Optimizing Weld Integrity for High-Strength Steels

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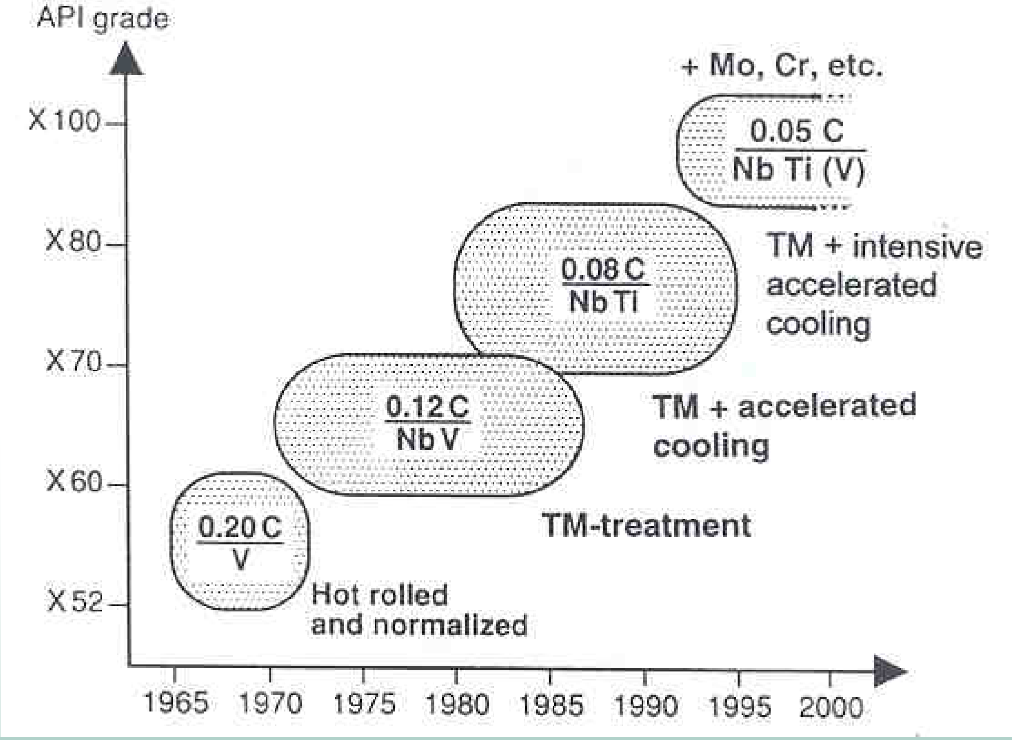
Advanced Welding and Joining Technical Workshop
Boulder, Colorado, USA
January 25-26, 2006

Overview of the Presentation

- Evolution of linepipe materials
- Characteristics of high strength steels and their welds
  - Chemical composition
  - Tensile property, strain hardening, ductility
  - Toughness
  - HAZ
- Significance of the characteristics
  - Weldability
  - Stress capacity
  - Strain capacity
- Material specifications for future applications
  - Tensile property
  - Toughness
- Acknowledgment:
  - U.S. Department of Energy
  - U.S. Department of Transportation
  - PRCI
  - TransCanada
  - Lincoln Electric
  - ExxonMobil

Evolution of Linepipe Steel Production

- *Ref: Hillenbrand, H., Liessem, A., Knauf, G., "Development of Large-Diameter Pipe in Grade X100," Pipeline Technology, Vol. I, Ed. R. Denys, 2000.*
- **Until late 1960's, Grade up to X60 were made using hot rolled and normalized plates**
- **From the late 1960's, thermal-mechanically process, accelerated cooling, and microalloying have allowed the production of grades up to X100.**



High Strength Steels and Welds

- **Linepipe steel, X100**
  - Thermal-mechanically processed
  - Heavily rolled
  - High strength
  - High toughness
  - Lean chemistry, good weldability
  - Transverse yield = 100-120 ksi
  - Transverse UTS = 120-135 ksi
- **Gas metal arc welding (GMAW)**
  - High quality
  - High productivity
  - Yield = 110-120 ksi
  - UTS = 120-135 ksi

Weld Failures, Old and New

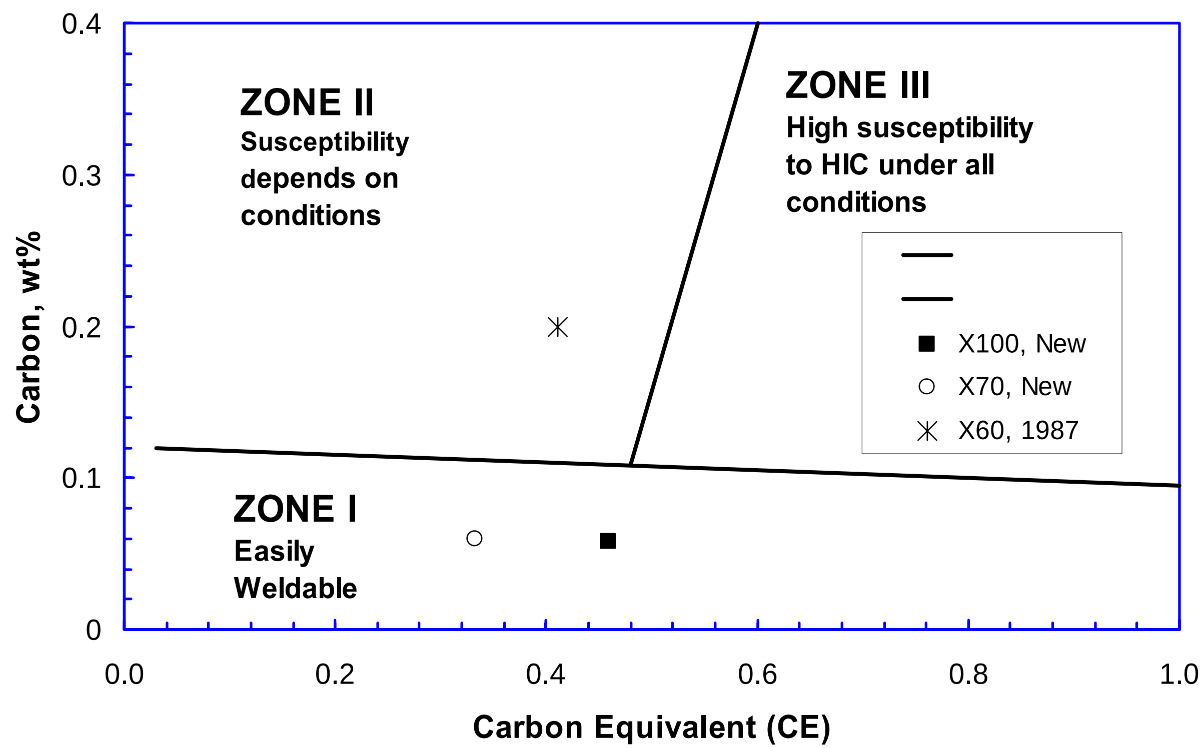
- For example, a 1940's girth weld on X52 pipe can have many welding defects, such as porosity, slag, undercut, etc.
- The old weld can fail from those welding defects.

- Modern girth welds have far fewer defects.
- The quality of modern girth welds is much more consistent.
- In a tension test, a well designed and completed girth weld may not fail without introducing an artificial defect.

Chemical Composition and Weldability

- Chemical composition has changed over time.

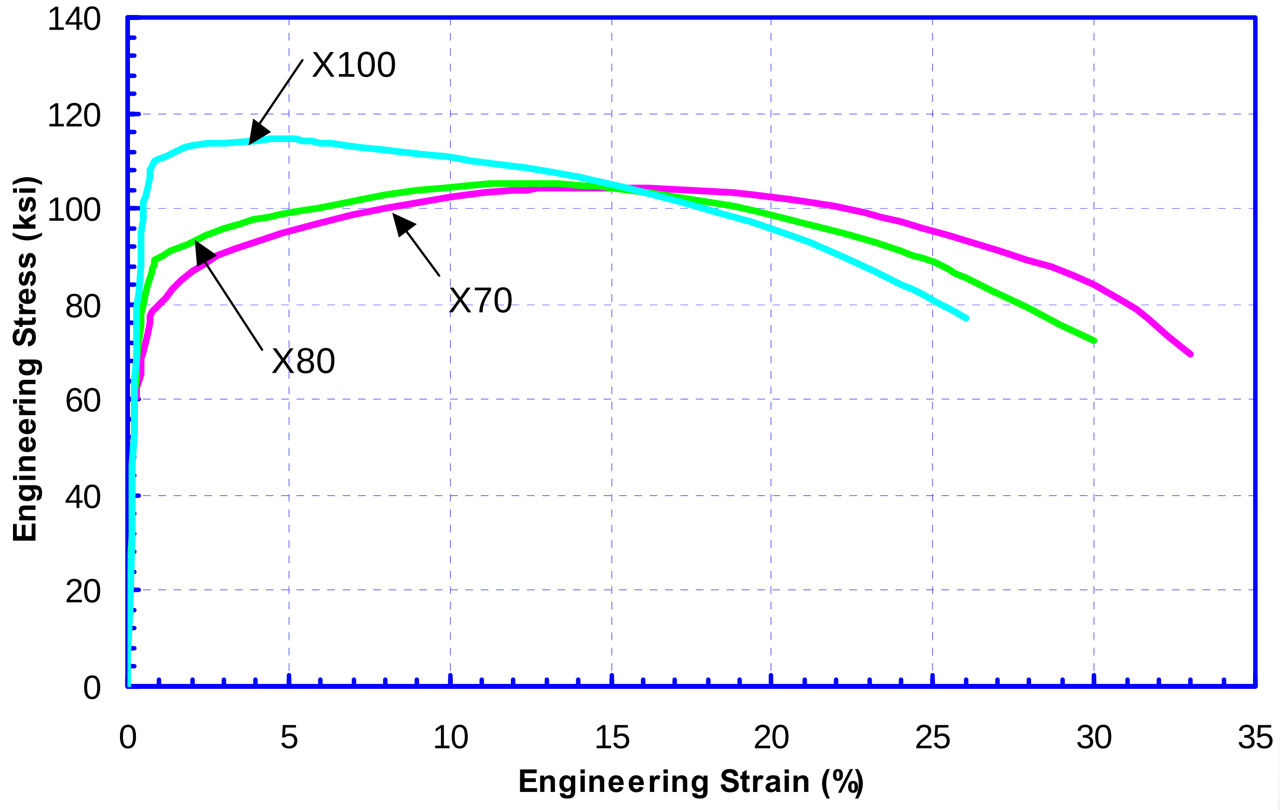
	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	Nb	Al	Ti	N	O	Ca	B	CE (IIW)	Pcm
X100, New	0.058	1.960	0.007	0.002	0.223	0.30	0.210	0.020	0.180	0.00	0.045	0.003	0.014	0.003	0.002		0.000	0.459	0.192
X70, New	0.060	1.500	0.010	0.007	0.280	0.023	0.017	0.033	0.004	0.062	0.037	0.044	0.016				0.001	0.332	0.154
X60, Glover 1987 report	0.200	1.160	0.008	0.007	0.440					0.086	0.025							0.411	0.281



CE=C+Mn/6+(Ni+Cu)/15+(Cr+Mo+V)/5

Tensile Properties vs. Pipe Grade (Schematic)

- **Lower strain hardening and ductility at higher grades**



- **Acknowledgment: David Horsley of TransCanada**

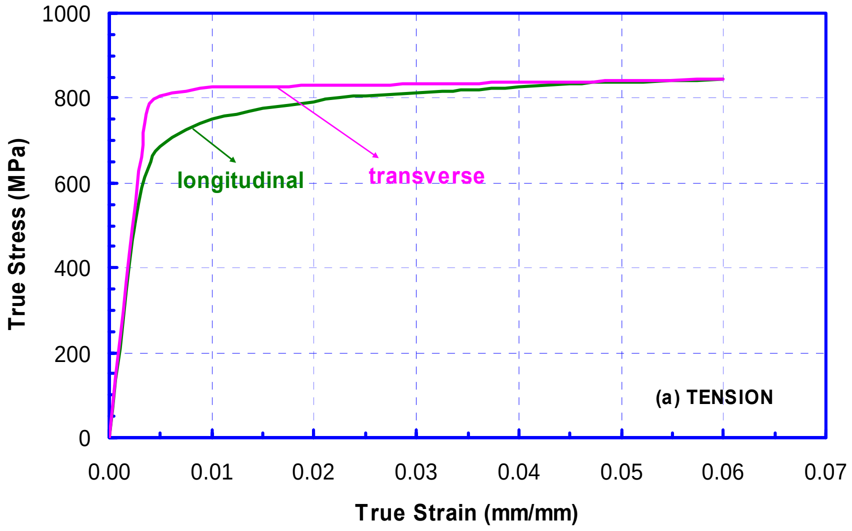
- **Implications:**
  - **Higher grades may have lower strain capacity (both tensile and compressive)**
  - **May have lower resistance to arresting ductile crack propagation**

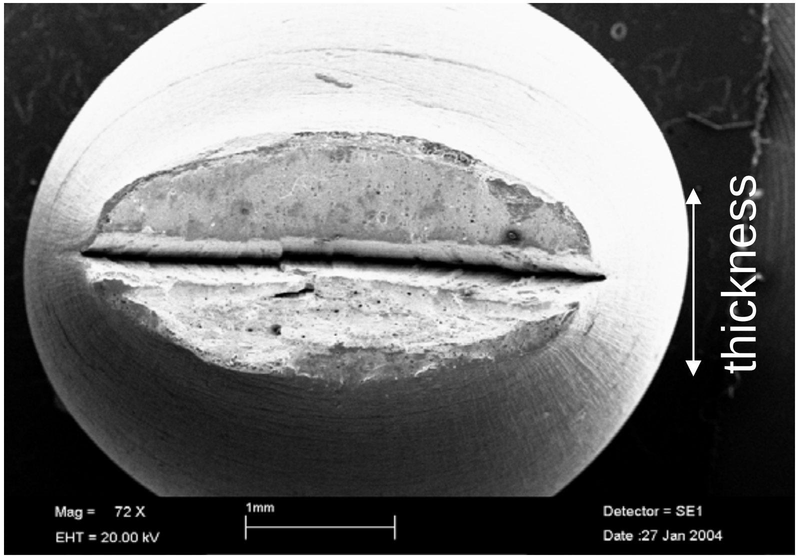
New and Old Linepipes

- X60 material tested by Glover for API (draft report dated June 25, 1987)
  - Yield (at 0.5% strain) = 63.85 ksi, UTS = 89.9 ksi, $\underline{Y/T=0.71}$
- A recent X60 pipe
  - Yield=74.9 ksi, UTS=84.5 ksi, $\underline{Y/T=0.89}$
- Implications:
  - Same grade, but not the same material any more!
  - Viewed solely from the tensile property, the implicit safety factor from the new material may be worse than the old material.

X100 Tensile Properties, Anisotropy

- **Anisotropy and splitting**



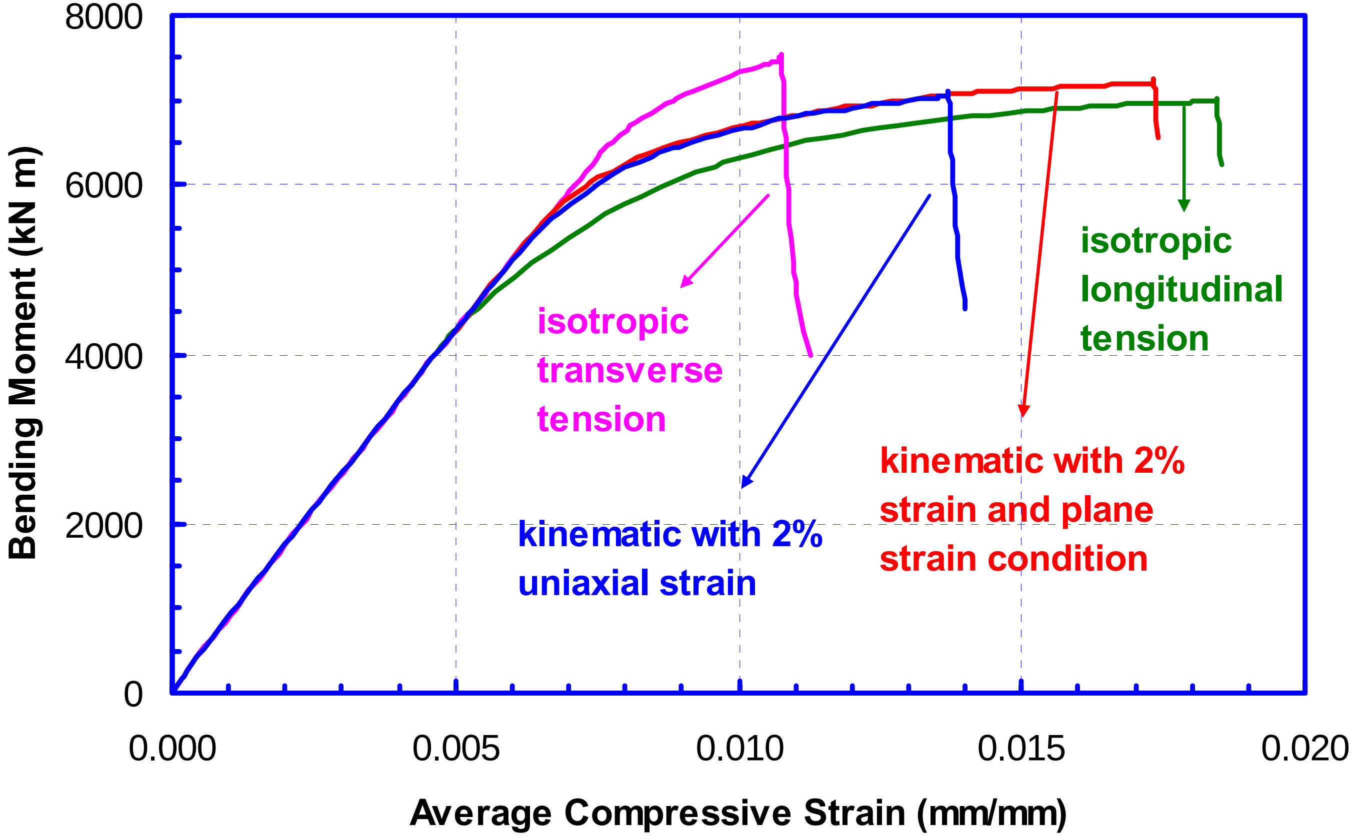


- **Implications:**
  - **What do we use for material specifications?**
  - **What property to use in design and assessment**

- **DOE Award No. DE-FC36-04GO14040**

Buckling Capacity vs. Material Model

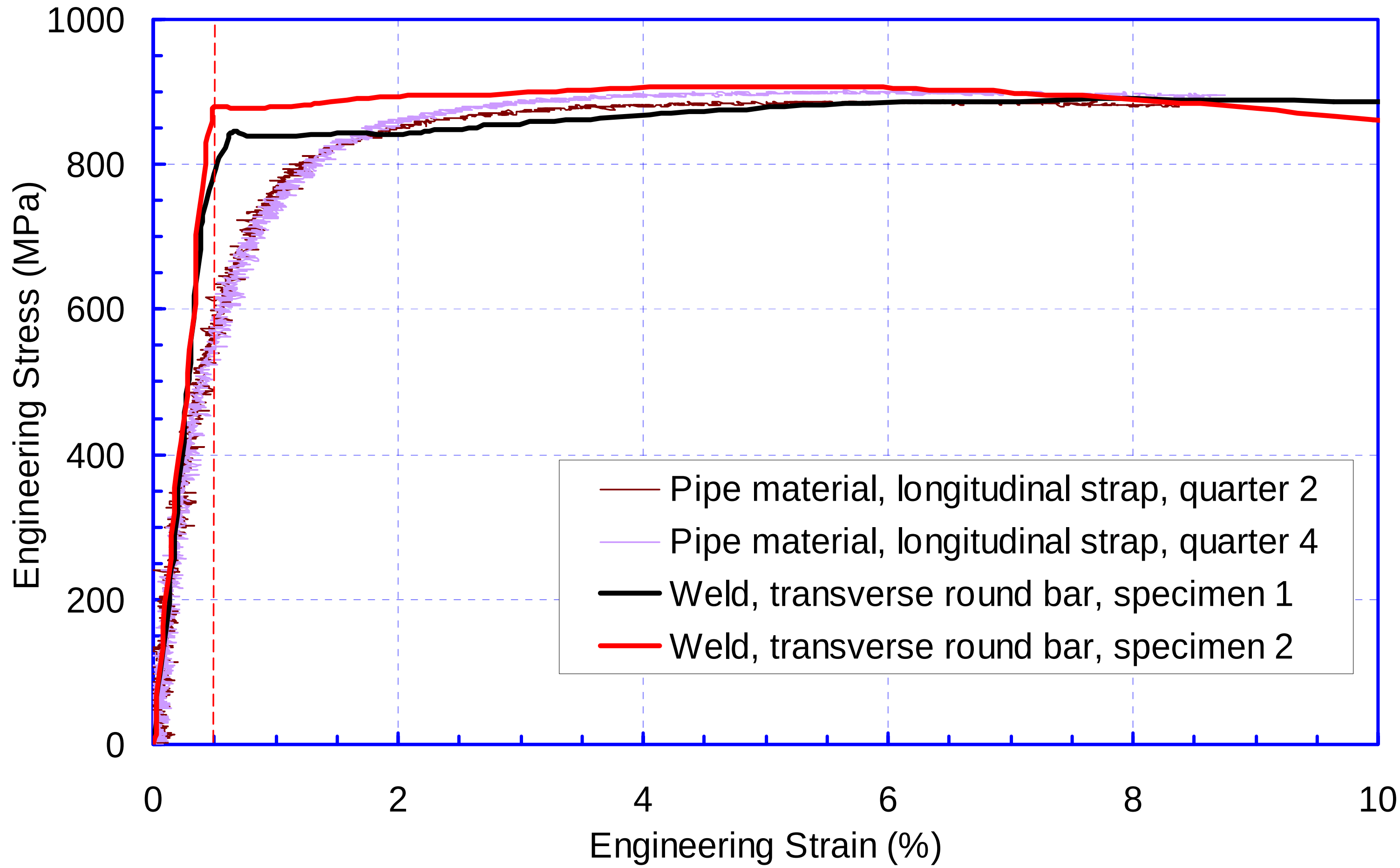
- Buckling resistance is one of the most critical pipeline design and maintenance criteria.



- Ref: Liu, M., and Wang, Y., "Modeling of Anisotropy of TMCP Linepipe Steels," Annual International Offshore and Polar Engineering Conference (ISOPE), San Francisco, USA, May 28 – June 2, 2006.

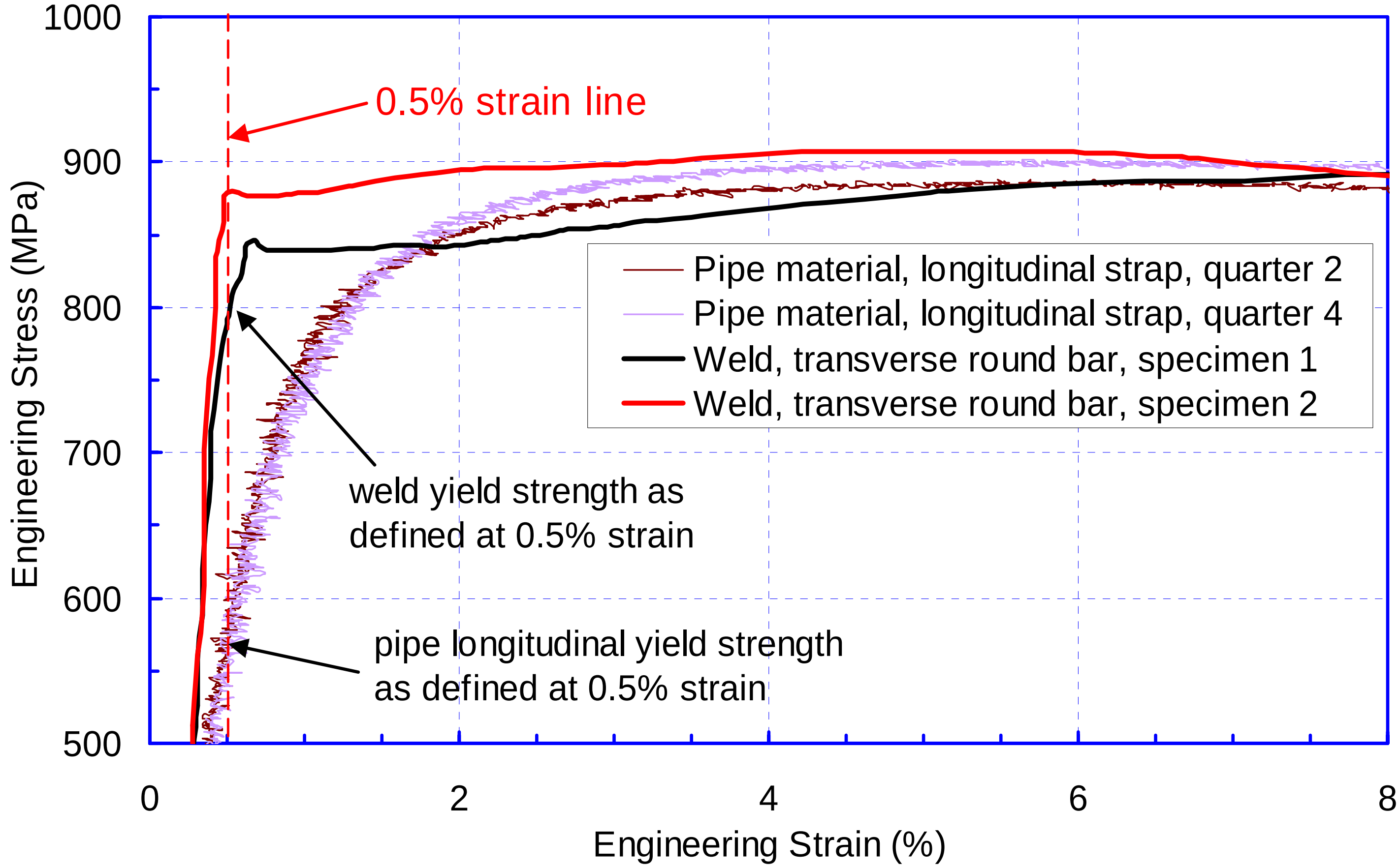
Weld Strength Mismatch vs. Yield Strength

- **Flat stress strain curve of high-strength weld metal**



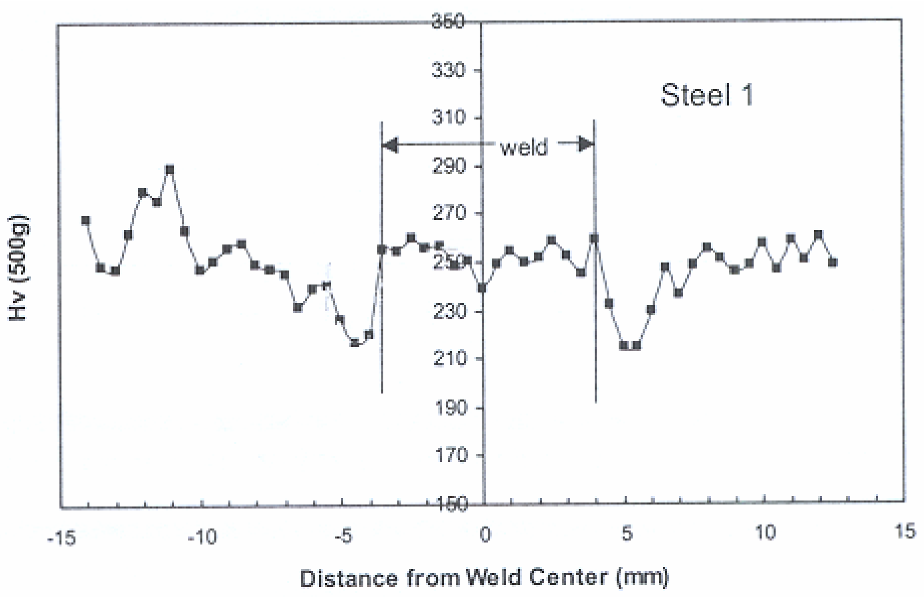
Y/T Ratio, Definition of Yield Strength

- **May not necessarily be a longitudinal property issue ONLY**
- **Linepipe: Yield= 570 MPa (82.7 ksi), UTS=900 MPa (130 ksi), *Y/T*=0.63**
- **Implications: How do we define weld strength mismatch level?**

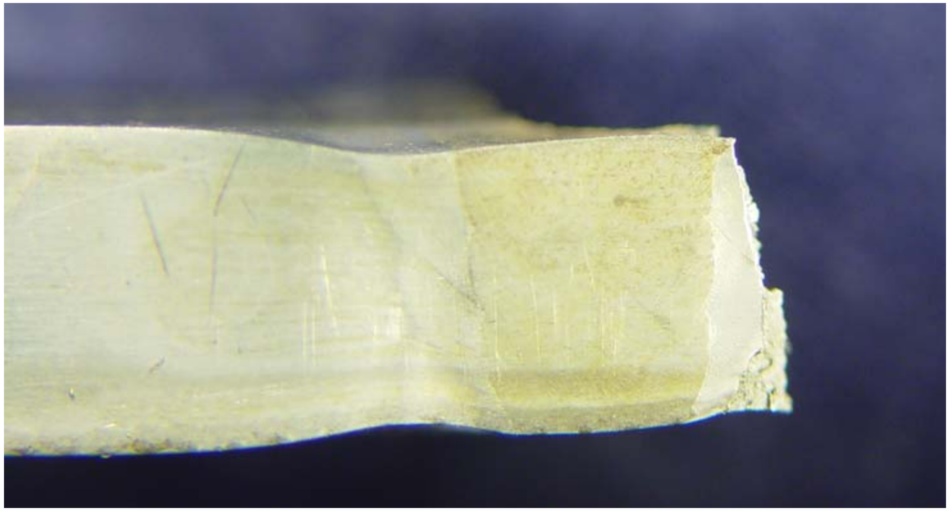


HAZ Softening and Weld Overmatching

- **Trial heat of early generation X100 (early 1990's)**
- **Girth weld**



- **X100 of early 2000's**
- **Girth weld**
- **Moderate degree of weld overmatching**



Major Challenges, Material Specifications

- Measurement of yield (SMYS)
  - Round versus flattened
  - At what strain level (0.2% offset, 0.5% total strain, something else)
- Anisotropy, impact
  - Strain capacity, particularly compressive strain
  - Specification of weld strength mismatch
- Weld strength mismatch
  - Use yield or tensile?
  - Degree of weld strength mismatch?
  - Against SMYS or against measured longitudinal property?

$\mathcal{E}mc^2$

Major Challenges, Material Specifications

- Chemical composition/rolling practice
  - How far can we take the TMCP process to achieve high strength?
  - HAZ softening
  - Fusion boundary integrity in the presence of slight HAZ softening
  - Strain hardening and uniform strain
  - Weldability
- Welds
  - Balance property of strength, ductility, toughness
  - How should these properties be measured?

Major Challenges, Integrity Assessment

- Grades ≥ X80 have not been examined in great details in most weld integrity assessment procedures.
- For stress-based design, should we put in requirements for
  - Minimum elongation,
  - Minimum uniform strain, and
  - Minimum strain hardening?
- Welds
  - Assessment of strength mismatch
  - Assessment of HAZ softening
  - Assessment of strain hardening difference between pipe and weld

"Good" Linepipe Property

- **Reasonable amount of work hardening**
- **Good ductility**
- **Narrow band of property distribution**
- **Upper bound strength level not too high**
- **Good weldability**
- **Low susceptibility to HAZ softening**
- **Good toughness**
- **Different strength behavior in transverse and longitudinal direction**

“Good” Weld Property

- Strength overmatching base metal
- Good ductility
- Some degree of strain hardening
- Reasonable Charpy energy at the design temperature

Considerations for High Strength Steels

- **Need to recognize that that yield and UTS are no longer sufficient to describe material's tensile properties.**
- **Need full stress-strain curves!**
- **Allow slight degree of undermatching given the strength distribution, 5-10% depending on welding process and application**
- **Specify weld property based on UTS, not on yield?**
- **Relate Charpy energy requirements to strength level**

Considerations for High Strength Steels

- **Need to understand the likely weakest link in weld integrity**
  - **Accurate predictive tools, i.e., modeling**
  - **Steel/pipe mills, weld consumable/equipment manufacturers, construction contractors, NDT vendors, owner companies, and regulator work together from the start of a project.**
- **Need more accurate analysis and experimental methods for strain-based applications**
  - **New applications are pushing the limits of materials' strain limits.**
- **Standards**
  - **Many standards are not up-to-date for the application of new high strength materials.**
  - **Lack of background information on how standards were set.**
  - **Potential gap in human resources**