Practical Microstructure Modeling of Welding for Perfect Weld

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Practical Microstructure Modeling of Welding for Perfect Weld

How welding simulation and modeling work

300 [amp]
20 [volt]
10 [mm/s]

Rapid heating
Quick cooling
Thermal History at all virtual points
Rapid heating
Modeling of weld consists of close coupling between TH, MS & ST analysis.

We need to know about **TH, MS and ST effects** as well as **right coupling** of them together.

**Practical: Sizable, Cost & Time Effective**
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Modeling for HAZ & BM Analysis;

• The algorithms for TH solve is power density. Frequent model; Double Ellipsoid
• The algorithm for MS solve are extend of heat-treatment models. Phase diagram and CCT
• Very practical for design of welded structures.

Modeling for Weld Pool (WP) Analysis;

• The algorithms for TH solve required a coupled solve of energy conservation and fluid flow (conservation of energy and Navier-Stokes).
  A successful approach; SPH (Smooth Particle Hydrodynamics) that is a mesh-less solve based on particles’ dynamics while it updates the temperature of each particle.
• The algorithm for MS solve are extend of casting and solidification models.
  A successful approach: Phase field and cellular automata (CA) that is solidification constitutive equations as rule of evolution over solidifying cells over time.
• HPC has been essential in recent development
Modeling for HAZ & BM Analysis;

Metallurgist uses TTT and CCT diagrams for tracking the microstructural transformations that occur over a range of cooling trajectory.

Limitation of use in welding:

- TTT/CCT is limited to max 900 C i.e shortly above Austenite decomposition (A1-A3)
- Grain growth of Austenite is non-uniform (Welding forms CGHAZ to FGHAZ)
- Presence of precipitates (e.g. NbC) is important in weld but not considered in TTT/CCT
- Not a convenient representation for computation
Modeling for HAZ & BM Analysis;

**Low Alloy Steels**

**Kirkaldy Model & extend of Watt & Henwood:**

Kirkaldy model developed in 1980s for Jominy test and extended by watt and Henwood in 1990s to model HAZ of welds in **Low Alloy Steels**
Low Alloy Steels
Kirkaldy Model & extend of Watt & Henwood;

MS Solver
{at each point over time $\varphi(x,y,z,t)$}

Input;
- Transient Temp. (analytical, FEM, ...)
- Composition of BM (C & alloying elements)
- Initial state of MS (phase fractions, grain size, ...)

Output;
- Fraction of Ferrite ($\alpha$)
- Fraction of Pearlite ($p$)
- Fraction of Austenite ($\gamma$)
- Grain size of Austenite ($\gamma$)
- Fraction of Bainite ($b$)
- Fraction of Martensite ($M$)
Step 1; Critical points

Thermal history of a point at 5 [mm] distance of weld centre line
(Material 1018 Steel)
Step 2: Pseudo-binary Fe-C equilibrium diagram (Hypoeutectoid steel)

\[ C_{\text{eut}} = \frac{[\phi_1 - \phi_2 - T]^2}{203^2} \]

\[ \phi_1 = 910 - 15.2Ni + 44.7Si + 104V + 315Mo + 13.1W \]
\[ \phi_2 = 30Mn + 11Cr + 20Cu - 700P - 400Al - 120As - 400Ti \]

\[ C_\alpha = 0.105 - 115.0 \times 10^{-6} \times T \]  \( T \text{ in } ^\circ\text{C} \)
715 < T[\text{in } ^\circ\text{C}] < 912

\[ C_\gamma = \frac{[\phi_1 - \phi_2 - T]^2}{203^2} \]
\[ \phi_1 = 910 - 15.2Ni + 44.7Si + 104V + 315Mo + 13.1W \]
\[ \phi_2 = 30Mn + 11Cr + 20Cu - 700P - 400Al - 120As - 400Ti \]

\[ C_\gamma = ((889 - T)/203)^2 \]  \( 715 < T[\text{in } ^\circ\text{C}] < 912 \)

\[ C_\alpha = \frac{T - 20.0}{A_1 - 20.0} \times (0.105 - 115.3 \times 10^{-6} \times A_1) \]  \( T \text{ in } ^\circ\text{C} \)

\[ C_\alpha \approx 3.25 \times 10^{-5} (T-20) \]  \( 20 < T[\text{in } ^\circ\text{C}] < 715 \)

\[ C_{ae} = 0.0225 \quad C_0 = 0.14 \]
Step 3; Determine pseudo-equilibrium phase fraction (Hypoeutectoid steel)

The volume fraction is given by the lever law

\[ X_F = \frac{C - C_{\gamma}}{C_{\alpha} - C_{\gamma}} \]

\[ X_{\gamma} = 1 - X_F \]

where

- \( X_{\gamma} \) = fraction of austenite
- \( C_{\gamma} \) = carbon content of austenite
- \( C_{\alpha} \) = carbon content of ferrite

\[ X_F = \frac{C - C_{\text{eut}}} {C_{\alpha} - C_{\text{eut}}} \]

\[ X_{\text{eut}} = 1 - X_F \]

where

- \( X_F \) = fraction of ferrite
- \( X_{\text{eut}} \) = fraction of pearlite
- \( C \) = carbon content of steel
- \( C_{\text{eut}} \) = carbon content of the eutectoid
- \( C_{\alpha} \) = carbon content of ferrite

C\(_{\alpha}e\) = 0.0225  \( C_0 = 0.14 \)
Step 4; Consider the Kinetics of transformation
4-1; Analyze the heating part

Callister's Relation:

$$g_t = g_0 + k \int_{t_{Ts}}^{t_{A3}} \exp \left( \frac{-Q}{RT(t)} \right) dt$$

coefficient dependent on material and T.

elapse time

$$g_t - g_0 = Kt$$

exponent typ. ~ 2

grain diam. at time t.
Step 4; Consider the Kinetics of transformation
4-1; Analyze the cooling part

Thermal history of a point at 5 [mm] distance of weld centre line
(Material 1018 Steel)

- Local State Grain Size
- Rate Eq.
  - Ferrite
  - Pearlite
  - Bainite
- Vol. frac. of Martensite

\[ \frac{dX}{dt} = B(G, T) X^m (1 - X)^p \]

\[ X_M = 1 - \exp[-k_1(MS - T)] \]

(Koistenen & Marburger)
**MS-Solve:**

Read thermal profile and initial state of every node  
Returns evolved state of MS (i.e. all phase frac.) for the nodes
A Real Example: Repair a Cracked Drum

Thrust Ring Stiffener Web

Drum 3.6 m OD Th 1” A36 Steel E7018
Repair a Cracked Drum

Martensite Formation

Martensite Map
Repair a Cracked Drum

Bainite Map
Pearlite Map
Ferrite Map
Hardness Map
Repair a Cracked Drum

Distortion 10X
Grid: Original Position
Repair a Cracked Drum

Residual Stress
(Effective Stress)
Repair a Cracked Drum

Plastic Strain
Another Example:
Overlay temper-bead

HY80
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Modeling for Weld Pool (WP) Analysis;
Solidification Modes:

- Planar
- Columnar
- Dendritic
- Equiaxed
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- **Temperature gradient, G**
  - Planar
  - Cellular
  - Columnar Dendritic
  - Equiaxed Dendritic

- **Growth rate, R**
  - Low G/R
  - High G/R

- **G/R determines morphology of solidification structure**
  - GxR determines size of solidification structure

- **Increasing constitutional supercooling**
  - Equilibrium
  - Planar
  - Cellular
  - Columnar dendritic
  - Equiaxed dendritic

- Actual constitutional supercooling
  - M
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200 amp 2 mm/s
HI = 1.5 kJ/mm

300 amp 3 mm/s
HI = 1.5 kJ/mm

400 amp 4 mm/s
HI = 1.5 kJ/mm
Summary

**Designer-driven weld optimization** for all levels of **application** and **complexity**:

- Distortion Mitigation, Residual Stress Control, Strain-based Design,
- Microstructure Prediction, Hardness Calculation,
- Crack Likelihood, Damage & Life Forecast,
- and Risk-Free Repair Procedure.

**Obtaining the Perfect Weld**

- State-of-the-art Welding Science & Engineering through modeling and simulation platform.
- Proven track record of experience with high quality consultancy, engineering, design, and inspection.
- Validate through high-profile experimental laboratory and mock-up test facilities. Microstructure, Mechanical and NDT testing services.

Synergy of combined Science, Engineering, Experience, Skills, and Facilities:
Welding moves from being an “art” to being a manufacturing science with the help of computers.

“virtual factory” where modeling and simulation tools become commonplace in welding operations

“Incorporate welding and joining considerations early in product-design stage [using computer models]”

“Smart Factories” where advanced computer modeling, automation and control are key technologies to help welding become more competitive, energy-efficient and innovative as part of manufacturing.
Thank You

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