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Properties Variation in Stainless Steel Laser Welds

C. V. Robino, B. L. Boyce, and C. C. Battaile

Sandia National Laboratories
Albuquerque, NM

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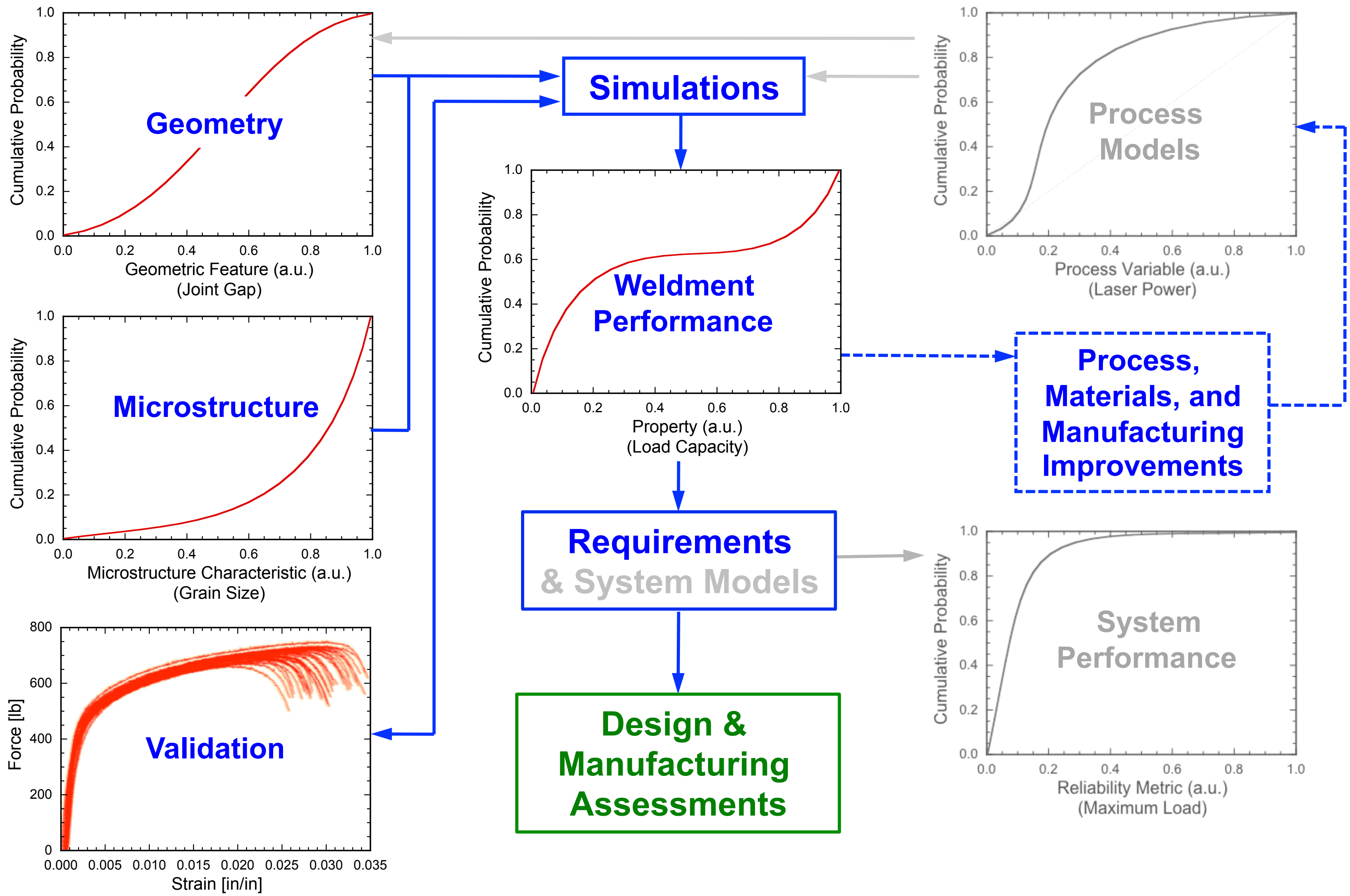
Background

- **Sandia must certify the safety and reliability of a wide range of laser welded components**
- We are moving toward reduced testing levels and increased application of design by analysis
- Development of a basis for inclusion of materials and process variability in predictive simulations is an integral part of this process
- Inclusion of variability also provides a foundation for assessment of deviations from certified practices

- **We have made variability measurements and have initiated variability model development for two types of laser seam welds (pulsed seam and continuous wave)**

Methodology

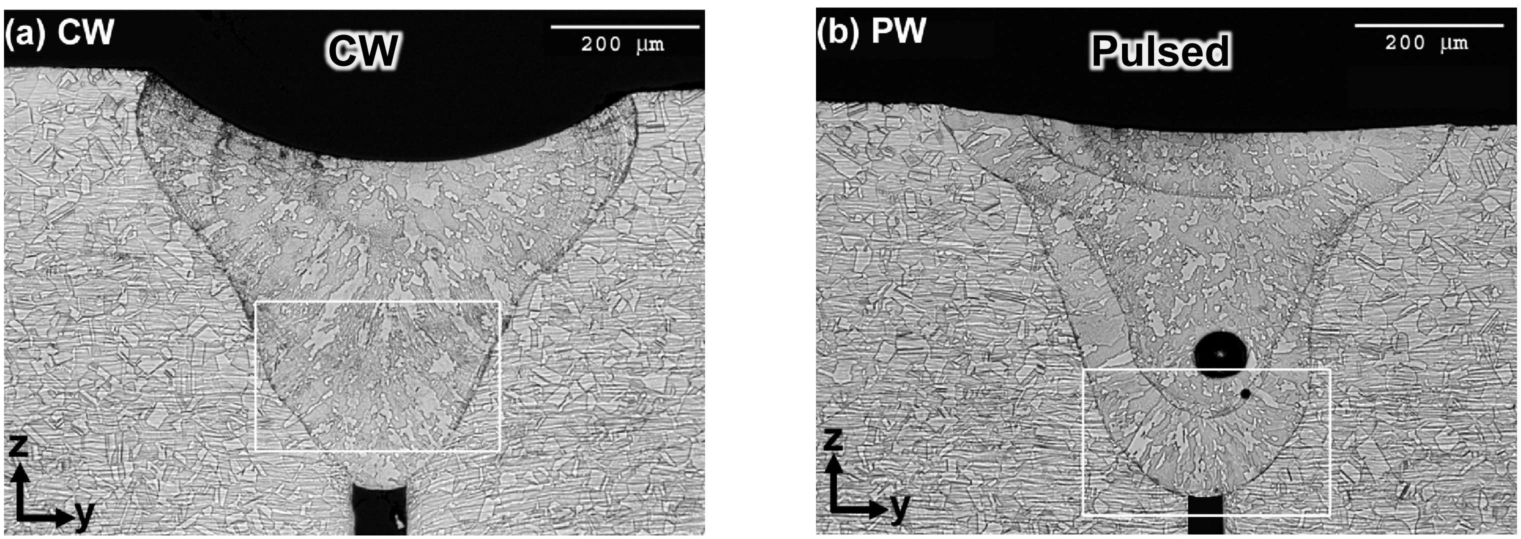


Welding Procedures

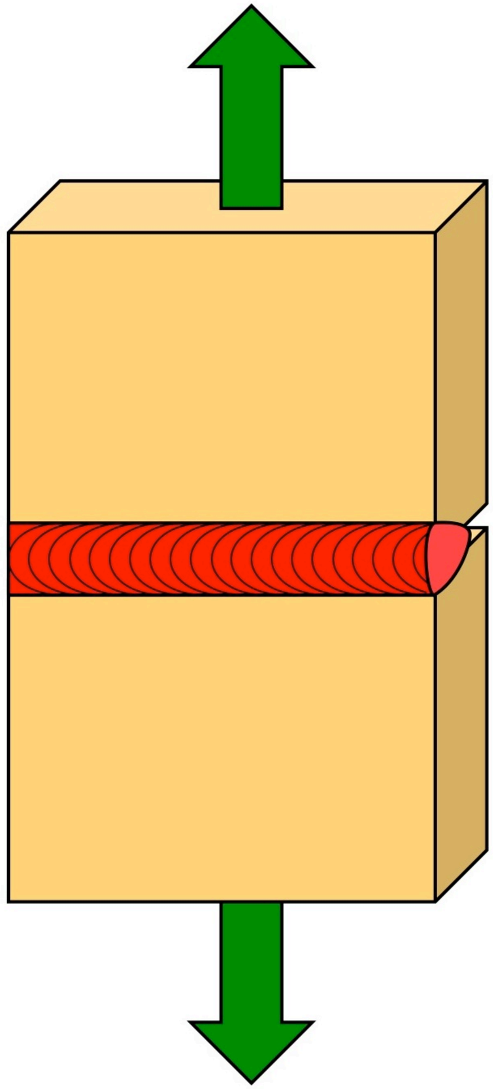
- Partial penetration seam welds in 1.6 mm thick, mill annealed 304L sheet
- Rofin-Sinar CW 015 HQ Nd:YAG

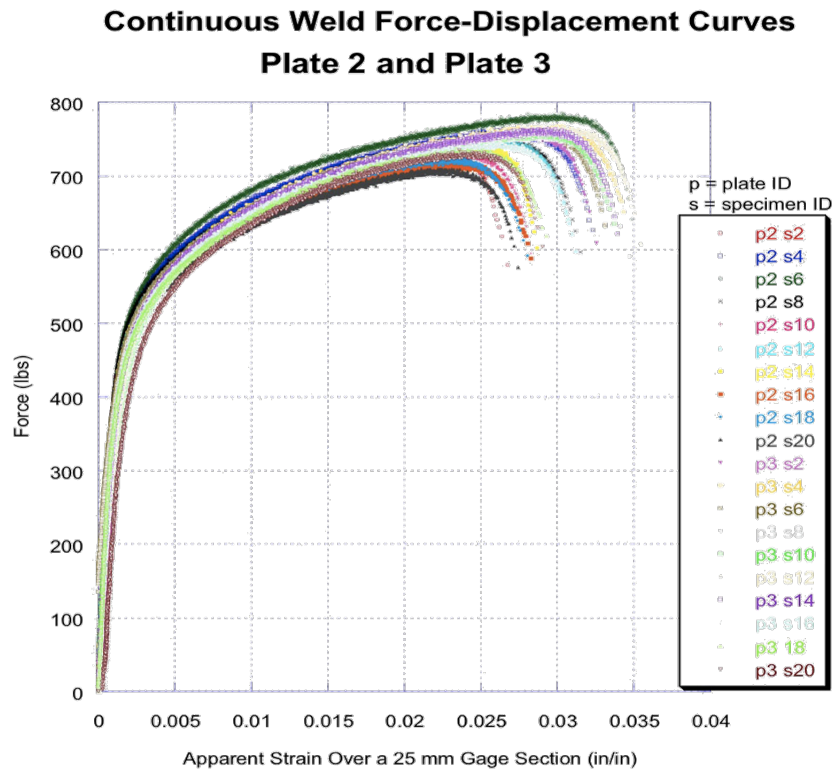
Cr	18.2	C	0.024	Cr_{eq}/Ni_{eq} (H&S) =
Ni	0.041	N	0.041	
Mn	1.83	P	0.030	
Si	0.45	S	0.001	
Cu	0.42	Fe	Bal	1.73
Mo	0.16			

- Procedures and setup capture attempt to capture a realistic range of joint gap and fit-up, but are nonetheless well controlled laboratory welds



Weldment Tests

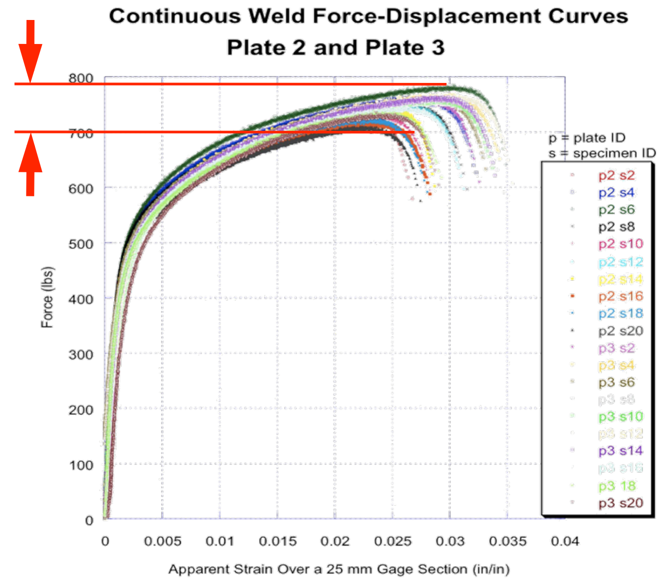


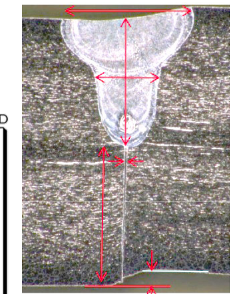


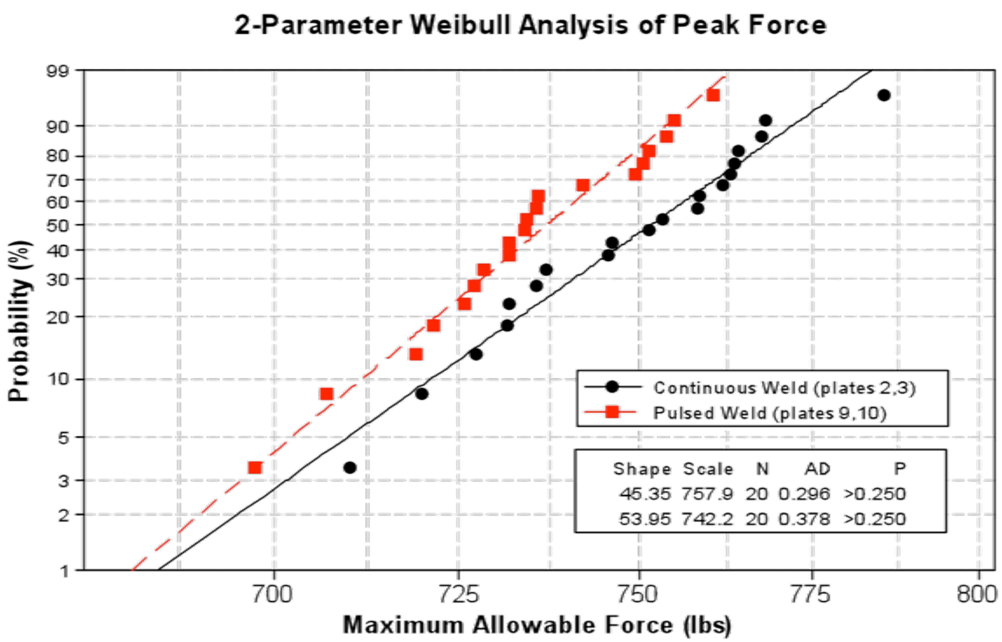
- Test sample included included weld root and reinforcement (or depression)
- One inch gauge length

Mechanical Properties Variability - Experimental

- Assessment conducted on load tests of a large number of nominally identical weldments produced by two laser procedures
- The results illustrate the substantial variability individually and between the two process types







Among 15 common distributions, Weibull provides best (Anderson-Darling) fit to maximum force:

1-in-1,000 Allowable Force (PW): 650 lbs

1-in-1,000,000 Allowable Force: 550 lbs

⇒ Weld must be de-rated 25% below its average strength for 1-in-10^6 design allowable

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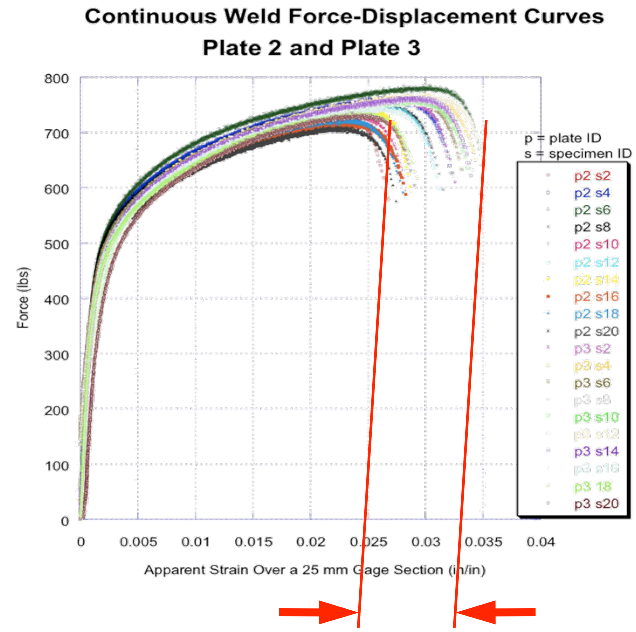
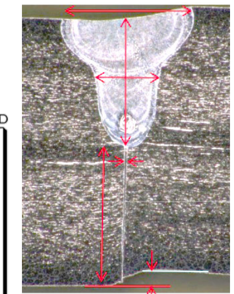
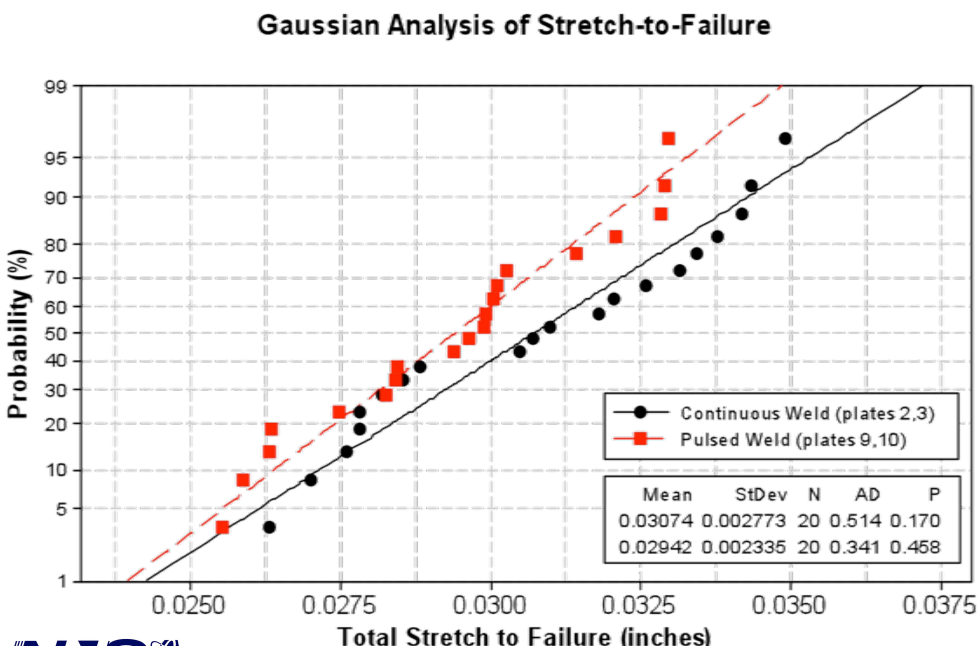
Mechanical Properties Variability - Experimental

- **Assessment conducted on load tests of a large number of nominally identical weldments produced by two laser procedures**
- **The results illustrate the substantial variability individually and in comparison**
- **Design by analysis and allowable stress methods are being incorporated where possible, but this type of testing cannot be applied to all situations**







Among 15 common distributions, Gaussian distribution provides best fit to stretch-to-failure:

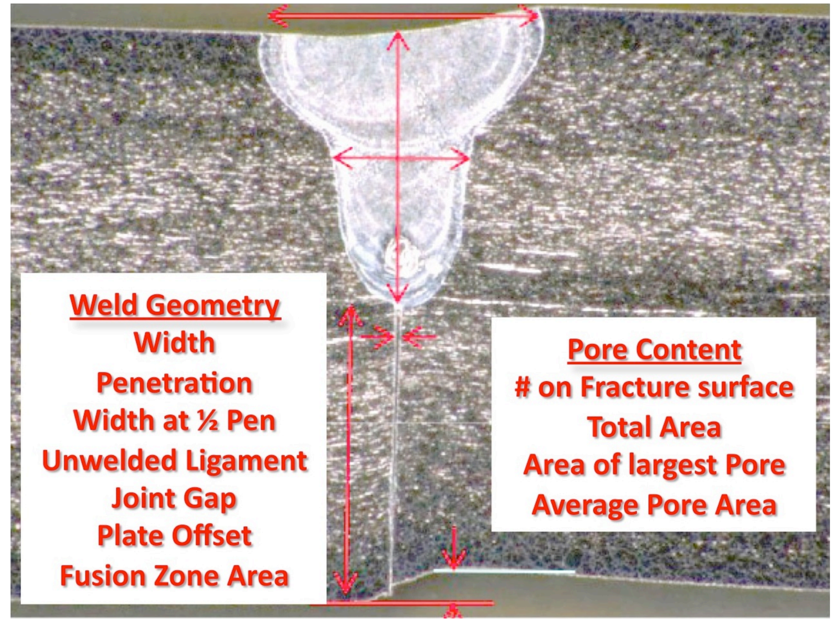
1-in-1,000 Allowable Displacement (CW): 22.2 mils
1-in-1,000,000 Allowable Displacement: 17.6mils

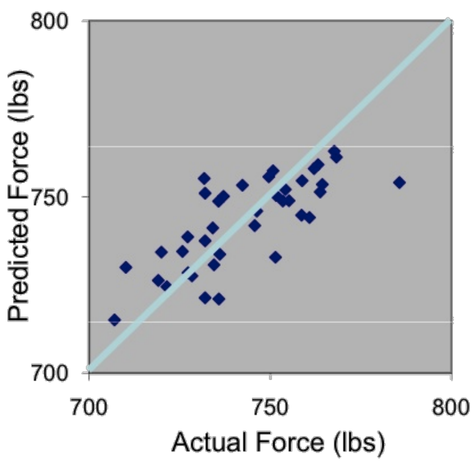
⇒ Weld must be de-rated 43% below its average stretch for 1-in-10^6 design allowable

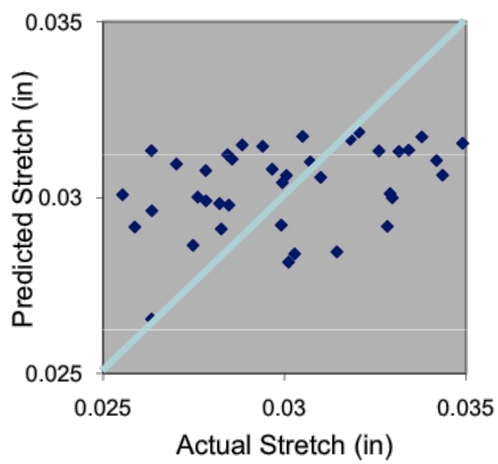
Regression Correlations with Geometric Features

- From a metallographic sample adjacent to each tensile test sample, eleven key geometric and pore features were measured for each of the forty samples (440 measurements)
- Multivariate linear regression applied to these features

Equation	S	R^2 (%)	R^2(adj) (%)
Max Force (all 11)	13.57	63.1	48.7
Max Force (top 6)	14.68	49.2	40.0
Total Stretch (all 11)	0.0022	48.2	30.4
Total Stretch (top 3)	0.0023	24.1	17.8



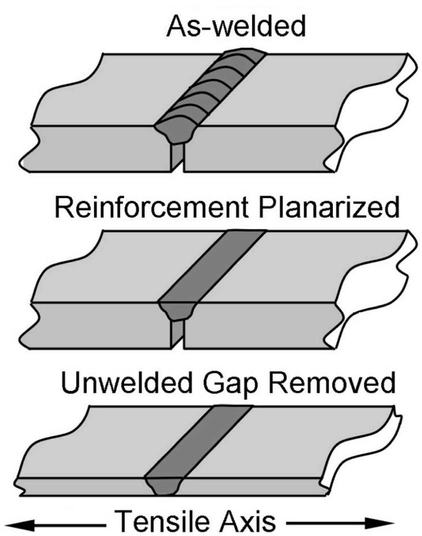


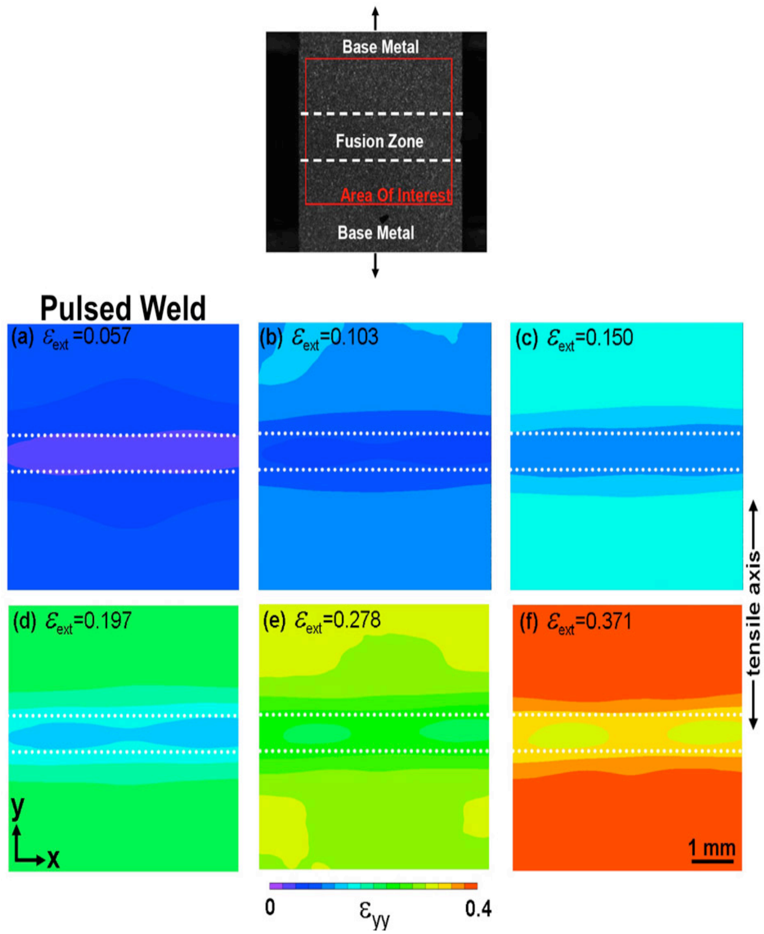


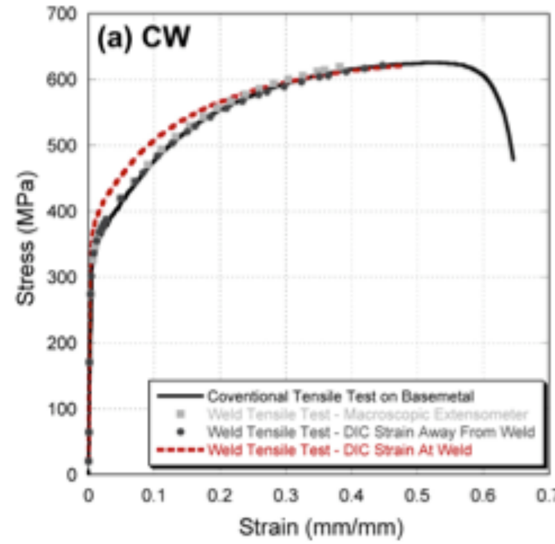
- Variation in geometric features are not sufficient to explain test variability
- Inclusion of microstructural features and variability is needed to account for properties variation

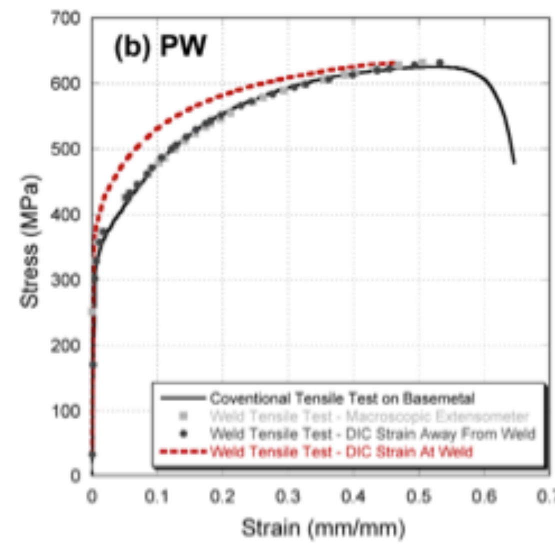
Digital Image Correlation and Weld Metal Properties

- Digital image correlation used to determine constitutive properties for the weld fusion zone
- These properties are then used in simulations









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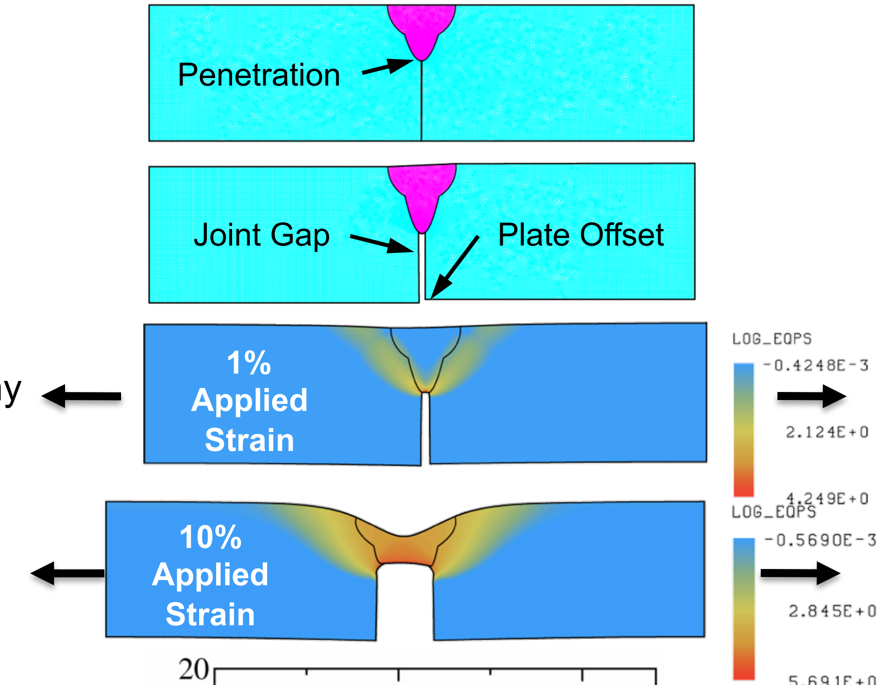
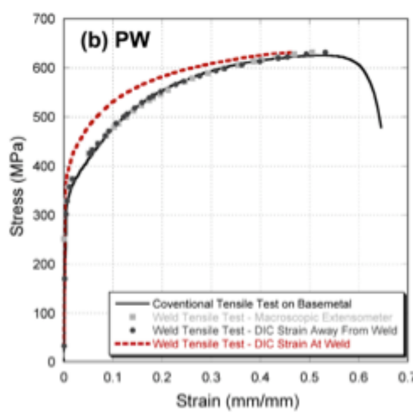
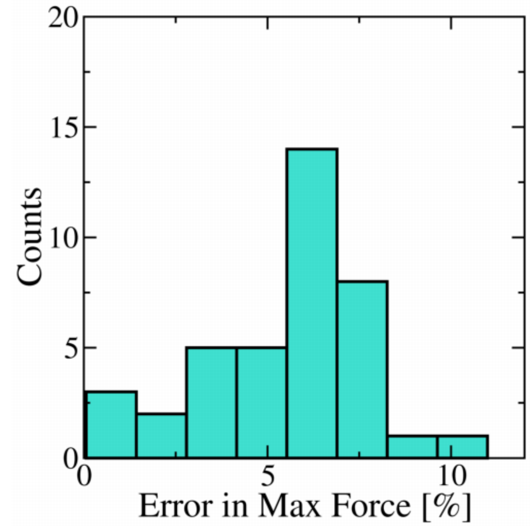
Mechanical Properties Variability – Simulations

- **Weldment load tests modeled by FEM methods:**
  - Elastic-plastic, power-law hardening constitutive models based on DIC data for each weld region
  - Weld geometry modeled after weld micrographs, procedures developed for rapid meshing
  - Statistical approach (many geometric variations, many iterations)
  - Initial simulations study focused on three parameters



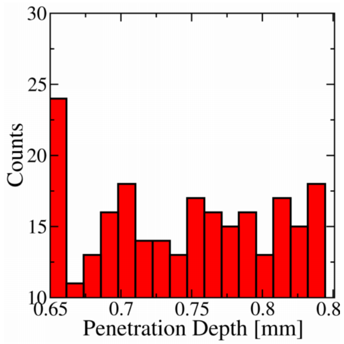


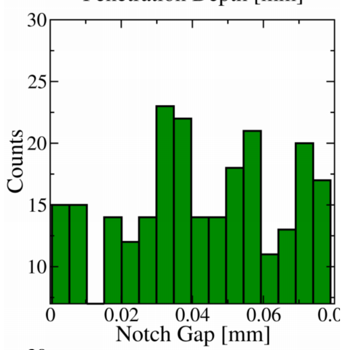


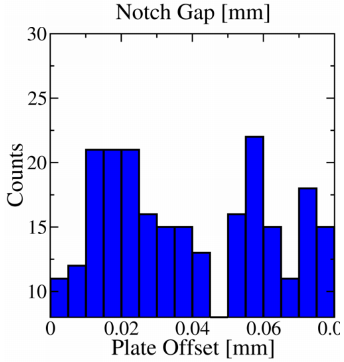
- **The approach has been validated against the forty weldment tests**

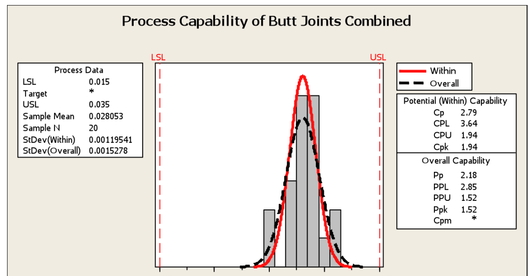
Initial Exploration of Weld Variability

- **250 simulations performed on randomized geometries**
- **Variables ranges informed by actual practice**

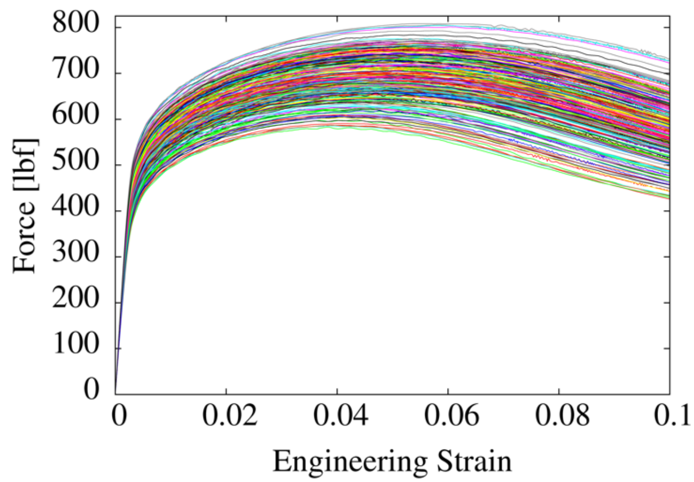


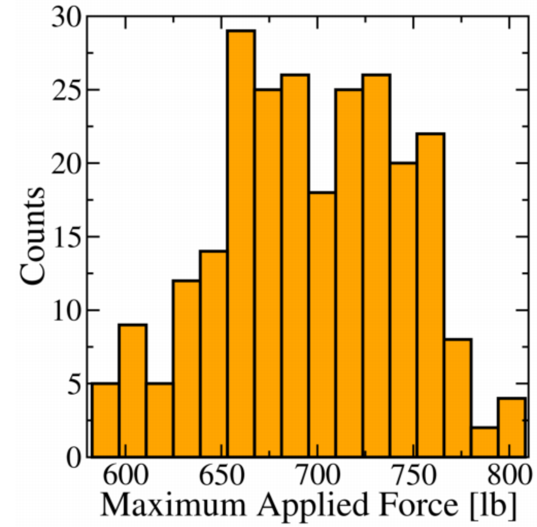


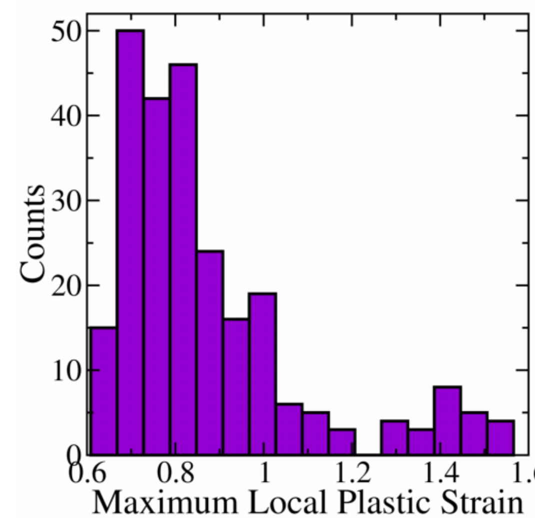




Typical penetration variance for production laser welds (*courtesy J. Samayoa, Kansas City Plant*)







- **The method provides a means for quantification of property *variability***

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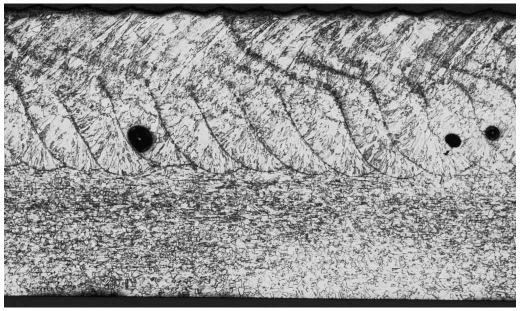
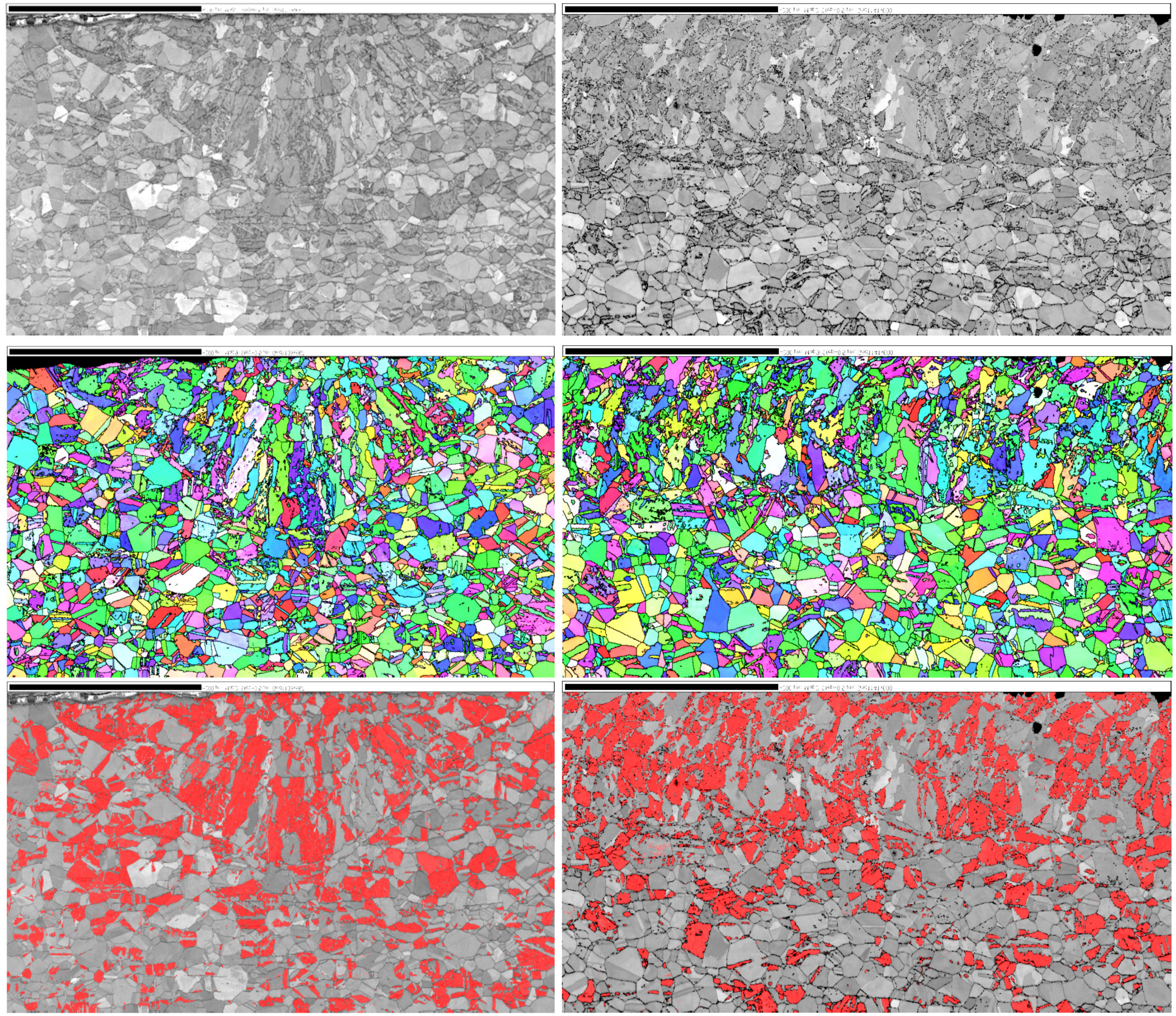
Laser Weld Microstructures



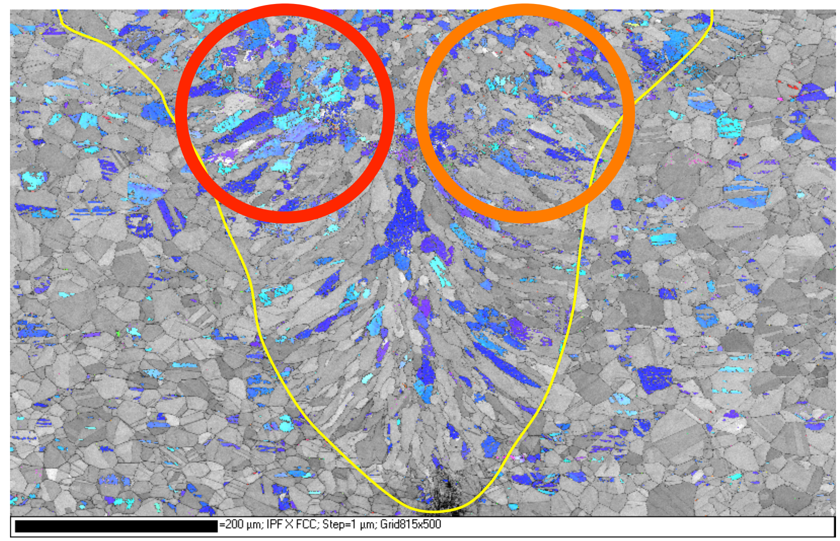


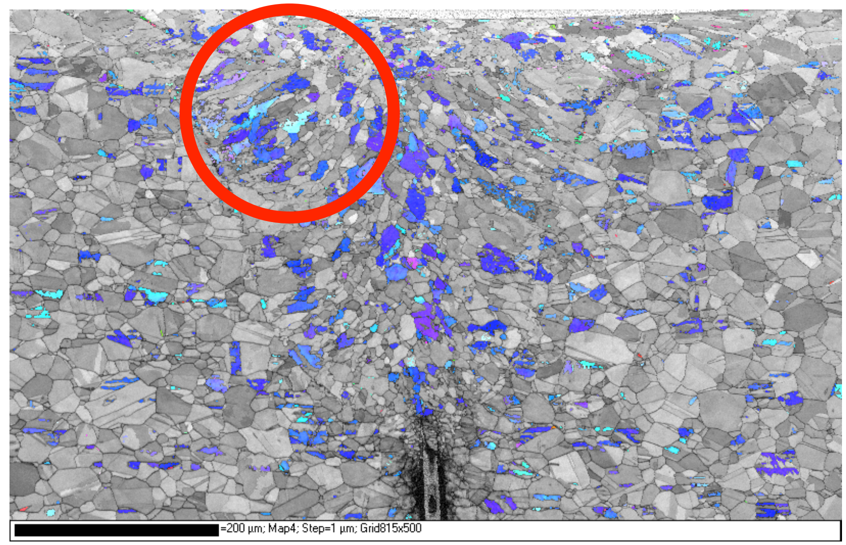
- **Weld microstructures are extremely complex**
- In pulsed welding solid liquid interface motion is not monotonic
- This results in non-homogeneous interfaces, grain shapes, and and phase distributions
- These distributions have not previously been quantified

- **Our long term goal is to quantify this variation and incorporate it into properties simulations**

Effect of Ferrite

- **For these high Cr_{eq}/Ni_{eq} alloys, ferrite fractions can vary appreciably in directions both transverse to and along the welding direction**
- Based on empirical relationships for austenitic steels, a +/- 4 to 6% absolute change in ferrite content can account for the observed +/- 35 lb variance in max load about the median
- Upper bound estimate neglecting the geometric variance



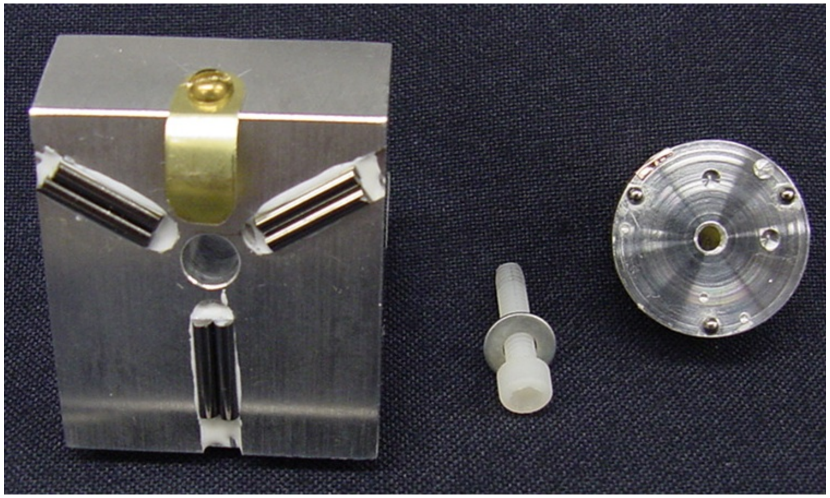


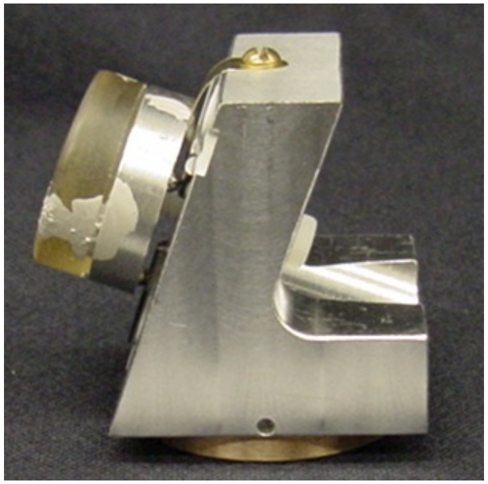
3-Dimensional Grain Shapes and Distributions

- **Designed, fabricated and characterized a new kinematic mount for EBSD analysis**

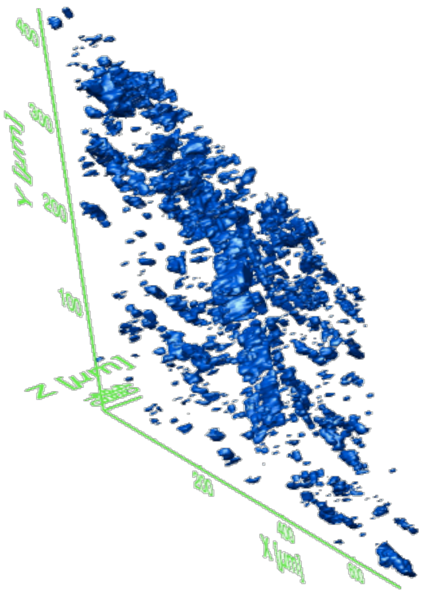
- Capable of precise angular and positional repeatability during the multiple dismounts associated with serial sectioning
- Repeatability demonstrated through multiple systematic mount/dismount trials
- Procedures developed for < 5 μm/section serial sectioning of 304L laser welds – hardness indent/confocal microscope used to accurately determine individual section depths

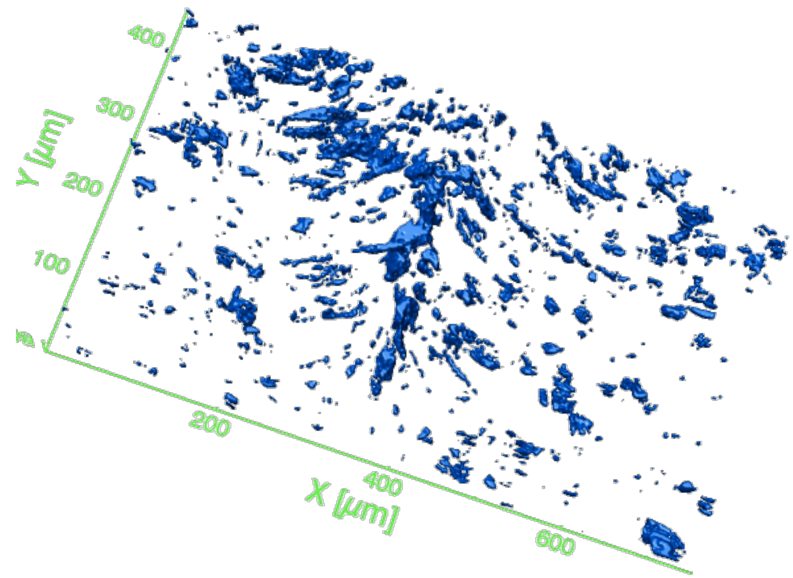
Kinematic SEM mount for 3-D EBSD analysis





Ferrite Reconstruction and Distributions





- **3-D reconstruction methods developed and applied eleven sections spaced at 5 µm intervals**
- Provides preliminary representation of microstructural variability, but additional sections are needed – similar approach envisioned for grain size/shape and porosity distributions
- Automatic sectioning capability (Robomet) acquired, but not yet operational

Summary

Significant progress has been made in both the experimental and modeling aspects of the work:

Experimental

- Statistical and parametric assessments of key properties using eleven geometric and pore features have been completed - these explain much but not all variation
- Detailed microstructural quantification methods are being developed to quantify the variance with processing and to provide appropriate model inputs

Modeling

- A method for efficiently generating and sampling realistic weld meshes has been developed and implemented
- Using a two material model based on DIC measurements, the approach is being used to model the variance associated with geometric features of laser welds
- Validation of the model continues, but initial variability estimates based on geometric feature variation demonstrates the utility of the approach

  - **The key (and challenging) longer term goal is to incorporate microstructural variance into the assessments in an efficient and appropriate manner**

Backups

Effect of Grain Size on Yield Strength

- Hall-Petch contribution can be expressed as:

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}}$$

where σ_y = yield strength
σ_0 = baseline yield strength
d = grain size
k_y = locking parameter (600 MPa·μm)

- This results in an expected increments in yield stress of:

Weld	$\Delta\sigma_y$ (MPa)
CW	9
PW	32

- Alternatively, multiple linear regression equations* for 86 austenitic stainless steels give:

Weld	$\Delta\sigma_y$ (MPa)
CW	17
PW	59

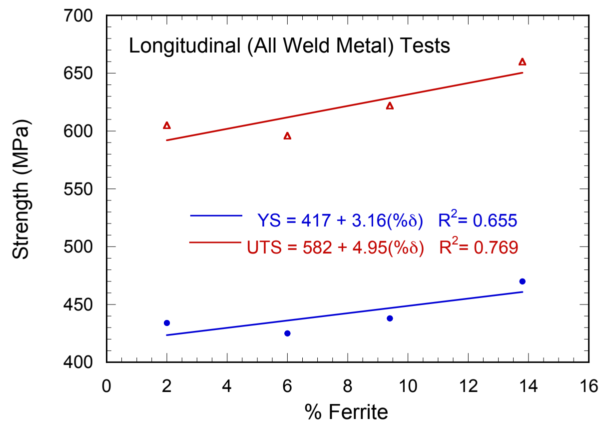
*K. J. Irvine, T. Gladman, and F. B. Pickering, "The Strength of Austenitic Stainless Steels", *Journal of the Iron and Steel Institute*, Vol. 207, p. 1017-1028, 1969.

- Combining these two estimates implies that the grain size contributions to fusion zone strengthening are on the order of :

Weld	$\Delta\sigma_y$ (MPa)
CW	9 - 17
PW	32 - 59

Effect of δ-Ferrite on Yield Strength

D. Hauser and J. A. Van Echo, "Effects of Ferrite Content in Austenitic Stainless Steel Welds", *Welding Journal Research Supplement*, Vol. 57, p. 81s-44s, 1978.



Yield strength dependency of:

3.2 Mpa/%δ

K. J. Irvine, T. Gladman, and F. B. Pickering, "The Strength of Austenitic Stainless Steels", *Journal of the Iron and Steel Institute*, Vol. 207, p. 1017-1028, 1969.

Multiple linear regression for 86 austenitic stainless steels gave dependencies of:

2.47-2.93 MPa/%δ

- **Combining these two estimates implies that the ferrite contributions to fusion zone strengthening are on the order of :**

Weld	$\Delta\sigma_y$ (MPa)
CW	12 - 16
PW	20 - 26

Total Contributions of Grain Size and δ-Ferrite

- Assuming there are no interactions between the strengthening mechanisms, combining these estimates gives:

Weld	Expected $\Delta\sigma_y$ (MPa)	Observed $\Delta\sigma_y$ (MPa)
CW	21 - 33	40
PW	52 - 85	70

- Simple analysis neglects crystallographic texture (not observed), 3-D grain shapes, dislocation substructure, statistical test variation, and potential interactions of these
- Nevertheless, the similarity of the estimates and measured values implies that these two mechanisms are likely dominant in the response of these 304L welds
- The reasons for lower initial work hardening rates in the welds are not yet clear