Advanced Integration of Multi-Scale Mechanics and Welding Process Simulation in Weld Integrity Assessment

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Overview of the Presentation

- Project summary
  - Background/Incentive/Industry needs
  - Barriers-Pathway-Matrix
  - Objectives
  - Partners
  - Work to date
  - Benefits
  - Commercialization
- Highlights of technical work
- FY 2006 Plan
- Concluding remarks
Extent of Welding Applications

- 50% of gross national product has elements of welding/joining [1].
- Welding is a critical enabling technology in 90% of durable goods production.
- Welding/joining is an IMF multiple-industry research priority.
- Example of affected industries:
  - Petroleum
  - Chemical
  - Mining
  - Metal casting
  - Steel and forest products

Phase Transformation during Welding

Schematic. Cooling rate not considered

welds being Studied
Weld Integrity Assessment and Infrastructures

- Very severe loads on infrastructure
- Welds can be the weakest points.
- “Bad welds” can have consequences in:
  - Energy consumption
  - Environment
  - Economy
- How do we know if a weld is “bad?”
- Hence, weld integrity assessment!
Welding Technology, Infrastructure, and Energy

- Key infrastructures are being planned and constructed in environmentally sensitive areas.
- Welding quality and productivity affects entire project cost as welding limits the pace of the construction.
Barriers, Pathway, Matrix

**Barriers**
- Prediction of weld microstructure and mechanical properties (strength and toughness)
- Measurement of materials’ resistance to failure (ductile processes)
- Determination of crack driving force to failure
- Reliability methods

**Pathway**
- Weld microstructure modeling
- HAZ microstructure modeling
- Toughness correlation via neural network
- Implement low constraint test procedure
- Develop new constitutive models to better describe crack driving force
- Implement reliability method in computer software

**Matrix**
- Application of technology in industry partner processes
  - Duke Energy
  - Lincoln Electric
- Industry-wide procedures and software
  - PRCI thermal model for in-service welding
- Codes and Standards
  - CSA
  - ASME
  - API
- Energy savings:
  - 246 trillion Btu per year

**Abbreviations:**
- PRCI: Pipeline Research Council International
- ASME: American Society of Mechanical Engineers
- API: American Petroleum Institute
- CSA: Canadian Standards Association
Project Objectives by Category

- Technical Objectives
  - Understand the interaction of welding process parameters and resulting microstructure and mechanical properties through welding process simulation, augmented by experimental testing
  - Understand structural integrity of weld joints under thermal, mechanical loading, with particular emphasis on post yield plastic behavior
  - Integration of welding process simulation and multi-scale mechanics

- Application Objectives
  - New construction, energy pipeline as an example
    - New steels
    - New welding processes deployed in hostile environments
    - Very severe loading
  - In-service welding
    - Hot taps
    - In-service repair
    - Cladding
Partners

- **Industry Partners:**
  - Pipeline Research Council International (PRCI)
  - TransCanada Pipelines Limited
  - Lincoln Electric
  - Duke Energy
  - Williams Gas Pipeline
  - Southern California Gas Company
  - ChevronTexaco

- **Research Partners:**
  - Oak Ridge National Lab (ORNL)
  - Massachusetts Institute of Technology (MIT)
  - Northwestern University (NWU)
  - CanMet, Natural Resources of Canada
Work Breakdown by Technical Scope

- Integrated welding process modeling
  - Material Properties
  - Residual Stress

- Understanding weld integrity using multi-scale mechanics
  - Explicit method
  - Damage mechanics
  - Dynamics fracture
  - Meshfree method
  - Multi-scale mechanics

- Making welds
  - Microstructure characterization
  - Residual stress measurement
  - Laboratory-scale mechanical property testing

- Weld integrity Assessment
  - Deterministic Weld Integrity Assessment
  - Probabilistic Method
  - Large-scale structural component testing

- ORNL, Emc², MIT, and industry partners

- MIT, NWU

- Emc²
Baseline Materials and Welding Processes

- Linepipe materials
  - Thermal-mechanically processed
  - Heavily rolled
  - High strength
  - High toughness
  - Excellent ductility
  - Lean chemistry, good weldability
  - Yield at 100 ksi (690 MPa)
  - UTS at 120 ksi (827 MPa)

- Gas metal arc welding (GMAW)
  - High quality
  - High productivity
  - Yield at 110 ksi (758 MPa)
  - UTS at 130 ksi (896 MPa)

- Pushing the technology envelope
- Enable the use of high strength steels
- Broad applications in other industries
Work to Date (Continued)

- **Welding Process Simulation**
  - Prediction of HAZ microstructure and hardness (Emc²)
  - Correlation of weld Charpy toughness via neural network (Emc² and ORNL)
  - Inclusion model for welds (ORNL)
  - Weld microstructure characterization (ORNL)

- **Multiscale mechanics**
  - Damage mechanics modeling of wide plate tests (Emc²)
  - Small specimen tests to understand ductile failure process (Emc² and MIT)
  - Constitutive models to account for anisotropy
    - Hill-type model (Emc²)
    - Taylor polycrystalline model (MIT), rolling texture and resulting anisotropy in mechanical properties
  - 2-D moving particle FEM (NWU)

- **Integration**
  - Effects of HAZ softening (Emc²)

- **Application**
  - Update PRCI thermal analysis software (Emc²)
  - Review public domain FEA codes (Emc²)
Benefits

- Relating weld process parameters with desired mechanical properties and weld quality
  - Welding defects
  - Cost
  - Energy use
- Allow use of high toughness and high strength materials that are otherwise not possible, savings in
  - Weight
  - Energy
- Safer and more economical operation of
  - existing infrastructures
  - sound construction and operating practices of new infrastructures
- The energy savings are realized through:
  - using less tonnage of steels for the same design and operating conditions
  - reduction in the amount of welding through the use of high strength steels
  - reduction in repair welding
  - reduction in unnecessary post weld heat treatments.
Commercialization

- Codes and Standards
  - ASME
  - API
  - CSA
- Industry Software
  - PRCI thermal analysis software
  - Reliability-based strain design
- Publications
Interesting heterogeneity patterns was observed within the base metal region.
HAZ softening is very subtle, but does exist.
Mechanical heterogeneity within the weld is as expected showing the presence of hard (primary) and soft (reheated) weld regions.
These mechanical heterogeneity affect the resistance to crack growth.
Microstructure Heterogeneity and Mechanical Behavior

MIT work

Variability in HAZ and weld toughness!
Optimization of Hot-Tap Welding (Emc²)

- In service welding, avoid shutdown
- Proper welding procedure is critical to safely install new connections.
- Risks
  - Hydrogen cracking
  - Burn through

Numerical Procedure

- Pipeline Geometry
- Pipeline Operation Conditions
- Welding Procedure
- Computational Tools
  - Heat Transfer, Microstructure & Hardness Models
- Optimization Tool

Risk of Burn-through: Thermal History
Risk of Hydrogen Cracking: Microstructure & Hardness

Predicted Peak Temperature
Predicted Hardness

Emc²
HAZ Microstructure and Hardness Model

USER INPUT:
Steel Chemistry
(C, Mn, Cr, Ni ...)
Welding Thermal Cycle
(Measurement, simulation, etc.)

Max Hv in HAZ

PHASE TRANSFORMATION
COMPUTATION ALGORITHMS

Transformation Thermodynamics
System equilibria: $T_s, A_3, A_1, B_S, M_S$ ...
Transformation driving force, $\Delta G$

Transformation Kinetics
Grain growth
Austenite formation on heating
Decomposition of austenite on cooling
– ferrite, bainite, martensite, etc
Fraction of phases

Property Module
$H_v$, $\sigma_y$
HAZ Property in Microalloyed TMCP Girth Weld

BM-TMCP Steel X100: 0.06C-1.86Mn-0.10Si-0.13Ni-0.27Cu-0.03Cr-0.23Mo-0.008V-0.04Nb-0.027Al-0.012Ti
WM-ER100S-1: 0.07C-1.8Mn-1.7Ni-0.4Mo

HAZ Softening

Welding:
P-GMAW
6 passes
Preheat 125°C
Interpass Temp: 150°C
Cross-Weld Hardness, Measurement and Prediction

Transverse Micro Hardness Profile (Middle Plane)

Hv (500g)

Distance from Weld Center (mm)

BM-TMCP Steel X100: 0.06C-1.86Mn-0.10Si-0.13Ni-0.27Cu-0.03Cr-0.23Mo-0.008V-0.04Nb-0.027Al-0.012Ti

WM-ER100S-1: 0.07C-1.8Mn-1.7Ni-0.4Mo
Crack Driving Force

Solid: HAZ width = 2.0 mm, HAZ reduction = 15%
Dashed: HAZ width = 0.0 mm

Crack Size $a$ (mm) × $2c$ (mm):
- $6 \times 25$
- $3 \times 50$
- $3 \times 25$
Macroscopic Failure Initiation Sites ($\text{Emc}^2$)

- Weld centerline notched specimen
- “Failure initiation” at the weld root on the fusion boundary
Damage Mechanics Modeling ($\text{Emc}^2$)
The parameters of Gurson-Tvergaard-Needleman (GTN) model for the weld metal were tuned from one test.

The same set of parameters were used in all other tests.

Maximum strains were predicted reasonably well.
Multi-Scale Modeling – Safety Design and Assessment Based on the Information from Quantum, Submicron, and Micro Scales (Northwestern University)

- Dislocation analysis - integrating underlying mechanisms
- Structural analysis
- Grain boundary & large inclusions (MPFEM simulation)
- Submicro scale: precipitates, oxidation, and small inclusions
- Atomic scale, theoretical strength

Modeling – Formulation – Application to Fatigue Life Prediction, A Precipitate Strengthening and Dislocation Piles-up Model (Northwestern University)

Formulation: dislocation obstacle stress

\[
\tau_{\text{obst}}^D = \frac{8}{Lb} \left( \gamma_F^{\text{particle}} + \gamma_F^{\text{matrix}} \right) \cdot r - \Gamma_{E}^{\text{pileup}} \cdot r^3
\]

- \( \Gamma_{E}^{\text{pileup}} \): piles-up energy
- \( \gamma_F^{\text{matrix}} \): fracture energy of alloy matrix
- \( \gamma_F^{\text{particle}} \): fracture energy of precipitated particles

Published in “J. Compute-Aided Materials Design”

Estimate of Fatigue Crack Incubation Life - Comparison with Experiments
FY 2006 Activities

**Welding Process Simulation**
Heat flow model, Emc²
HAZ microstructure/property model, Emc²/ORNL
Weld microstructure model, ORNL
Weld inclusion model, ORNL

**Welding parameter-property relations, Emc²**

**Deterministic Assessment Procedure**
Driving force relations
- Poly-crystal plasticity model, MIT
- Anisotropic plasticity model, Emc²
- Relate damage parameter to microstructure, Emc²/NWU
- Driving force under varied welding conditions, Emc²

Material resistance measurement
- Back bend testing, Emc²/MIT
- Standardize back bend test procedure, Emc²

**Test data from Lincoln Electric, PRCI, etc.**

**Welding Parameters**
Material Composition
Structure Geometry
- From industrial partners, such as TransCanada, Lincoln Electric, and PRCI

**Material Properties**
- Microstructure
- Hardness
- Tensile strength
- Toughness
- Residual stress

**Field Experience and Validation**
TransCanada, Southern California Gas Company, Williams, ChevronTexco, Lincoln, etc.

**Testing and Validation**
Welding, industrial partners
- Microstructure characterization, ORNL/Emc²
- Microscale properties, CanMet/Lincoln
- Microscale and macroscale correlations, Emc²
Concluding Remarks

- There is a strong industry participation.
- The implementation strategy is meant for the broadest impact.
- Critical technical basis has been built.
- The focus for the next two years will be the integration of welding process simulation and multiscale mechanics.
- There are close correlations between experimental and numerical work.
Publications and Patents

- **Public domain papers:**

- **Limited distribution of industry reports:**

- **Presentations**

- **Patents**
  - None
Milestones

- Milestone 1 to be completed by June 30, 2005: Develop fundamental understanding and multiscale mechanics approach to crack driving force, material toughness measurement, and welding process simulation
  - Correlate crack driving force with microscopic features in the weld region
  - Develop small-scale material fracture resistance measurement techniques
  - Refine weld metal thermodynamics prediction
  - Develop microstructure algorithm for deposited weld metal

- Commercialization Milestone 1 to be completed by June 30, 2005: Lead and assist the code development in pipeline weld integrity assessment
  - API
  - ASME
  - CSA
The next step is to transfer the program to FORTRAN code.

In addition, the driving force for complex oxides needs to be obtained from ThermoCalc calculations.
Inclusion Formation during Cooling (ORNL)

- The cooling curves were calculated using analytical model.
- The cooling curves from actual welds can be incorporated.
Microstructure at the Fusion Boundary (ORNL)

- HAZ microstructure shows gradient from fine grain size to coarse grain structure to transformed microstructure.
Spatial Hardness Distributions (ORNL)

- Spatial hardness distributions confirm the presence of soft HAZ.
Fracture Surface of Tensile Test in Longitudinal D.

- X100 donated by TransCanada Pipelines
- Work done at MIT

Transverse strain ratio up to necking: 0.6
Ratio between minor and major axis at failure: 0.58
Texture, Comparison of Pole Figures (MIT)

Experiments  
Taylor Model (125 grains)  
Prediction
Low Constraint Back Bend Tests (Emc²)

- Test video
  - To compare deformation profile with numerical simulation
- Interrupted tests