Virtual Welded-Joint Design Integrating Advanced Materials and Processing Technologies

Z. Yang

Caterpillar Inc.

Project Participating Organizations

Battelle Memorial Institute

Colorado School of Mines

Oak Ridge National Laboratory

Pennsylvania State University

QuesTek Inc.

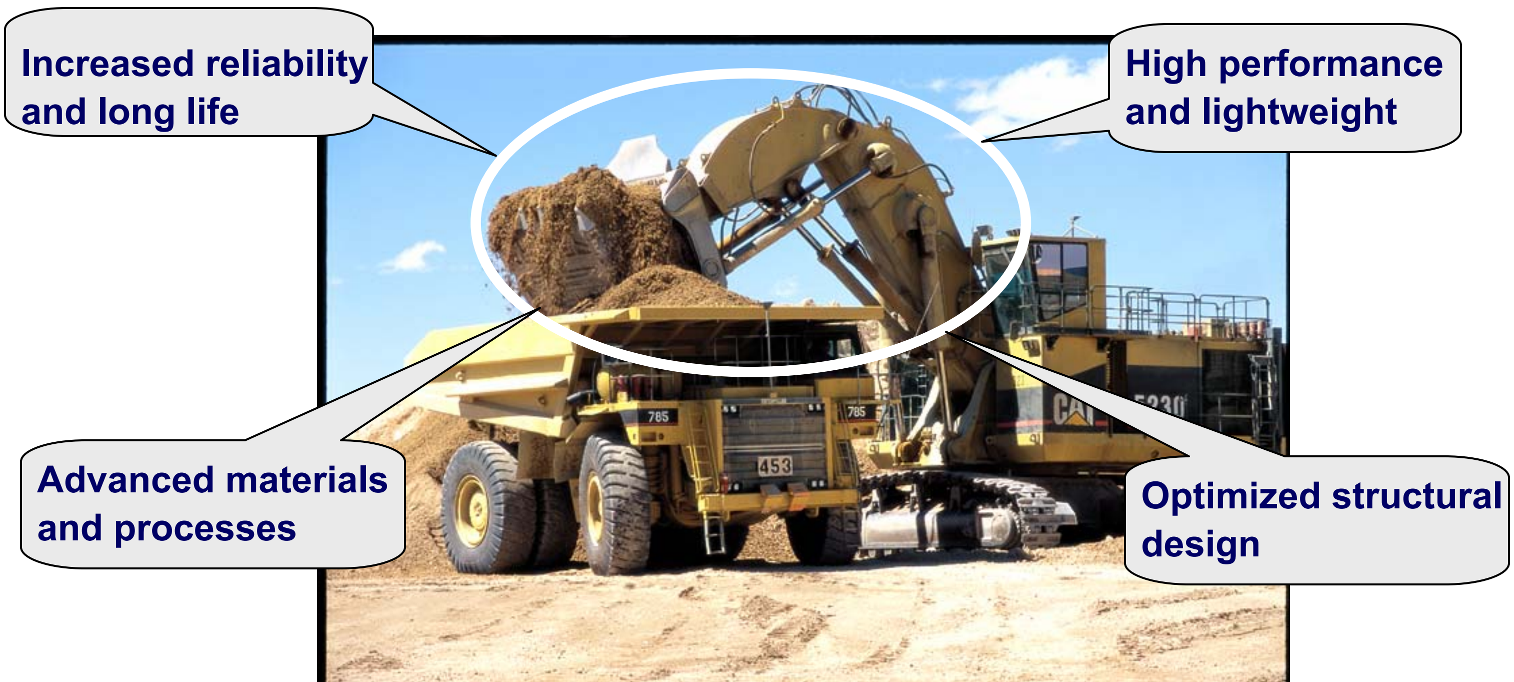
Project Duration: 10/01/2001~09/30/2004

Project Team

- Caterpillar Inc.
  - Z. Yang (PI), H. W. Ludewig, X. L. Chen, H. Kyuba, N. Chen, and T. Hong
- Battelle Memorial Institute
  - P. Dong, Z. Cao, and J. K. Hong
- Colorado School of Mines
  - G. Edwards, S. Liu, and F. Martinez
- Oak Ridge National Laboratory
  - S. S. Babu
- Pennsylvania State University
  - T. DebRoy and W. Zhang
- QuesTek Inc.
  - G. B. Olson, H. Jou, and J. Wright

Objective

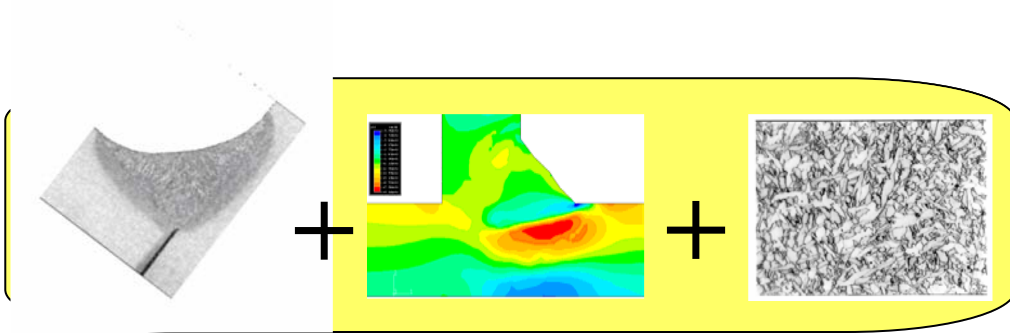
- Increase welded-joint fatigue life by 10 times and reduce energy by 25% through product performance and productivity improvements using an integrated modeling approach.
  - Increased product life and vehicle up time
  - Accelerated application of HSS and increased load capacity
  - Reduced welding energy, rework, and welding emission
  - Increased competitiveness of U.S. manufacturing base

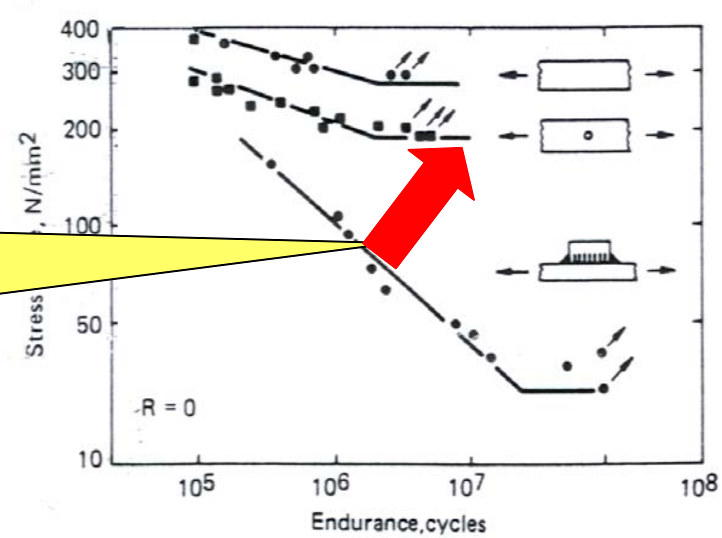


Fatigue Strength of Welded-Joints

Welded-Joint Fatigue Strength

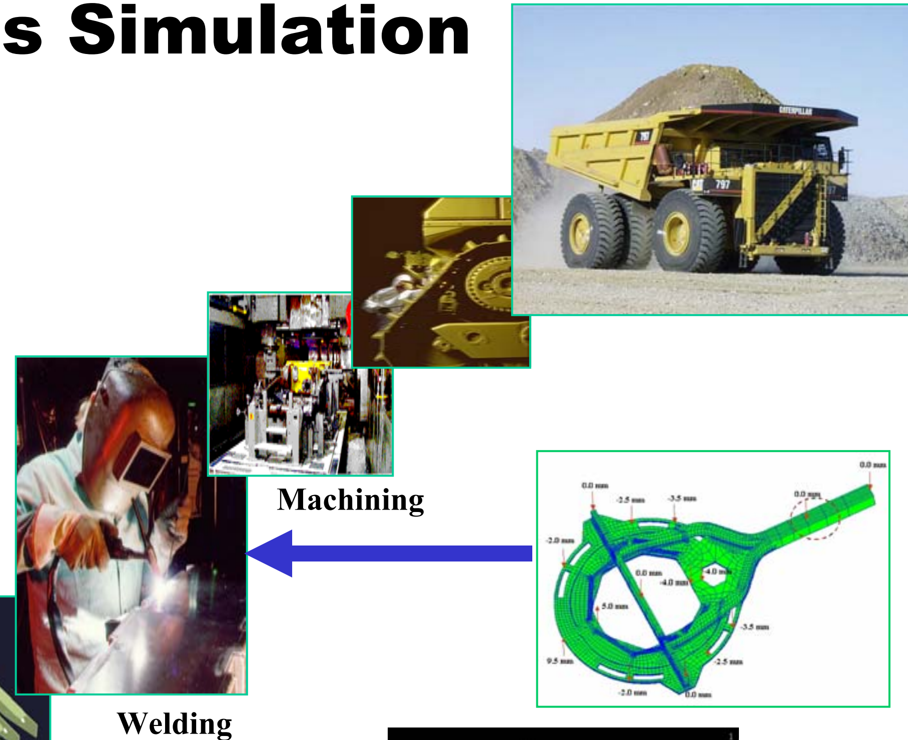
- **Weld bead shape** (smooth at weld toe)
  - FASIP welds
  - Postweld bead modification
    - TIG dressing
    - Burr grinding
    - Hammer peening
- **Weld residual stress** (compressive at weld toe)
  - Postweld stress modification
    - Shot peening
    - UIT
    - Laser peening
  - New consumable
- **Weld microstructure** (phases, grain size, inclusions)
  - New consumable
  - Fatigue resistant base material

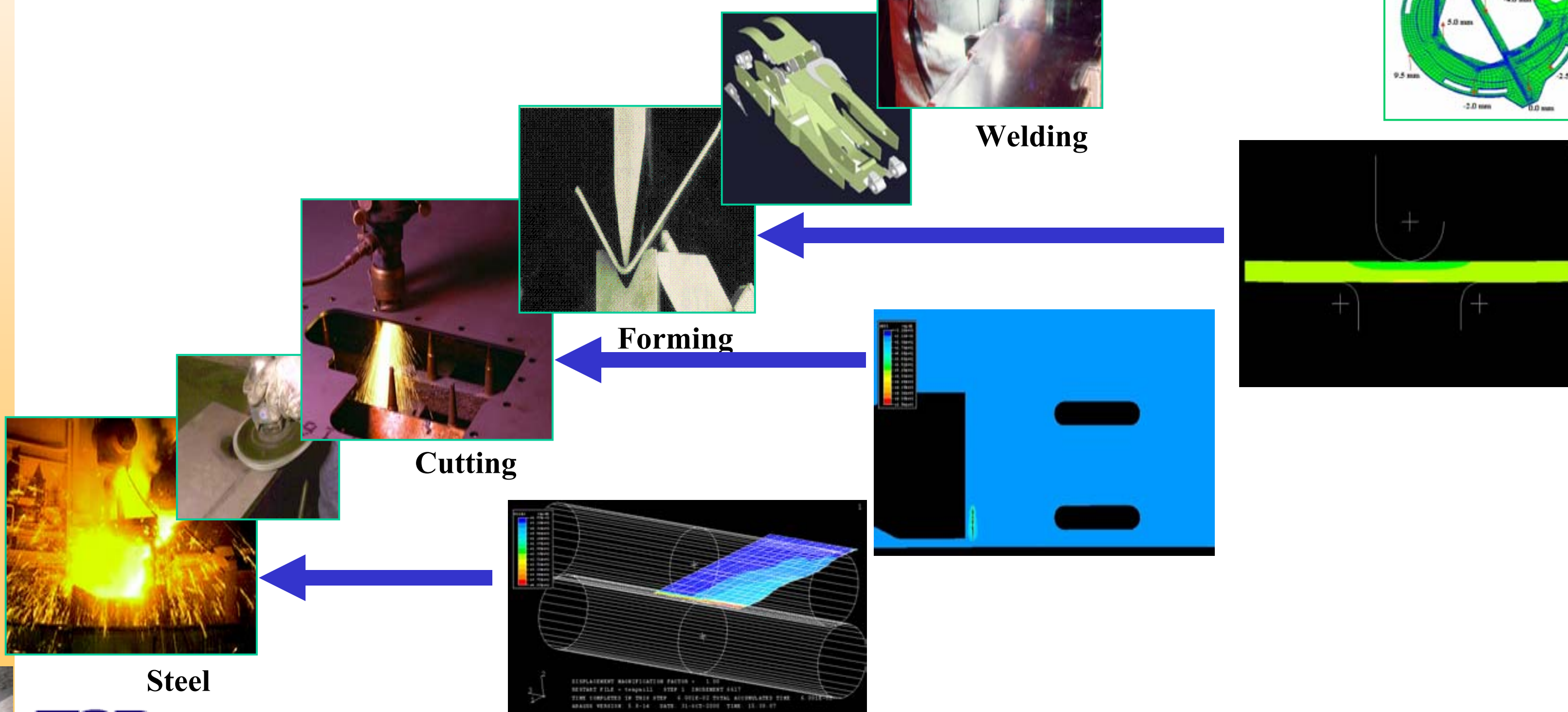




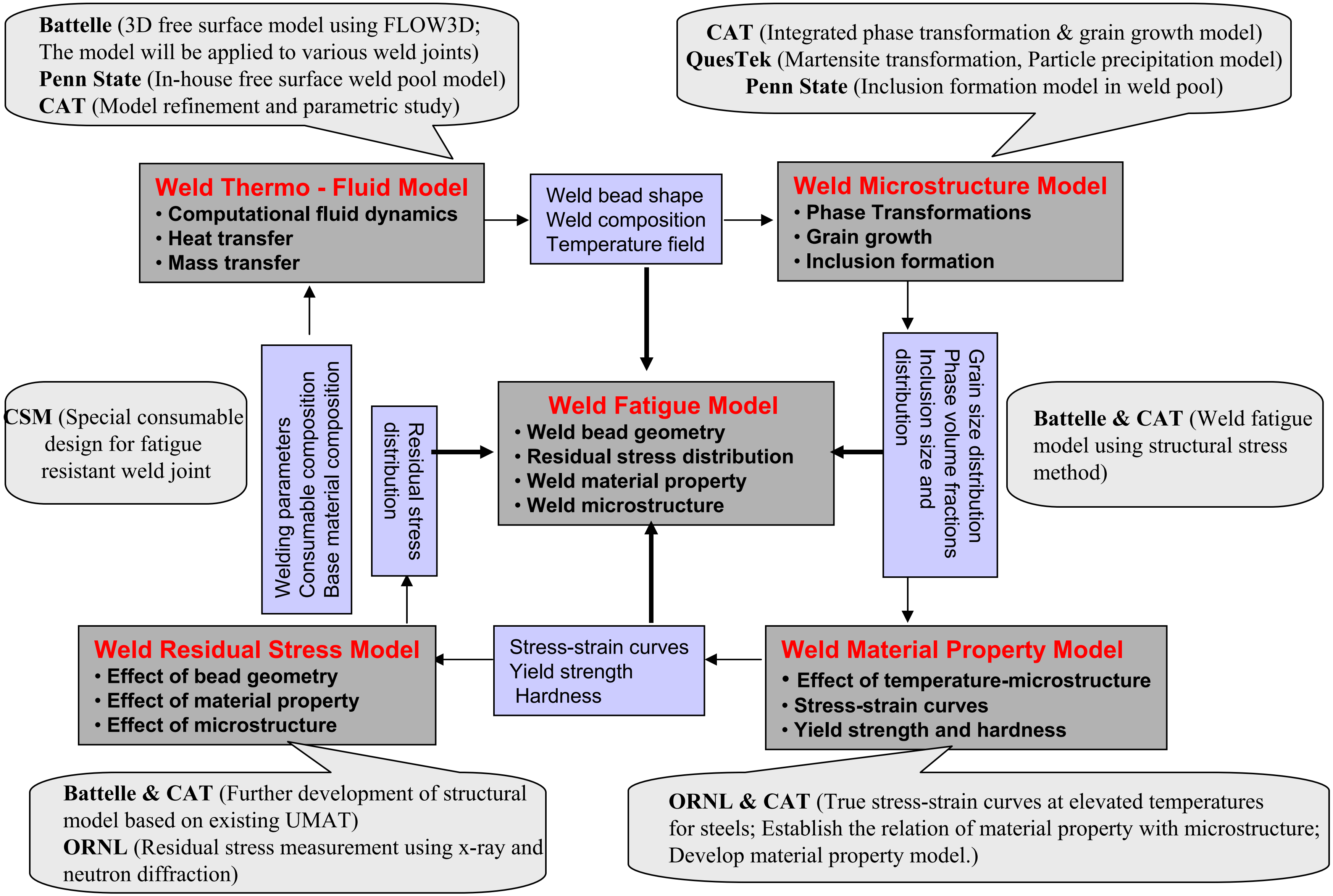
Manufacturing Process Simulation

- Virtual Manufacturing
- Six-Sigma strategy





Virtual Welded-Joint Design



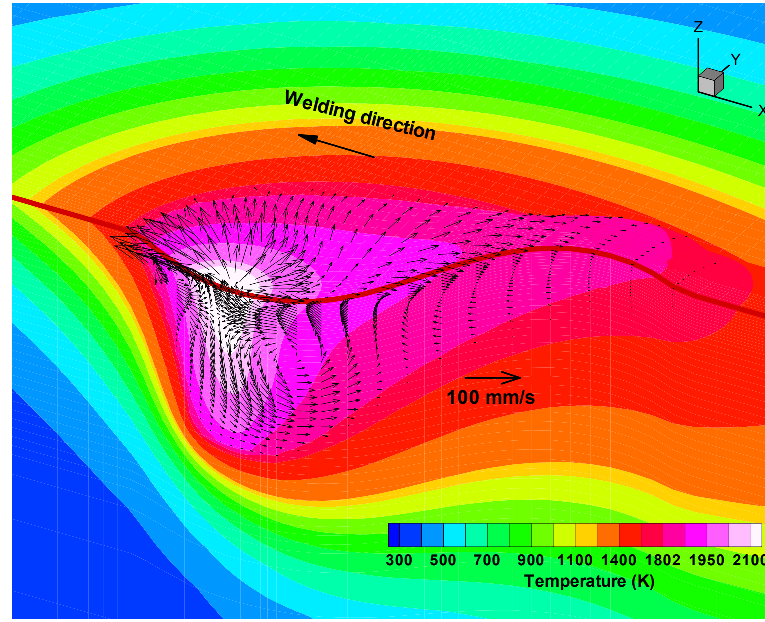
Milestones

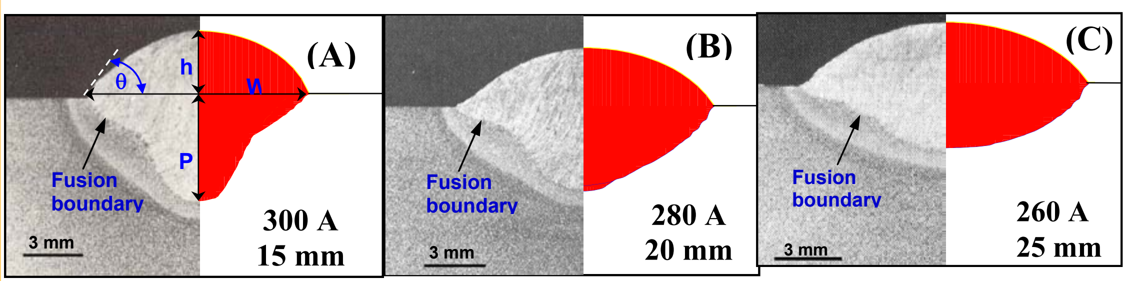
M1. Weld Thermo Fluid Model (WTFM)	Plan	Actual
T1. Development of 3-D Free Surface Weld Pool Model	9/30/2002	Completed
T2. Weld Zone Composition Prediction	6/30/2003	90% Completed
T3. Weld Consumable Design Optimization	9/30/2003	70% Completed
M2. Weld Microstructural Model (WMM)		
T4. Grain Size and Phase Transformation Prediction	6/30/2003	Completed
T5. Consumable Design for High Alloy Composition	9/30/2003	80% Completed
T6. Inclusion Formation Prediction	12/30/2003	60% Completed
T7. Laser Welding of Higher Strength Materials - Microstructure	3/30/2004	NO-GO?
M3. Weld Property Model (WPM)		
T8. Relation of microstructure-property at room temperature	12/30/2002	80% Completed
T9. Determination of Stress-Strain Curves at Elevated Temperature	3/30/2003	50% Completed
T10. Development of Weld Material Property Model	9/30/2003	50% Completed
T11. Laser Welding of Higher Strength Materials - Property	12/30/2003	NO-GO?
M4. Weld Structural Model (WSM)		
T12. Further Development of 3-D Residual Stress Modeling	6/30/2003	90% Completed
T13. Residual Stress Measurements	12/30/2003	
T14. Model Verification and Refinement	9/30/2003	50% Completed
M5. Weld Fatigue Model (WFM)		
T15. Crack Nucleation	9/30/2002	In progress
T16. Small Crack Growth	3/30/2003	In progress
T17. Paris Law Dominated Crack Growth	6/30/2003	30% Completed
T18. Model Integration and Parametric Study	12/30/2003	
T19. Component Fatigue Demo Test	9/30/2004	
M6. Integration (I)		
T20. Incorporation of Thermal History from WFTM into WMM	3/30/2002	90% Completed
T21. Incorporation of Thermal History from WFTM into WSM	6/30/2003	90% Completed
T22. Incorporation of Phase Transformation and WPM into WSM	9/30/2003	50% Completed
T23. Incorporation of WMM and WPM into WFM	12/30/2003	30% Completed
T24. Incorporation of Residual Stress into WFM	12/30/2003	30% Completed
T25. Case Studies	3/30/2004	
M7. Technology Demonstration - Proof of Concepts		
T26. Technology Demo	9/30/2004	30% Completed
M8. Project Administration		
T27. Program Management		
T28. Reporting and Technology Transfer		

Virtual Welded-Joint Design

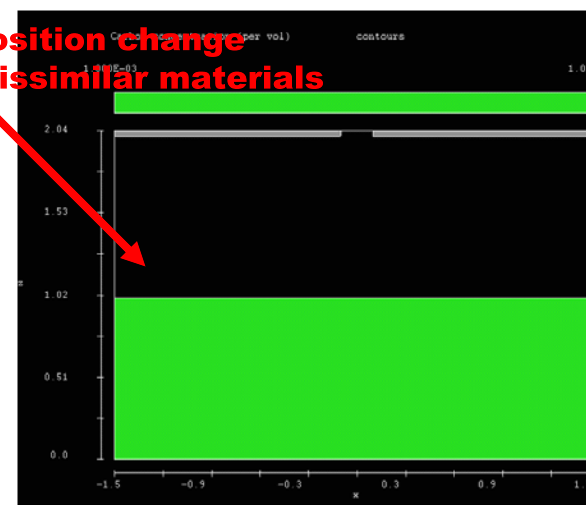
Weld Thermo-Fluid Model

- Driving forces in weld pool
  - Electromagnetic force
  - Surface tension gradient force
  - Droplet impact
  - Arc pressure
  - Buoyancy
- Heat transfer in welding process
  - Distributed heat from arc
  - Super heat from metal droplet
  - Latent heat for melting/solidification
  - Convection, radiation, and evaporation
- Mass Transfer
  - Interaction of droplet with weld pool
  - Change of chemical composition



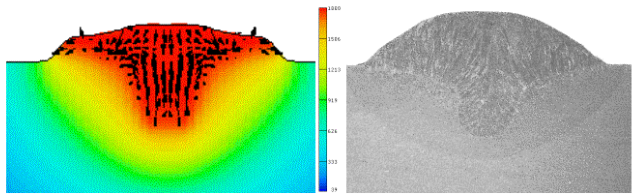


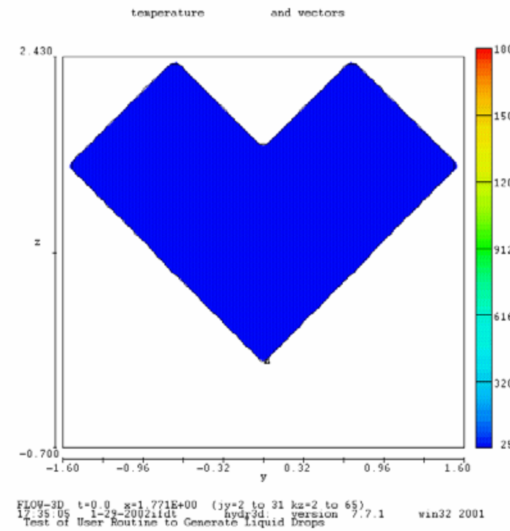
Chemical composition change for welds with dissimilar materials



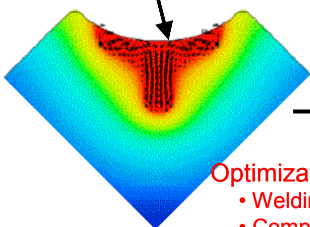
Virtual Welded-Joint Design

Virtual Design Weld Bead Shape

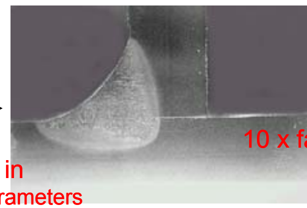




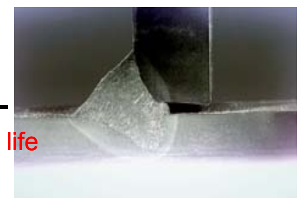
- Larger toe radius
- Deeper penetration



FASIP WELD

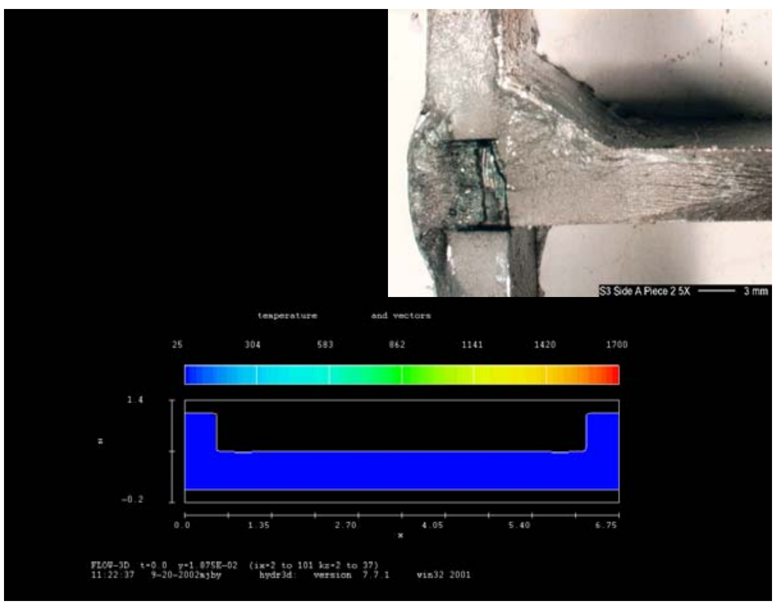


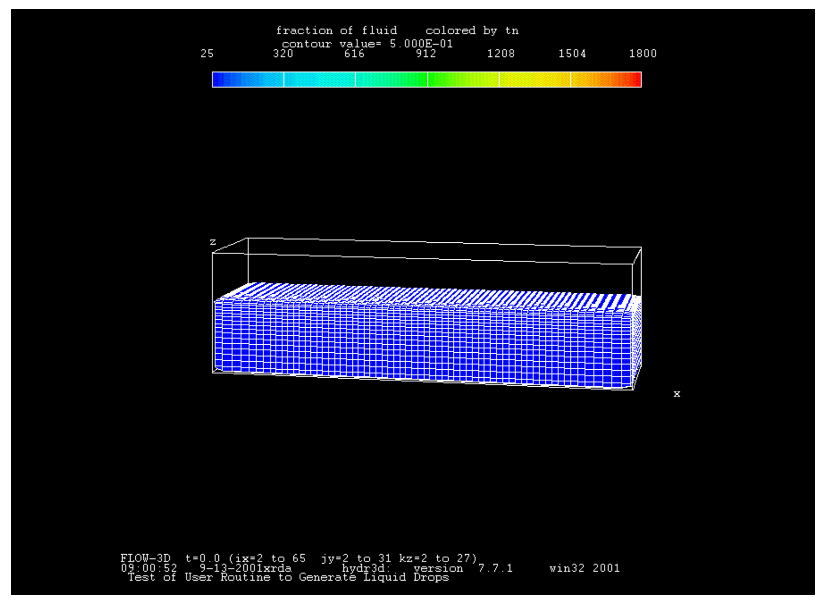
CONVENTIONAL WELD



10 x fatigue life

Optimizations in
- Welding parameters
- Composition
- Weld position

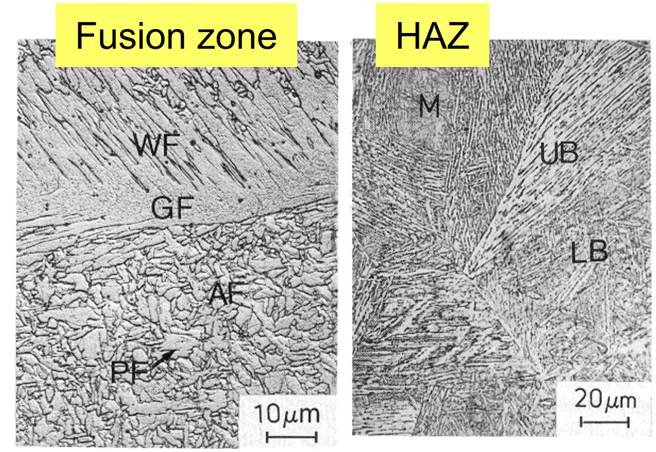


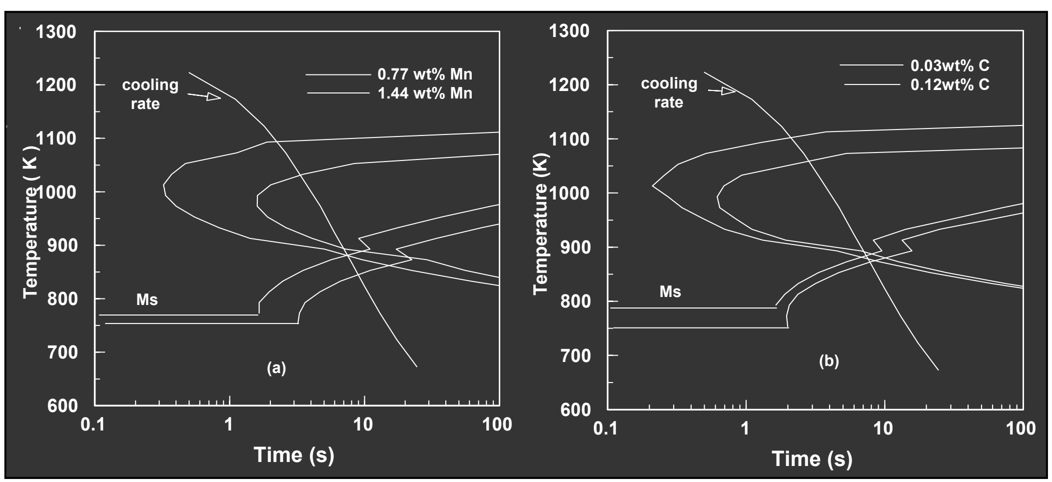


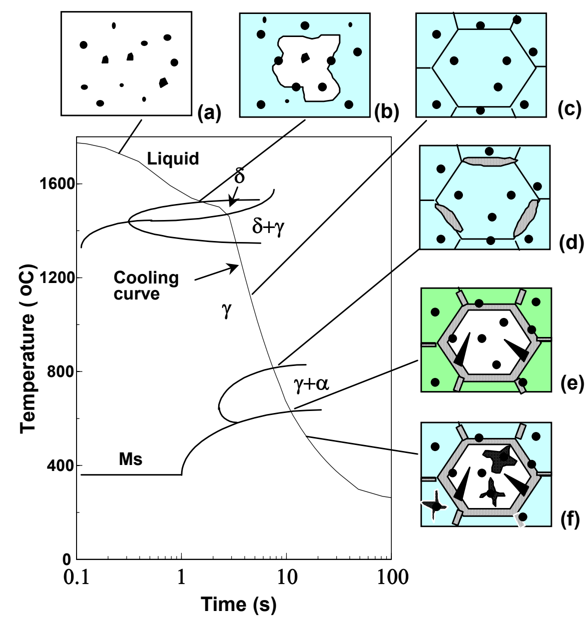
TSD Technical Services Division

Weld Microstructure Model

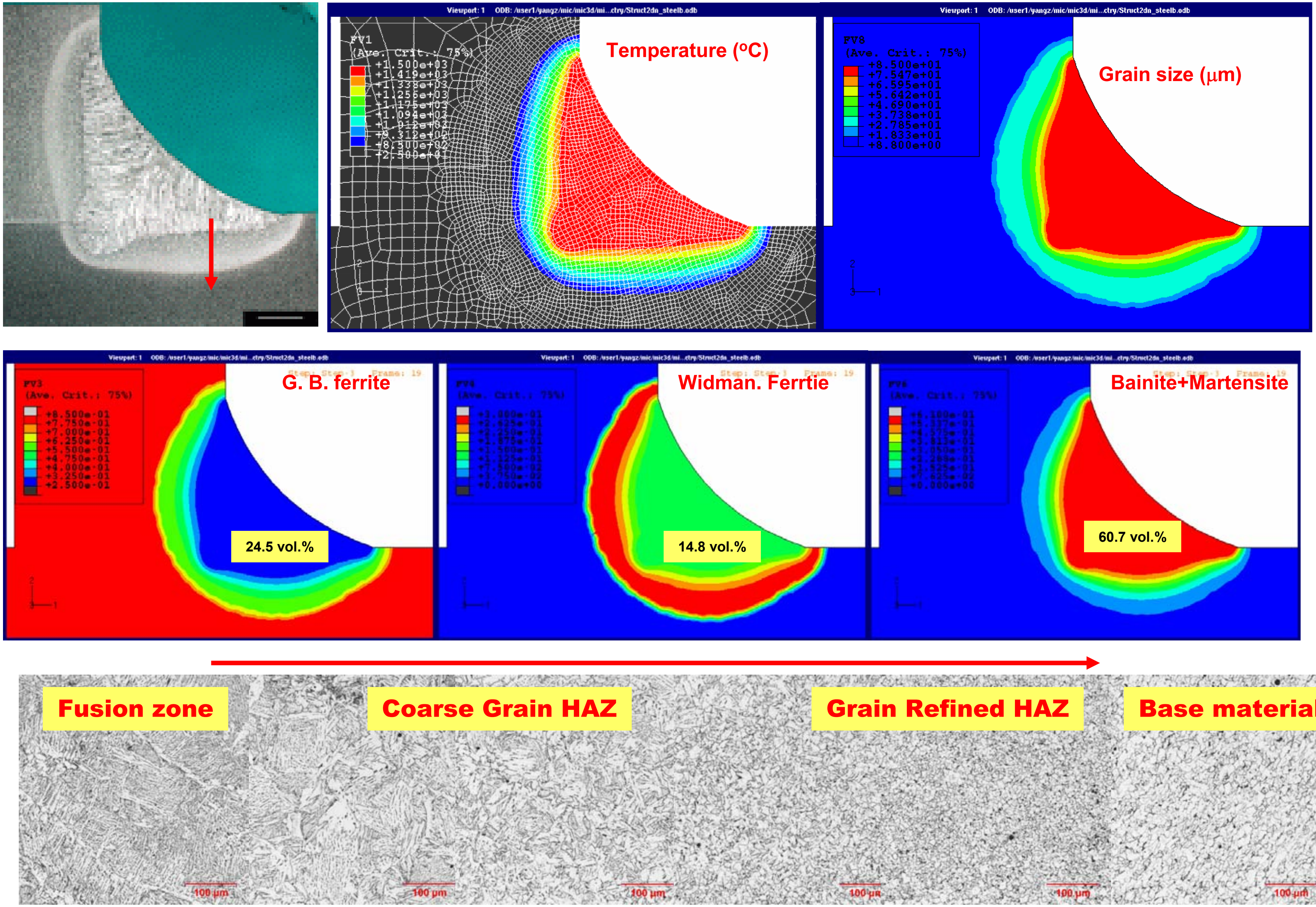
- Weld microstructure model based on H.K.D.H. Bhadeshia's model
  - Calculation of TTT and CCT diagrams
  - Calculation of various phase volume fractions
    - Grain boundary ferrite
    - Widmanstatten ferrite
    - Bainite/acicular ferrite
    - Martensite
- Grain size and phases in weld zone and HAZ
  - Thermal cycles from 3D thermal model
  - Grain growth in HAZ considering the pinning effects
  - Coupling thermal model with microstructure model



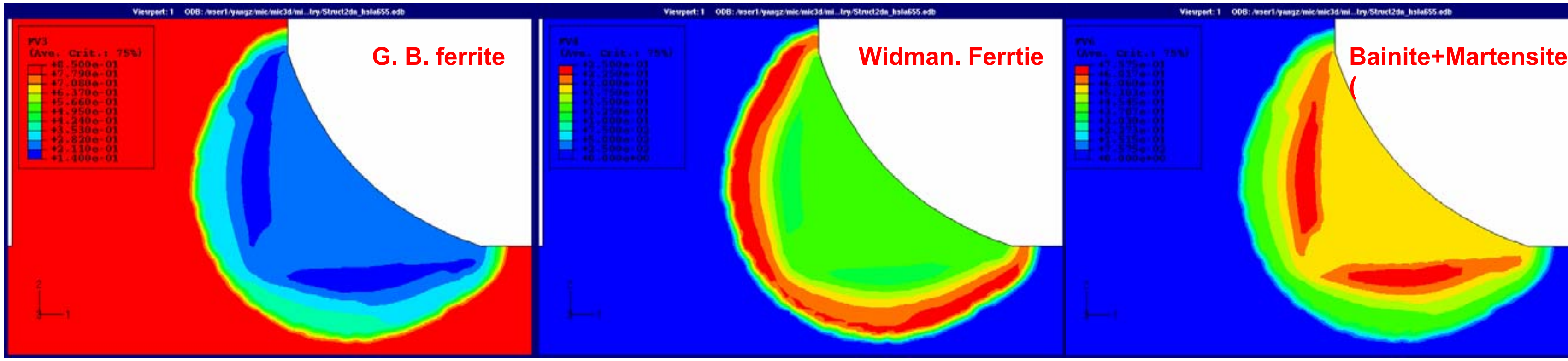


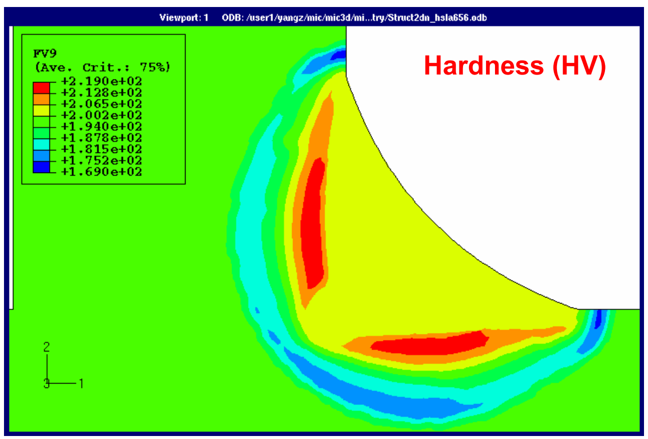


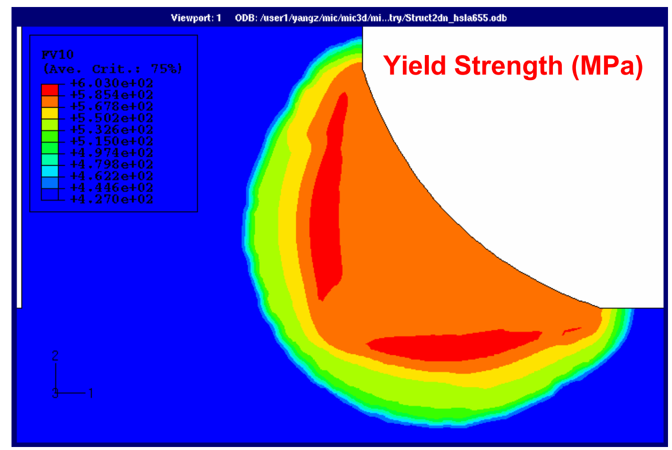
Microstructure Prediction in Weld A

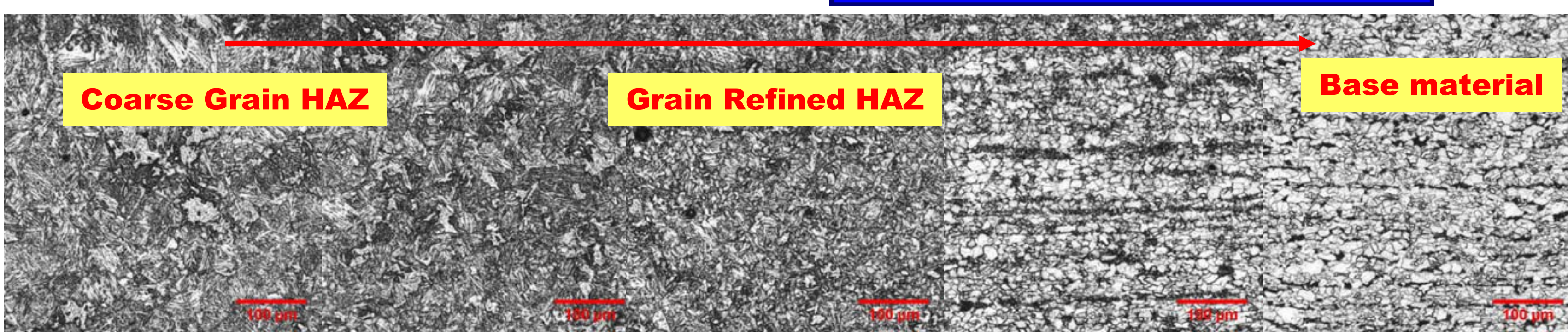


Microstructure and Properties in Weld B with Dissimilar Materials



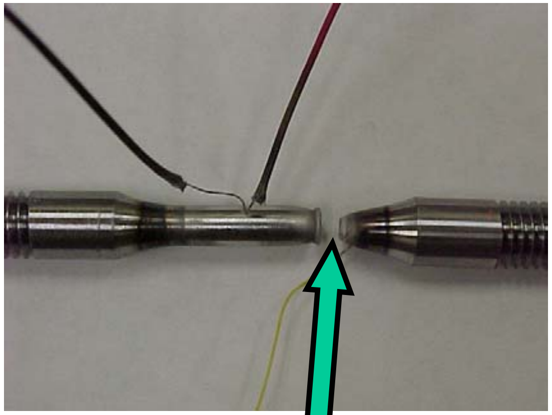




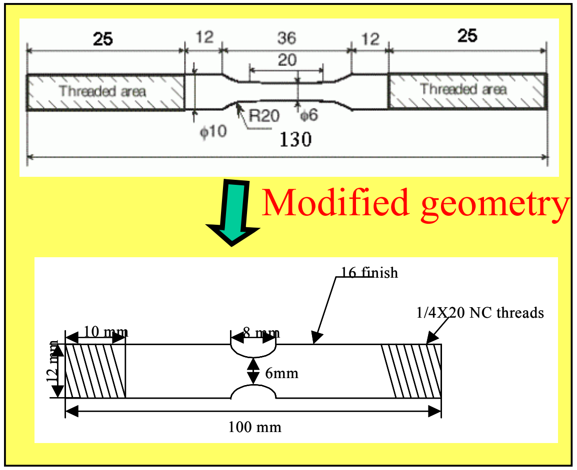


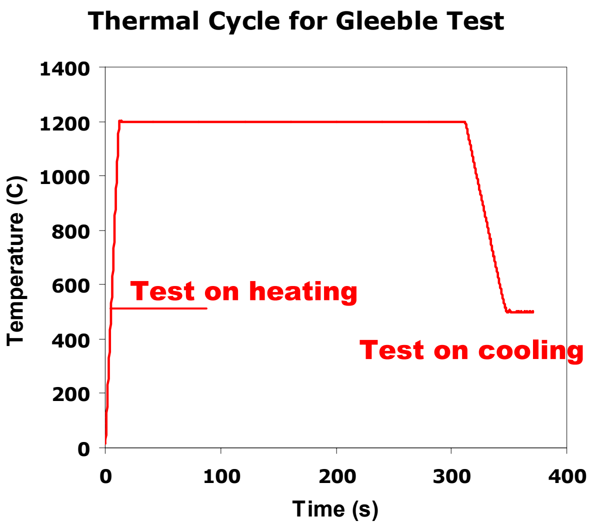
Gleeble Test for Stress-Strain Curves

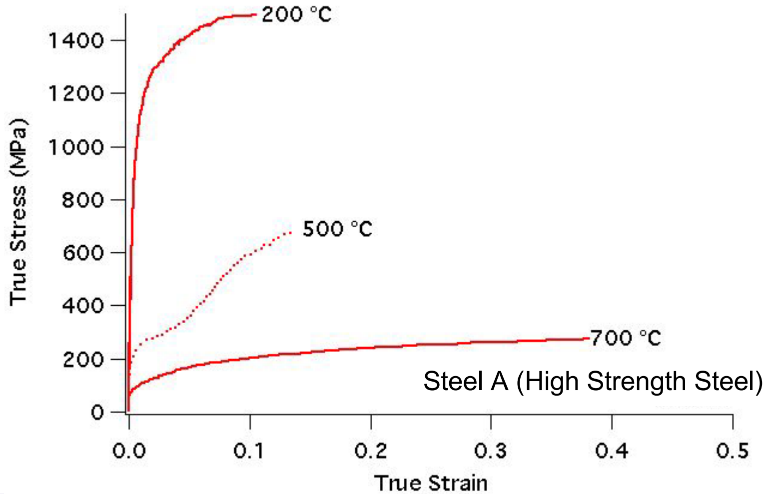
- Gleeble® 3500 was used to evaluate stress-strain characteristics at ambient and elevated temperatures

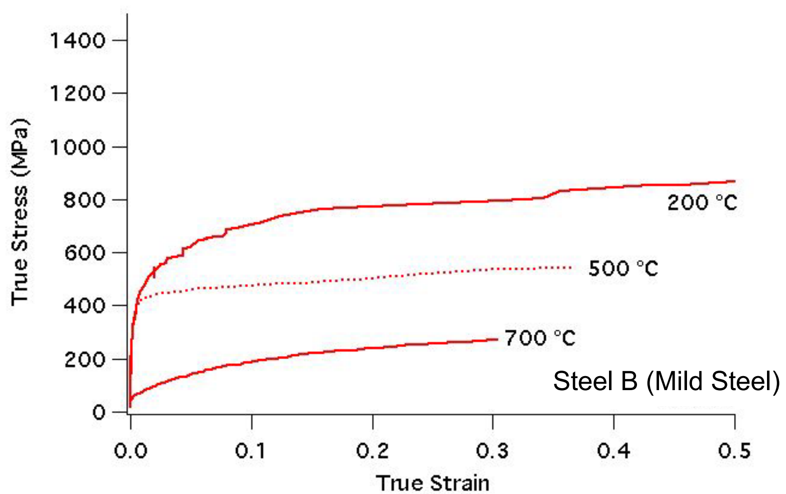


Failed at soft region

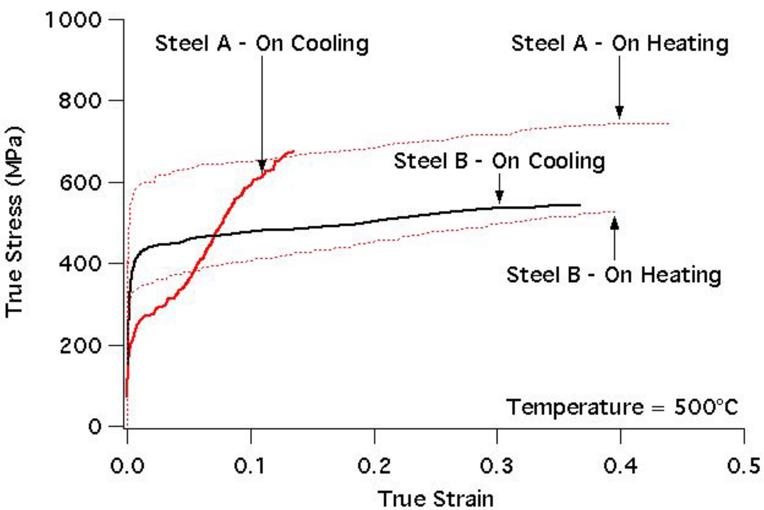


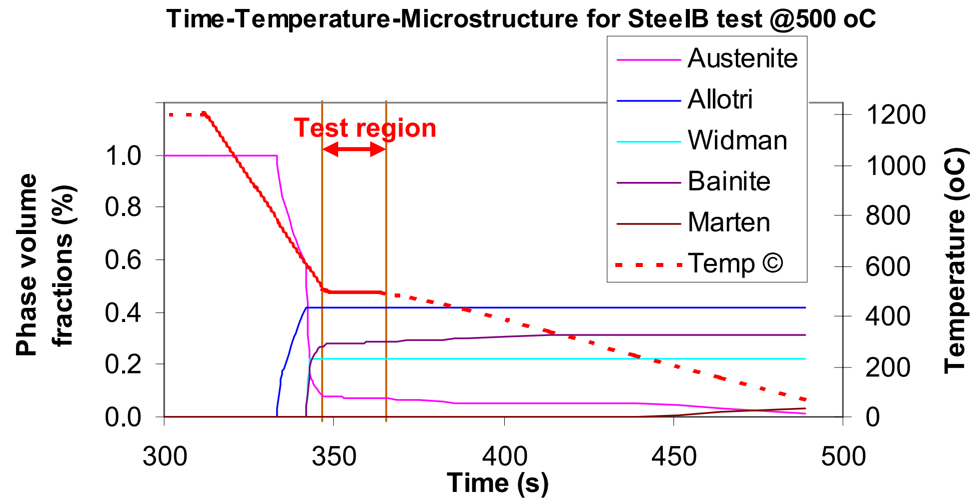


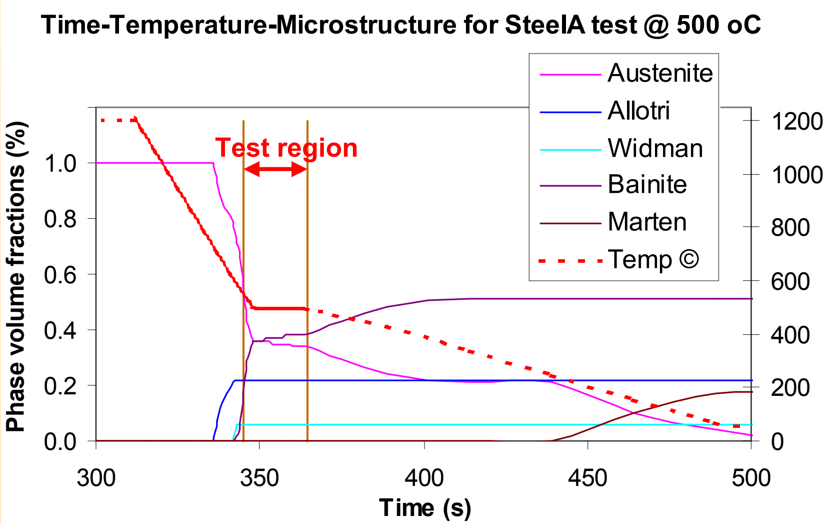


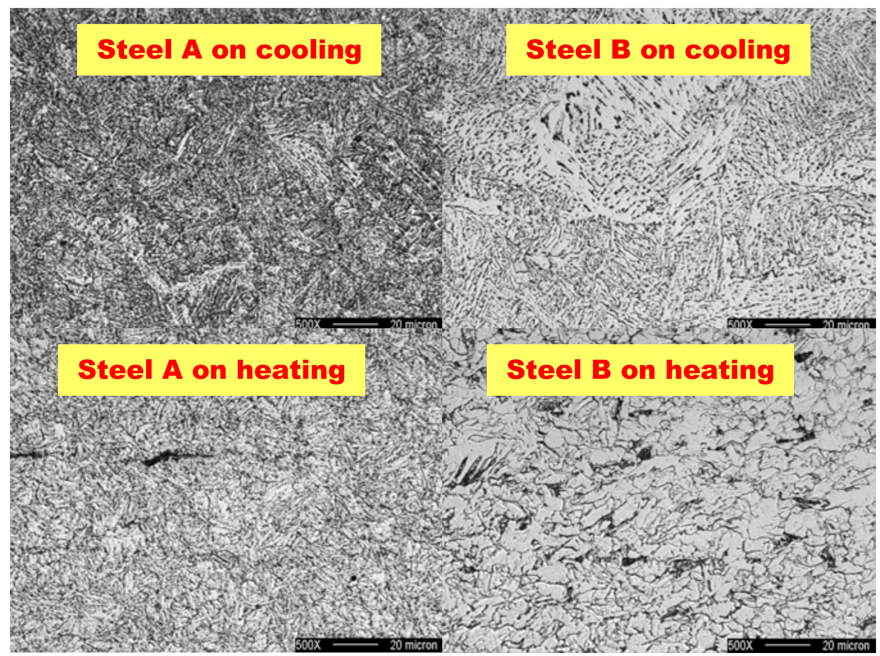


Microstructure vs. Property





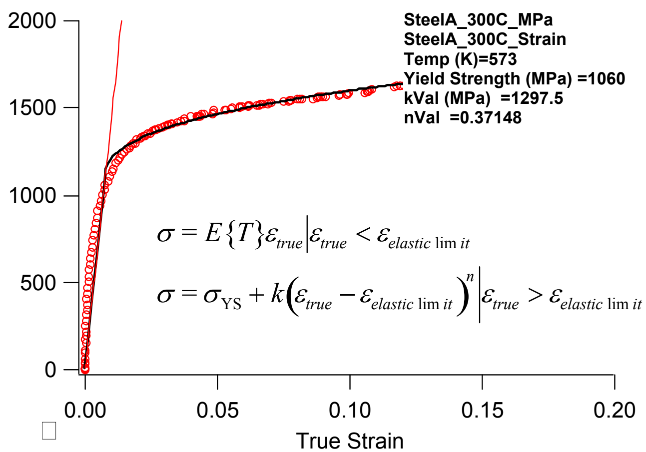




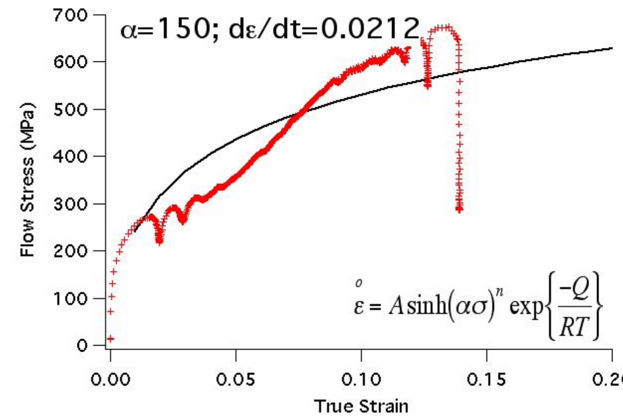
TSD Technical Services Division

Prediction of Stress-Strain Curves

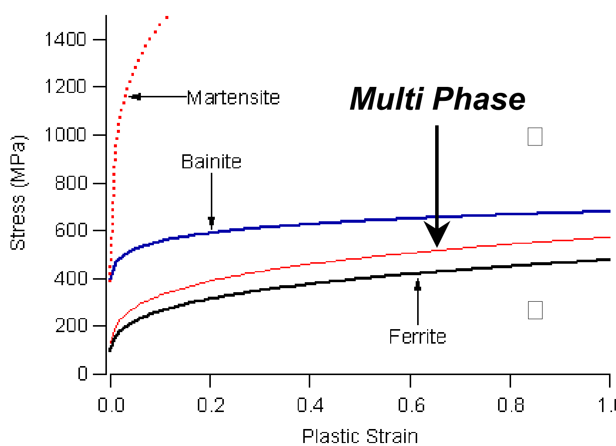
(1) Simple model: Relate yield strength, K and n to microstructure and composition



(2) Strain rate model can capture the trend, but the predictions are not good due to the Q, n and α values used in this calculation.



(3) Additive Law Model: We need to extend this model for all phases (austenite, ferrite, bainite and martensite)



$$\sigma = \sum E_i M_i^* f_i \varepsilon_t$$

Stage 1: All Elastic

$$\sigma = \sum E_i M_i^* f_i \varepsilon_t + \sum a\left(b + M_j^{**}\varepsilon_t\right)^{N_j} f_j$$

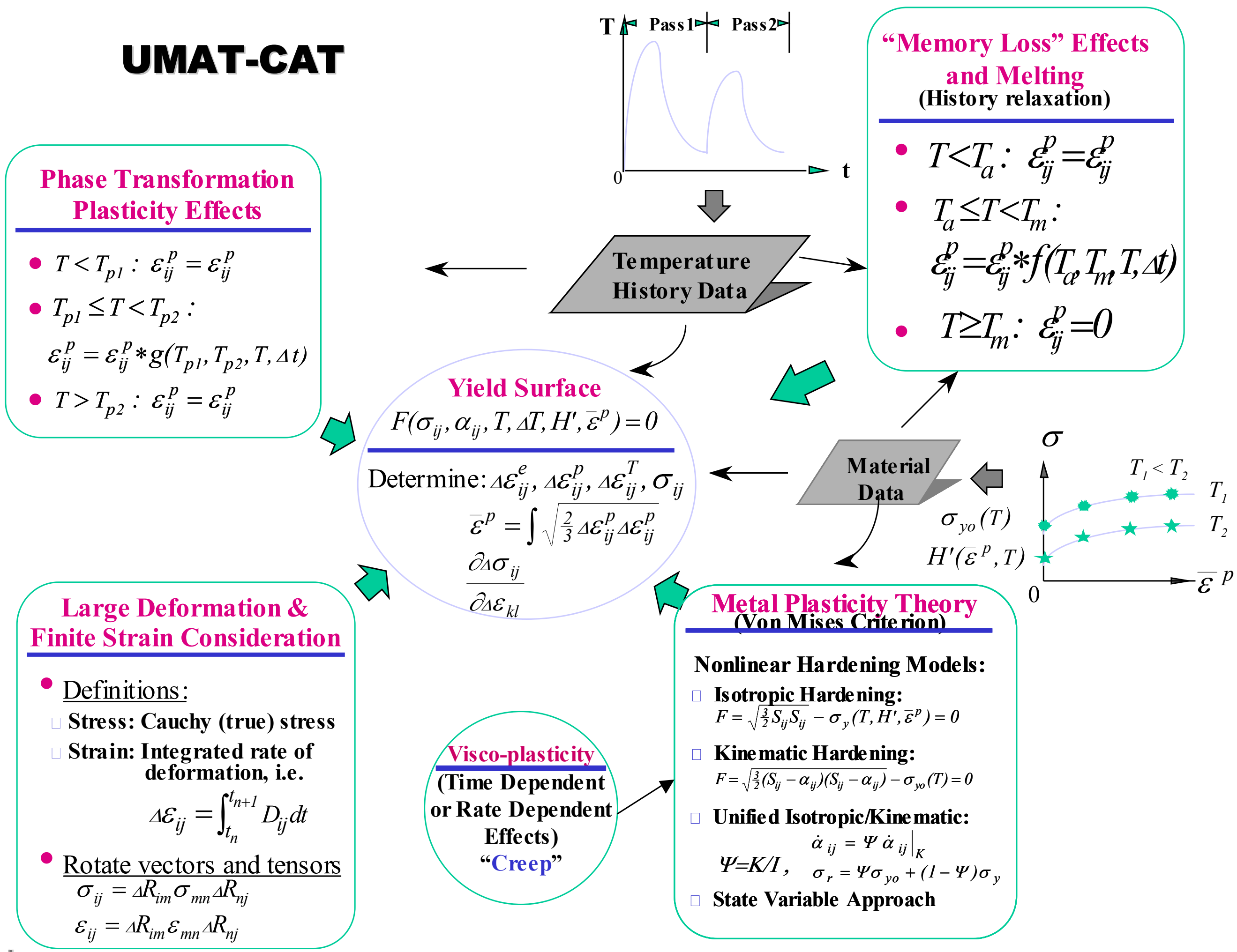
Stage 2: Elastic and Plastic Phases

$$\sigma = \sum a\left(b + M_i^{**}\varepsilon_t\right)^{N_i} f_i$$

Stage 3: All Plastic

Weld Residual Stress Model

- Effects of phase transformation induced plasticity
- Incorporation of microstructure and material property model into residual stress analysis



Effects of Phase Transformation on Weld Residual Stress

- Strain decomposition

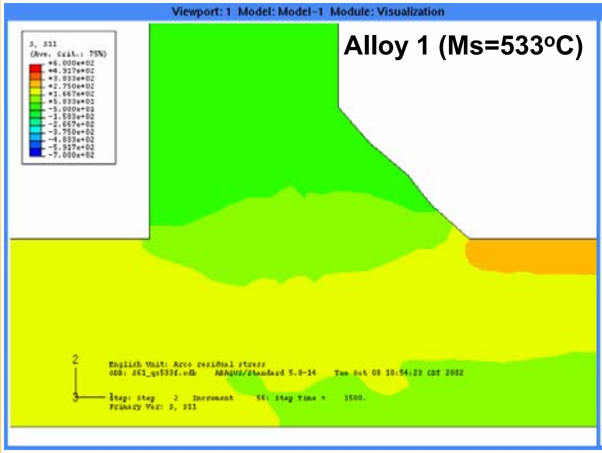
$$\epsilon_{ij} = \epsilon_{ij}^{e} + \epsilon_{ij}^{pl} + \epsilon_{ij}^{th} + \xi \frac{\delta}{3}\delta_{ij} + \epsilon_{ij}^{TP}$$

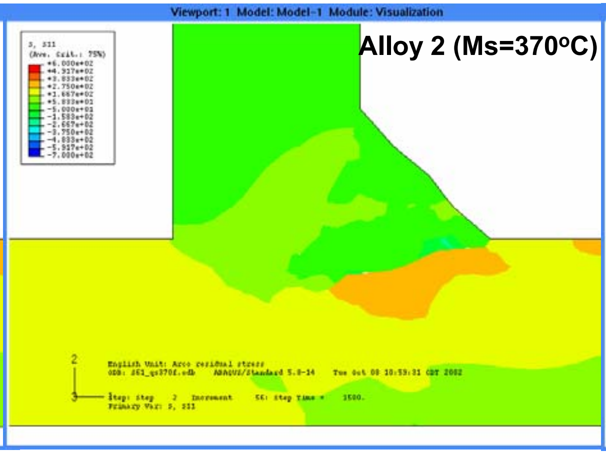
- Fischer's model

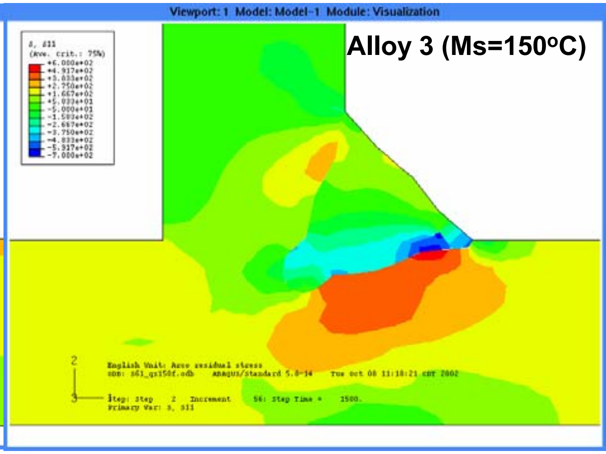
$$\epsilon_{ij}^{TP} = \frac{5}{4}\frac{\left(\delta^2 + 3/4\gamma^2\right)^{1/2}}{\sigma_{y^*}} s_{ij}^{L}$$

$$\sigma_{y^*} = \sigma_y^n \left(\frac{1 - \sigma_y^0 / \sigma_y^n}{\ln\left(\sigma_y^0 / \sigma_y^n\right)} \right)$$

$s_{ij}^{:L}$ **Local mesoscopic stress deviator** σ_y^0 **Yield stress of the parent** σ_y^n **Yield stress of the product**





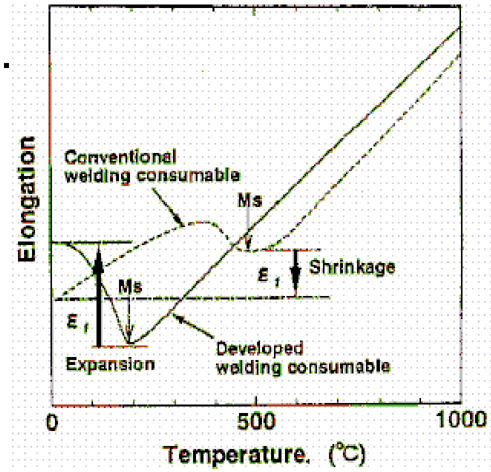


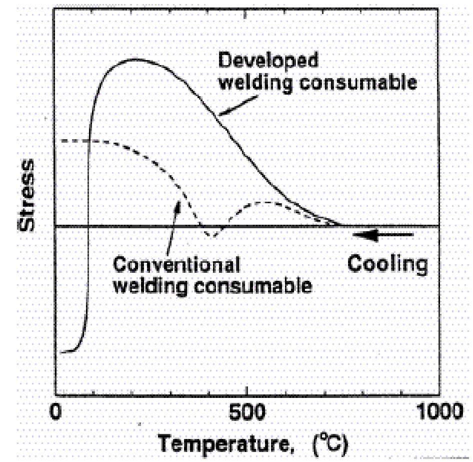
Virtual Welded-Joint Design

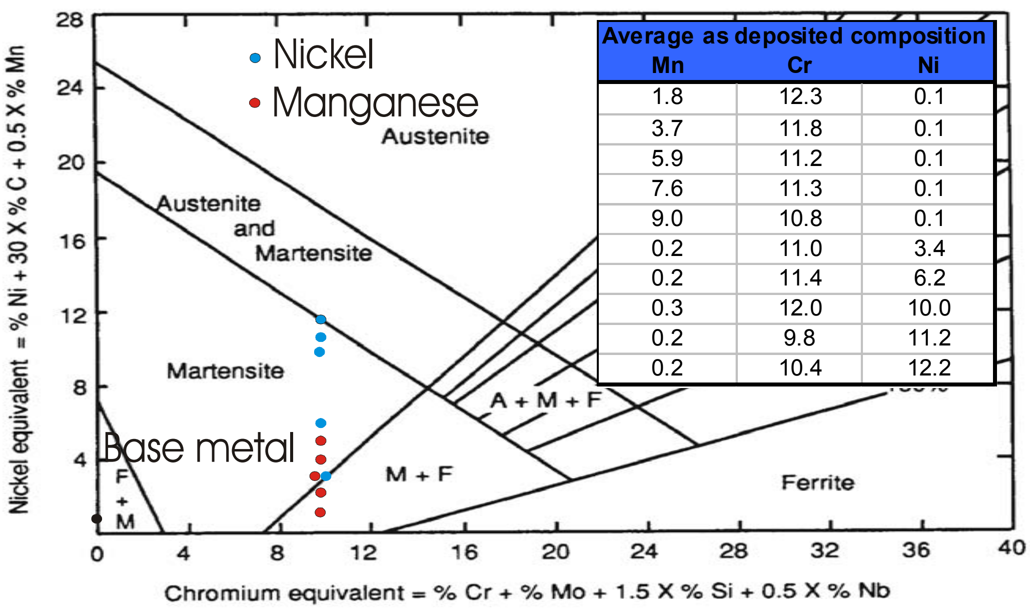
TSD Technical Services Division

Design Welding Wire for Compressive Residual Stress

- Previous results from Ohta et al.
  - 10Cr10Ni welding wire
  - Low martensite transformation temperature
  - Compressive residual stress
  - Fatigue strength improvement







Average as deposited composition		
Mn	Cr	Ni
1.8	12.3	0.1
3.7	11.8	0.1
5.9	11.2	0.1
7.6	11.3	0.1
9.0	10.8	0.1
0.2	11.0	3.4
0.2	11.4	6.2
0.3	12.0	10.0
0.2	9.8	11.2
0.2	10.4	12.2

- New wire development
  - Cost effective
  - Cr-Mn alloy system

J.Self model:

Ms = 521 -350C -13.6Cr -16.6Ni **-25.1Mn** –30.1Si-20.4Mo -1.07CrNi +21.9(Cr+0.73Mo)C

Andrews's model

Ms = 539 -423C -12.1Cr -17.7Ni **-30.4Mn** –7.5Mo

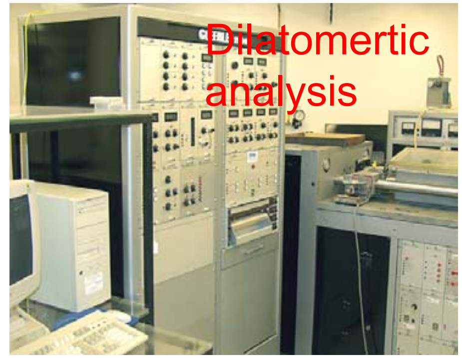
Schaeffler

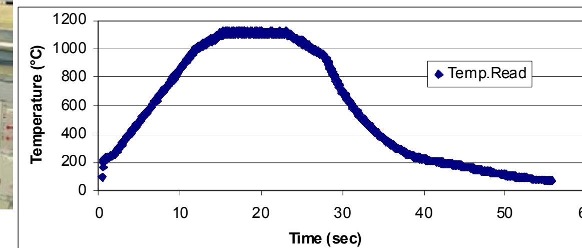
Ms = 520 -600C -15.6Cr -20Ni **-10Mn** –23.4Si-15.6Mo –7.8Nb

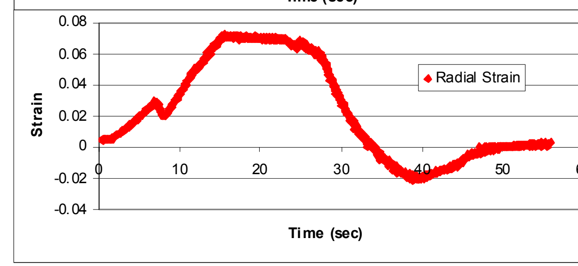
Virtual Welded-Joint Design

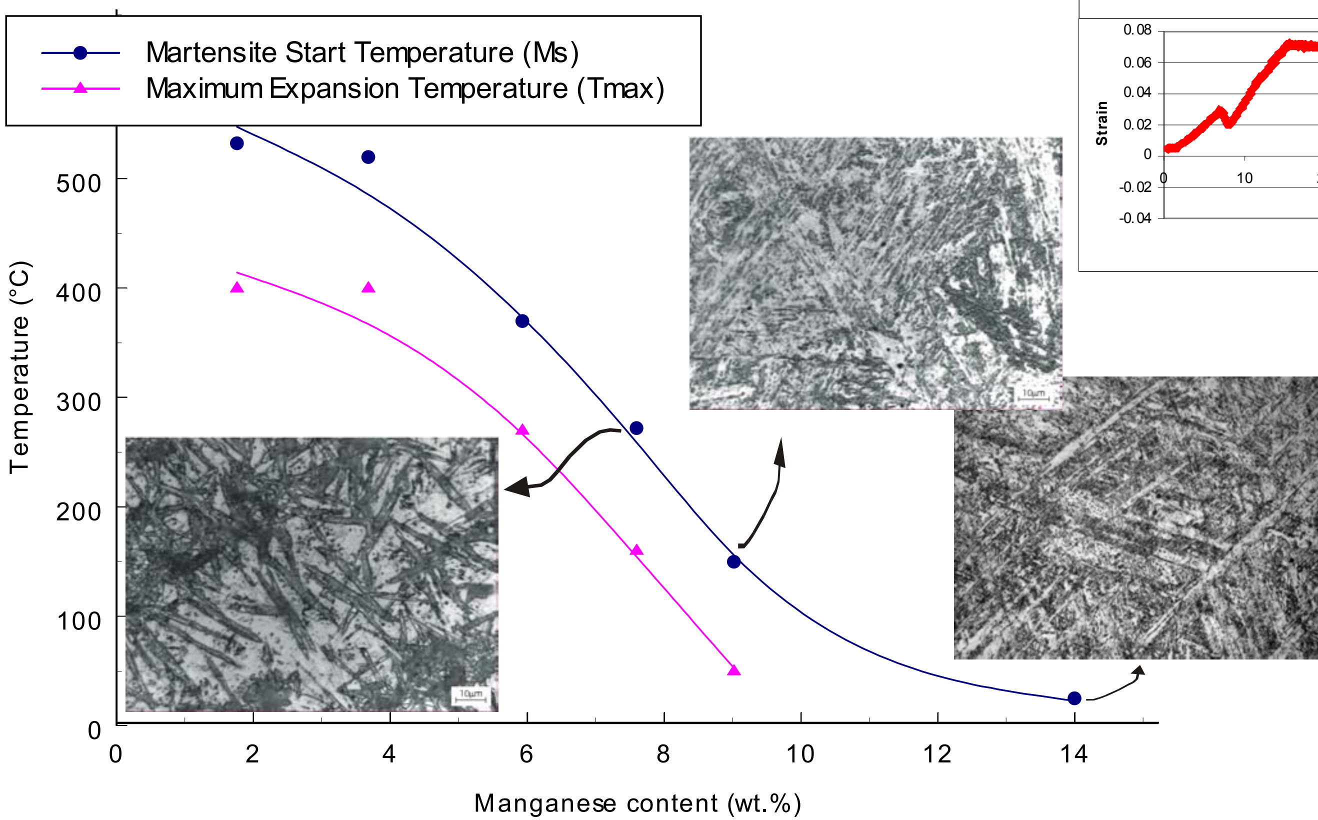
New Wire Development

Virtual Welded-Joint Design



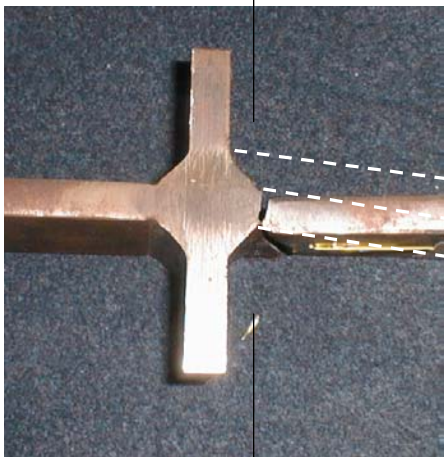


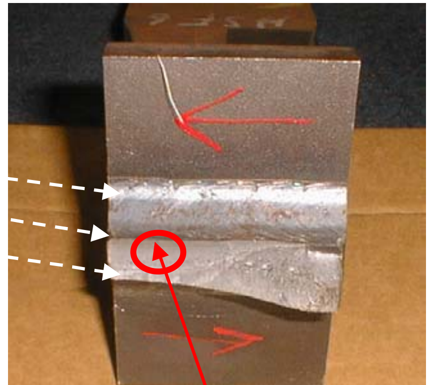




Weld Fatigue Fracture Macro and Microstructures

A

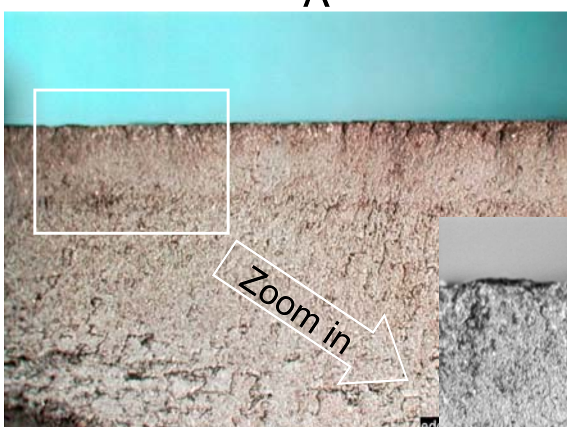




A-A

Crack origins along weld toe

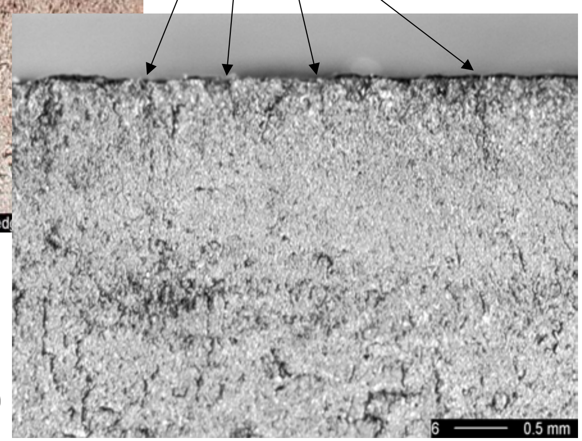
A



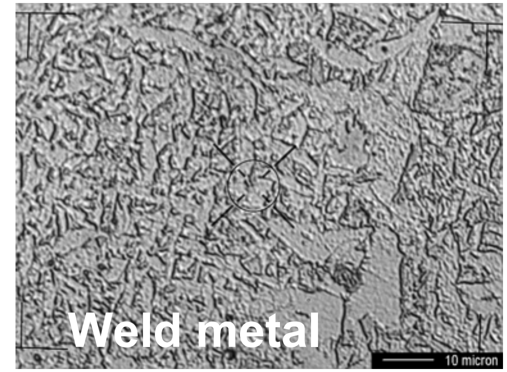
X10

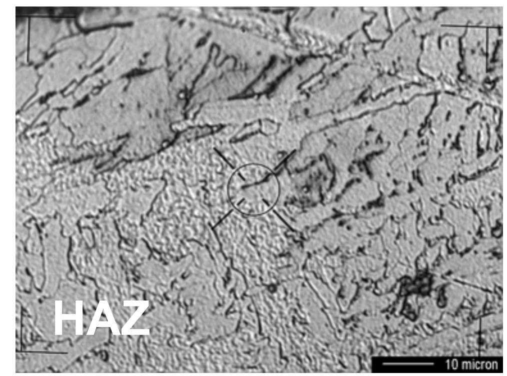
Vertical lines show crack junction:

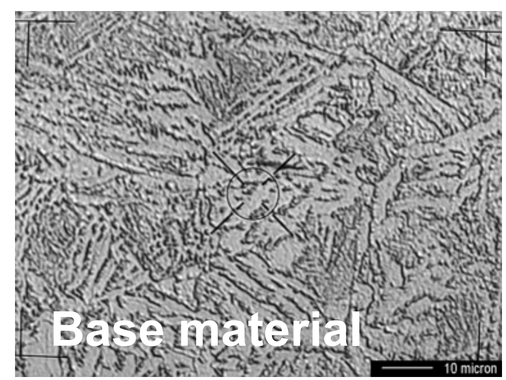
Ratchet line



X30



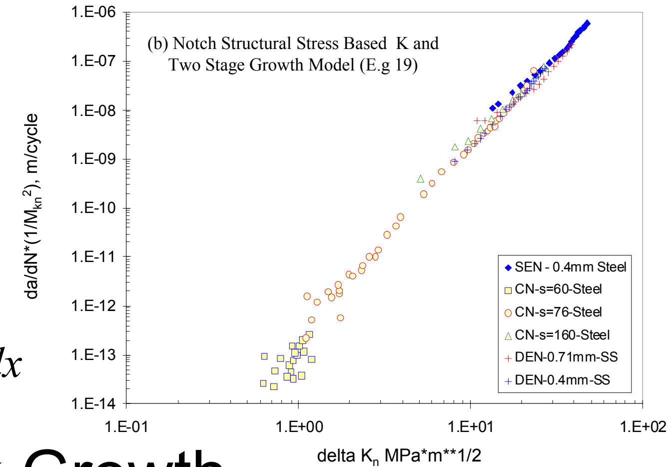




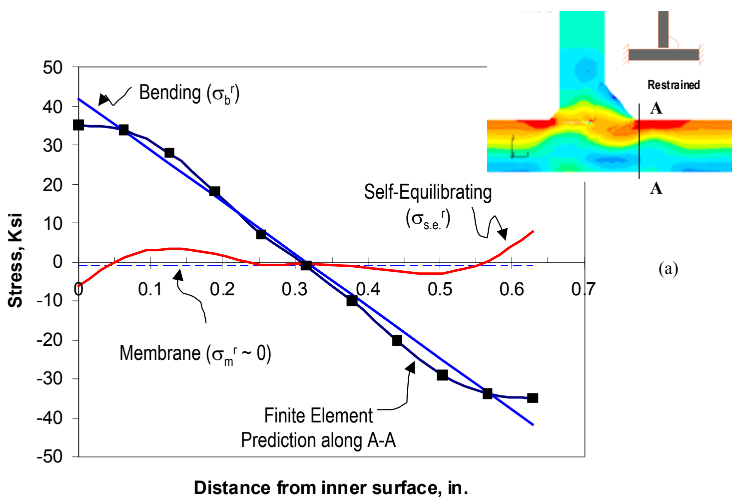
Weld Fatigue Model

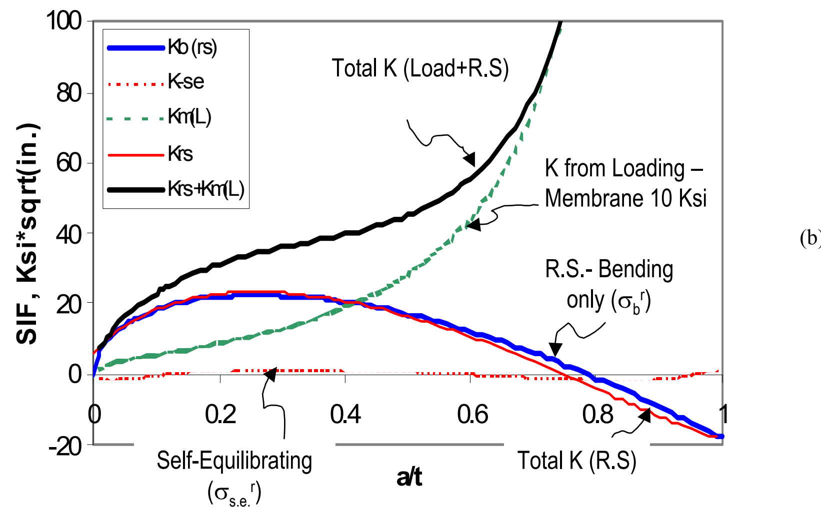
- Geometry
  - Mesh-insensitive structural stress methods
- Residual Stress Effects
  - Residual stress effects in ΔK_{eff} formulation

$$K(a) = \int_0^a \left(\sigma_m^r + \sigma_b^r (1 - 2x/t) + \sigma_{s.e.}^r(x)\right) \cdot w_p(a,x)dx$$



- Crack Nucleation and Short Crack Growth
  - Two-stage growth model $\dfrac{da}{dN} = C\ (M_{kn})^n (\Delta K_n)^m$



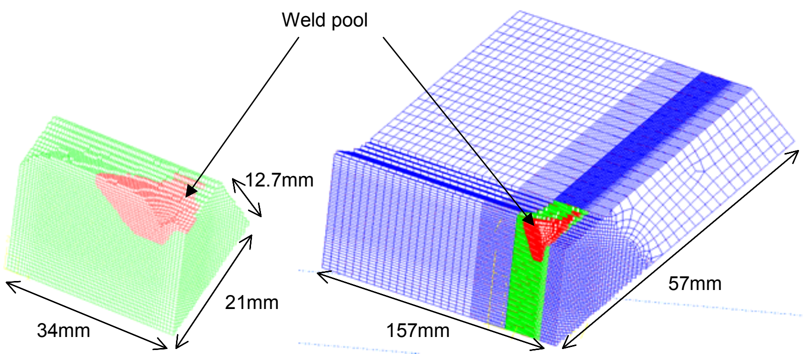


Virtual Welded-Joint Design

Model Integration

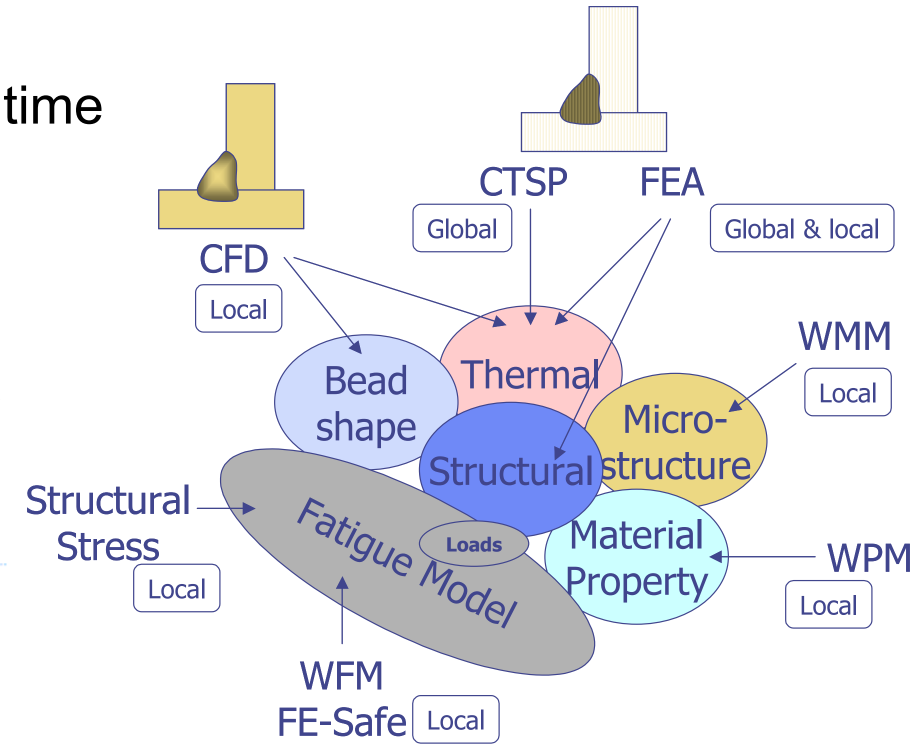
- Approach
  - Sequentially coupled
  - An integrated modeling approach
- Challenges
  - Interdisciplinary principles
  - Multi-scale (µm~m)
  - Differences in computation time

- Integration software
  - iSIGHT
  - OptiStruct
  - Epogy
  - In-house



Domain in weld fluid model

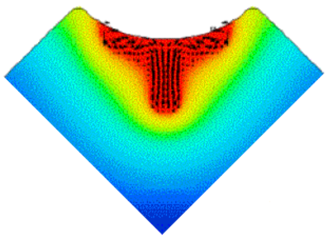
Domain in FEA analysis
Quasi-static

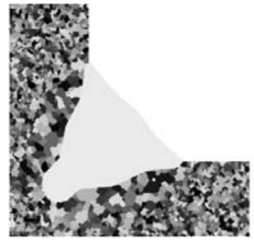


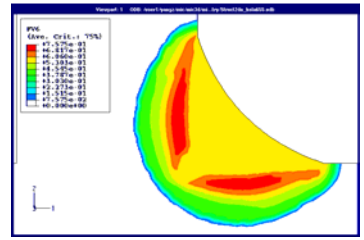
Future Work

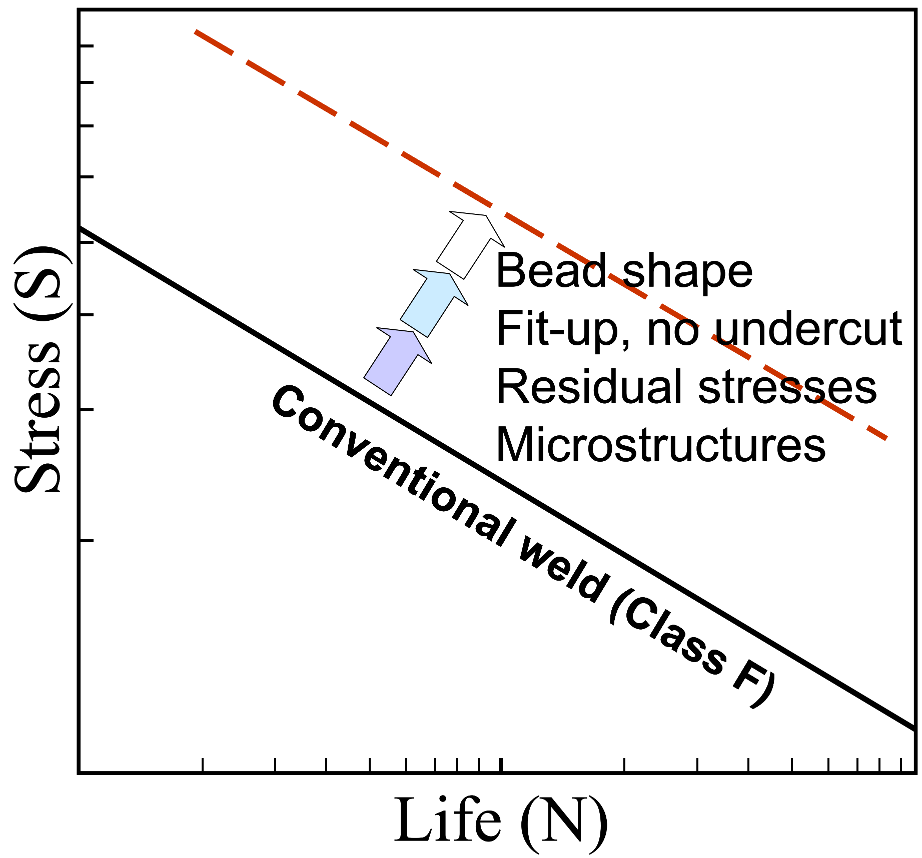
- Model Development
  - Prediction of weld zone composition
  - Pinning effects of precipitates on grain growth in HAZ
  - Prediction of stress-strain curves at elevated temperatures
  - Phase transformation induced plasticity in weld stress model
  - Weld fatigue model
- Experiments
  - Quantitative microstructure analysis
  - Gleeble tests on stress-strain curves for two more steels
  - Continuing development on the special welding wire
  - Weld residual stress measurement using x-ray and neutron diffraction
  - Component fatigue tests
- Technical Demo
  - An integrated model for systematic welded-joint design
  - 10x weld fatigue life improvement for a real welded structure

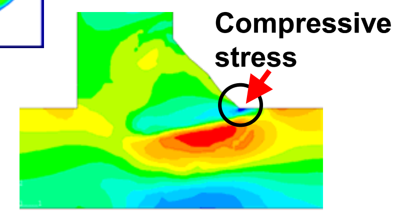
Summary

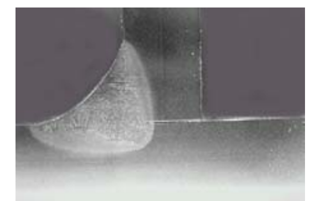


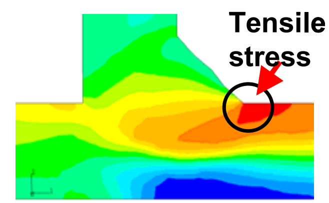





Bead shape
Fit-up, no undercut
Residual stresses
Microstructures
Conventional weld (Class F)
Stress (S)
Life (N)


Compressive stress

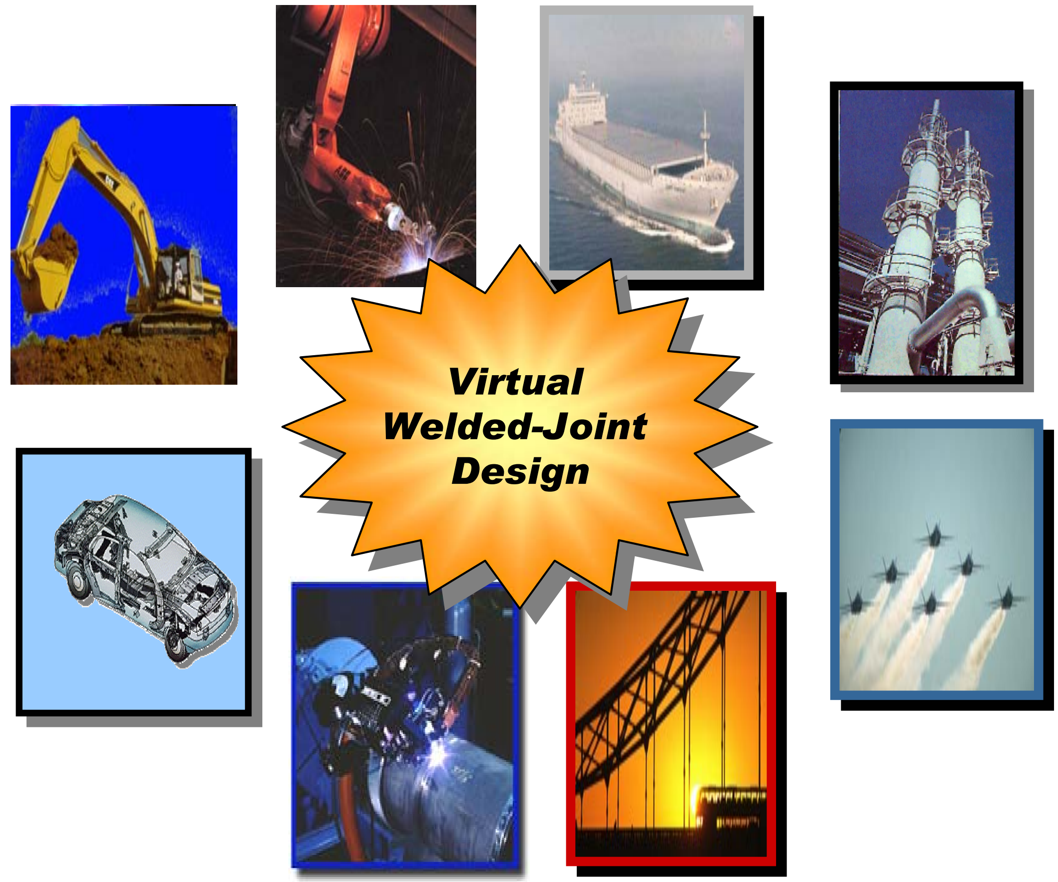



Tensile stress


CONVENTIONAL WELD

Commercialization Plan

- Presentations and Papers
  - Seven technical presentations
  - Two technical papers
- Advisory Council
  - Participants
    - Industry
    - Research Institute
    - National Laboratory
    - Universities
  - Meetings
- Consortium Group



Budget History and Projection

			Approved Spending Plan			Actual Spent to Date		
Phase / Budget Period			DOE Amount	CAT Cost Share	Total	DOE Amount	CAT Cost Share	Total
	From	To						
Year 1	10/01	09/02	250 k$	250.6k$	500.6 k$	250 k$	250.6 k$	$500.6 k$
Year 2	10/02	09/03	250 k$	250.8k$	500.8 k$	331.5 k$	331.2 k$	$662.7 k$
Year 3	10/03	09/04	250 k$	250.4 k$	500.4 k$			
Totals					1,501.8 k$			

* ORNL's spending in year 2 is not counted in this table.