laser power: 1067 W, pulse duration: 3.0 ms, and beam radius: 0.225 mm.
Composition Change of Weld Pool

Laser power: 1067 W, pulse duration: 3.0 ms, and beam radius: 0.325 mm
Recoil and Surface Tension Forces

Laser power: 1067 W, pulse duration: 3.0 ms, and beam diameter: 0.405 mm.

Surface tension force: \( F_s = 2\pi r_0 \sigma \)

Recoil force: \( F_r = 2\pi \int_0^{r_B} r\Delta P(r)dr \)

Recoil force > Surface tension force => Expulsion of metal drops
Recoil and Surface Tension Forces

$t > 2.6 \text{ ms}, \text{ Recoil force} > \text{ Surface tension force} \Rightarrow \text{Expulsion of metal drops}$
Free Surface Deformation

Progressive deformation of the free surface
Free Surface Deformation

Power density (kW/mm²)

No expulsion

Expulsion

l/d

3 4 5 6 7 8 9 10 11 12

0 0.1 0.2 0.3 0.4 0.5
Critical Laser Power Density

3.0 ms pulse

4.0 ms pulse

Critical laser power density:
8.0 kW/mm²

Critical laser power density:
7.0 kW/mm²
Effects of Welding Variables

- Heavy expulsion
- Intermittent expulsion
- Vapor
- No vapor

Power Density (kW/mm²) vs. Pulse Duration (ms)

- Heavy expulsion
- Intermittent expulsion
- Vapor
- No vapor
7. Dissolution of gases
Nitrogen concentration in the weld metal is much higher than that predicted by Sievert's law.

But why?
Nitrogen dissolution from a plasma environment

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>GAS/METAL</th>
<th>PLASMA/METAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPECIES</td>
<td>$N_2/Fe$</td>
<td>$N_2, N_2^<em>, N_2^+, N, N^</em>/Fe$</td>
</tr>
<tr>
<td>LAW</td>
<td>SIEVERTS’ LAW</td>
<td>??</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td>Source of N Gas</td>
<td>Thermal Dissociation</td>
<td>Thermal Dissociation Electron Impact Electromagnetic Effects</td>
</tr>
<tr>
<td>Partial Pressure</td>
<td>$\frac{1}{2} N_2 (g) \rightarrow N (g)$</td>
<td>$P_N &gt; K_{eq}^{T_s} P_{N_2}^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>$P_N = K_{eq}^{T_s} P_{N_2}^{1/2}$</td>
<td>$P_N = K_{eq}^{T_d} P_{N_2}^{1/2}$</td>
</tr>
</tbody>
</table>

$T_s = $ Sample Temperature $T_d = $ Temperature at which $N_2(g)$ dissociates
Nitrogen - Iron System

DIATOMIC NITROGEN

MONATOMIC NITROGEN
Physical modeling with isothermal metal drops

Diagram:
- Optical Pyrometer
- Prism
- Fibre Optic Cable
- CCD Detector
- Nitrogen
- Water
- CCD Detector Controller
- Detector Interface
- Computer System
- Emission Spectrograph
- Power Source, RF Generator
- Plasma
- Gas Mixture
- Sample
- Sample Holder
- Pump and Pressure Control
- Pressure Gauge
- Computer System
- Gas Mixture
- Sample
- Sample Holder
Enhanced dissolution of nitrogen in isothermal metal drops

- Nitrogen solubilities up to 30 times larger than Sieverts’ Law predictions.
- Small changes in sample temperature cause large variations in $N$. 
Emission spectroscopy of glow discharges

He-1%N₂

- Experimental verification for the presence of species in the plasma phase.
Nitrogen dissolution in the weld pool

Much higher than Sieverts' law values of nitrogen concentration can be predicted by a two temperature model

But how?
Two temperature model - useful and simple
back of the envelop estimation of concentration

\[ N(\text{wt.\%}) = \sqrt{P_{N_2}} \exp\left( -\frac{1}{R} \left( \frac{\Delta G^\circ_{Td}}{T_d} + \frac{\Delta G^\circ_{Ts}}{T_s} \right) \right) \]

- Dissociation temperatures are 100-215 K above the sample temperature
  But welds are not isothermal!
Nitrogen concentrations at the weld pool surface

Inside Arc Column
\[ N(g) \rightarrow [N](ppm) \]
\[ [N] = P_N \exp \left(-\frac{\Delta G_{N(g)}}{RT}\right) \]

Outside Arc Column
\[ \frac{1}{2} N_2(g) \rightarrow [N](ppm) \]
\[ [N] = \left(P_{N_2}\right)^{1/2} \exp \left(-\frac{\Delta G_{N_2(g)}}{RT}\right) \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Phase</th>
<th>Free Energy (J/mol)</th>
<th>Temperature Range (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 N_2 (g) → N (g)</td>
<td>gas</td>
<td>(362,318.0 - 65.52 T)</td>
<td>273 to 1811</td>
</tr>
<tr>
<td>N (g) → N (wt pct)</td>
<td>liquid</td>
<td>(-358,719.4 + 89.56 T)</td>
<td>(&gt;1811)</td>
</tr>
<tr>
<td>N (g) → N (wt pct)</td>
<td>solid-(\delta)</td>
<td>(-349,265.3 + 74.01 T)</td>
<td>1663 to 1810</td>
</tr>
<tr>
<td>N (g) → N (wt pct)</td>
<td>solid-(\gamma)</td>
<td>(-353,698.6 + 10.29 T)</td>
<td>1185 to 1662</td>
</tr>
<tr>
<td>N (g) → N (wt pct)</td>
<td>solid-(\alpha)</td>
<td>(-349,265.3 + 74.01 T)</td>
<td>273 to 1184</td>
</tr>
<tr>
<td>1/2 N_2 (g) → N (wt pct)</td>
<td>liquid</td>
<td>(3598.2 + 23.89 T)</td>
<td>(&gt;1811)</td>
</tr>
<tr>
<td>1/2 N_2 (g) → N (wt pct)</td>
<td>solid-(\delta)</td>
<td>(13,052.4 + 8.49 T)</td>
<td>1663 to 1810</td>
</tr>
<tr>
<td>1/2 N_2 (g) → N (wt pct)</td>
<td>solid-(\gamma)</td>
<td>(-8619.0 + 37.40 T)</td>
<td>1185 to 1662</td>
</tr>
<tr>
<td>1/2 N_2 (g) → N (wt pct)</td>
<td>solid-(\alpha)</td>
<td>(13,052.4 + 8.49 T)</td>
<td>273 to 1184</td>
</tr>
</tbody>
</table>
Species concentrations in the plasma

\[ \text{Ar} \rightarrow \text{Ar}^+ + e^- \]  
\[ \frac{n_e n_{\text{Ar}^+}}{n_{\text{Ar}}} = \frac{2(2\pi m_{\text{Ar}} kT)^{3/2} Z_{\text{Ar}^+}}{\hbar^3} e^{-\frac{e_{\text{Ar}}}{kT}} \]  
\[ \text{Ar}^+ \rightarrow \text{Ar}^{++} + e^- \]  
\[ \frac{n_e n_{\text{Ar}^{++}}}{n_{\text{Ar}^+}} = \frac{2(2\pi m_{\text{Ar}} kT)^{3/2} Z_{\text{Ar}^{++}}}{\hbar^3} e^{-\frac{e_{\text{Ar}}}{\gamma kT}} \]  
\[ \text{N}_2 \rightarrow \text{N}_2^+ + e^- \]  
\[ \frac{n_e n_{\text{N}_2^+}}{n_{\text{N}_2}} = \frac{2(2\pi m_{\text{N}_2} kT)^{3/2} Z_{\text{N}_2^+}}{\hbar^3} e^{-\frac{e_{\text{N}_2}}{\gamma kT}} \]  
\[ \text{N} \rightarrow \text{N}^+ + e^- \]  
\[ \frac{n_e n_{\text{N}^+}}{n_{\text{N}}} = \frac{2(2\pi m_{\text{N}} kT)^{3/2} Z_{\text{N}^+}}{\hbar^3} e^{-\frac{e_{\text{N}}}{kT}} \]  
\[ \text{N}_2(g) \rightarrow 2\text{N}(g) \]  
\[ K = \frac{p_{\text{N}_2}^2}{p_{\text{N}_2}^2} = \frac{(P)^2(X_{\text{N}})^2}{(P)X_{\text{N}_2}} = \frac{p}{X_{\text{N}_2}} = \frac{(n_{\text{N}_2})^2}{n_{\text{N}_2}^2} \left( \frac{RT}{N_A} \right) \]

\[ n_e = n_{\text{Ar}^+} + 2n_{\text{Ar}^{++}} + n_{\text{N}_2^+} + n_{\text{N}^+} \]  
\[ X_{\text{Ar}}(N_A) \left( \frac{p}{RT} \right) = X_{\text{Ar}}(n_{\text{Ar}} + 2n_{\text{Ar}^+} + 3n_{\text{Ar}^{++}}) \]  
\[ X_{\text{N}_2}(N_A) \left( \frac{p}{RT} \right) = X_{\text{N}_2}(n_{\text{N}_2} + 2n_{\text{N}_2^+} + n_{\text{N}} + 2n_{\text{N}^+}) \]

Important species: Ar, N2 and N
Main tasks:

Compute temperature and velocity fields in the weld pool

Compute species concentrations in the plasma above the weld pool

Compute nitrogen concentrations on the weld pool surface

Compute nitrogen concentrations in the entire specimen
Comparison between modeling and experimental results

TRAVEL SPEED: 0.847 cm/sec

Modeled results with nitrogen supersaturations between 50 and 75% higher than Sieverts’ Law calculations for P(N₂) = 1 atm correspond well with experimental results.
Many other applications

http://www.matse.psu.edu/modeling

<table>
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<th>Flow and temperature fields in friction stir welding</th>
<th>Keyhole mode welding</th>
<th>Weld pool temperature and velocity fields</th>
<th>Liquid metal flow and free surface shape</th>
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<td>Bead shape development in GMA welding</td>
<td>Inclusion motion in the weld pool</td>
<td>Fillet weld development and thermal cycle</td>
<td>Monte Carlo simulation of isothermal grain growth</td>
</tr>
<tr>
<td>Grain growth during welding of Ti-6Al-4V</td>
<td>Cooling during spot welding</td>
<td>Heating and cooling of spot weld surface</td>
<td>Phase transformation in 1008 steel during welding</td>
</tr>
</tbody>
</table>

From http://www.matse.psu.edu/modeling
Grain Growth in Ti-6Al-4V Heat Affected Zone

S. Mishra and T. DebRoy
The Pennsylvania State University
Tailoring weld geometry – has been done

Tailoring structure and properties?
Designer welds via multiple paths

**Requirements:** Geometry, cooling rate, or microstructure

- Variable set 1
- Variable set 2
- Variable set 3
- Variable set 4
- Variable set 5
- Variable set 6
- Variable set 7
- Variable set 8

Target weld geometry, cooling rate or other attributes
Tailoring weld geometry

Genetic Algorithm

Sets of \( \begin{pmatrix} I & V & U \\ I_r & V_r & U_r \end{pmatrix} \)

\( \text{Calculated weld pool geometry} \)

\( \text{Desired weld pool geometry} \)

\[ O_2(f) = \left( \frac{p^c}{p^e} - 1 \right)^2 + \left( \frac{w^c}{w^e} - 1 \right)^2 \]
Tailoring weld attributes

Target: Form a weld of the following dimensions:

Penetration : 1.23 mm  Width : 4.47 mm

This weld was actually fabricated by GTA welding

Bag, De and DebRoy, Materials and Manufacturing Processes., 2009
Objective function

\[ O(f) = \left( \frac{w^c - w^{\text{obs}}}{w^{\text{obs}}} \right)^2 + \left( \frac{p^c - p^{\text{obs}}}{p^{\text{obs}}} \right)^2 \]

\( W \) - weld pool width
\( P \) - weld pool penetration
\( \text{Superscript } c \) - computed values
\( \text{Superscript } \text{obs} \) - experimentally observed values

\( \{f\} \equiv \{ f_1, f_2, f_3 \} = \begin{bmatrix} I \\ I_{mn} \\ V \\ V_{mn} \\ V \end{bmatrix} = \begin{bmatrix} I^* \\ I_{mn}^* \\ V^* \\ V_{mn}^* \\ \nu^* \end{bmatrix} \)

\( f \) - welding variable set
\( \nu \) - welding speed
\( I \) - Current
\( V \) - Voltage
\( \text{Subscript } mn \) - minimum allowed value
\( \text{Subscript } mx \) - maximum allowed value

Bag, De and DebRoy, Materials and Manufacturing Processes., 2009
Objective function with $I^*$, $V^*$ and $v^*$

$O(f)$ for the initial population

$O(f)$ after ten generations

Eight alternate welding conditions achieved after fifteen generations
Multiple combinations of welding parameters result in roughly the same target geometry

Target geometry: penetration = 1.23 mm, width = 4.47 mm
\[ I = 140 \text{ A}, \ V = 11.2 \text{ V}, \ \text{Welding speed} = 7 \text{ mm/s} \]

<table>
<thead>
<tr>
<th>Individual solutions</th>
<th>I (amp)</th>
<th>V (Volt)</th>
<th>U (mm/s)</th>
<th>Penetration (mm)</th>
<th>Width (mm)</th>
</tr>
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Bag, De and DebRoy, Materials and Manufacturing Processes., 2009
Geometries of fabricated welds

1) 134 A, 9.8 V, 4.3 mm/s
   - 4.54 mm wide
   - 1.24 mm height

2) 140 A, 11.5 V, 7.1 mm/s
   - 4.57 mm wide
   - 1.24 mm height

3) 135 A, 10.6 V, 5.1 mm/s
   - 4.60 mm wide
   - 1.25 mm height

4) 163 A, 10.3 V, 9.6 mm/s
   - 4.34 mm wide
   - 1.18 mm height

Bag, De and DebRoy, Materials and Manufacturing Processes., 2009
Geometries of fabricated welds

117 A, 14.4 V, 8.2 mm/s

149 A, 12.6 V, 9 mm/s

106 A, 12.5 V, 4.8 mm/s

166.5 A, 10.5 V, 8.6 mm/s

Bag, De and DebRoy, Materials and Manufacturing Processes., 2009
Multiple sets of welding variables can produce a target geometry

Arc welding of SS304 to produce 4.47 mm wide and 1.23 mm deep pool

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Thank you very much

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