Interfacial Surface Measures as a Tool for Investigating Porosity in Laser-Welds of 304L Stainless Steel

J. Madison, L. K. Aagesen

SAND2013-1706C

Exceptional service in the national interest

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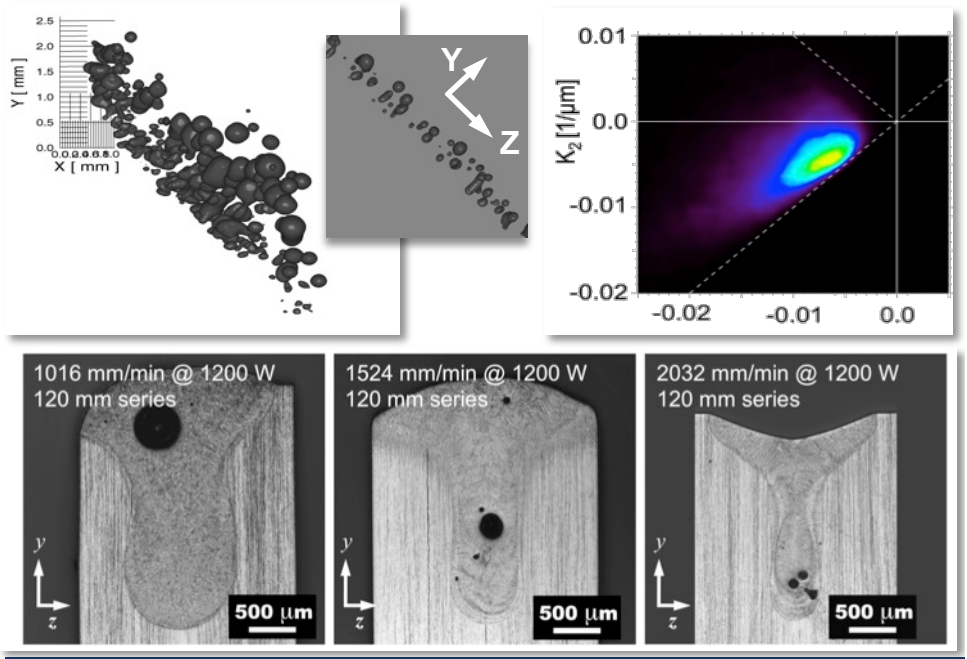

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  - John Emery, Org. 1524 – Solid Mechanics
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  - Bethany Lust, Org. 1814 – Computational Materials
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Laboratory Directed Research & Development

Outline

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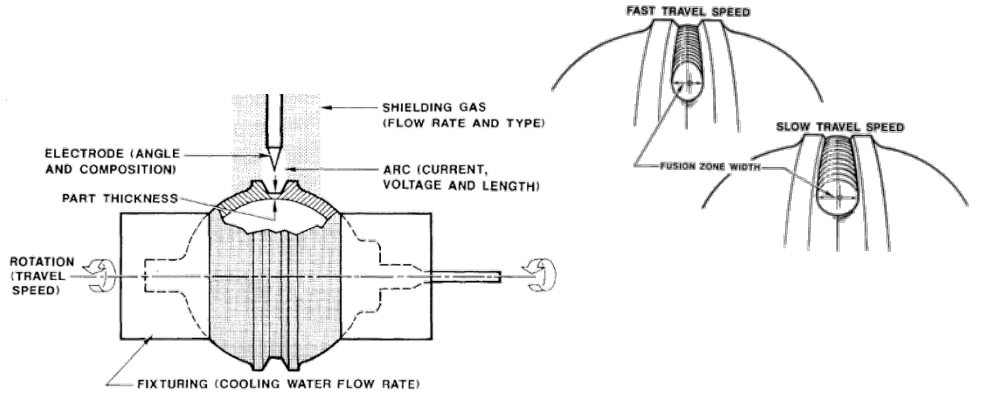
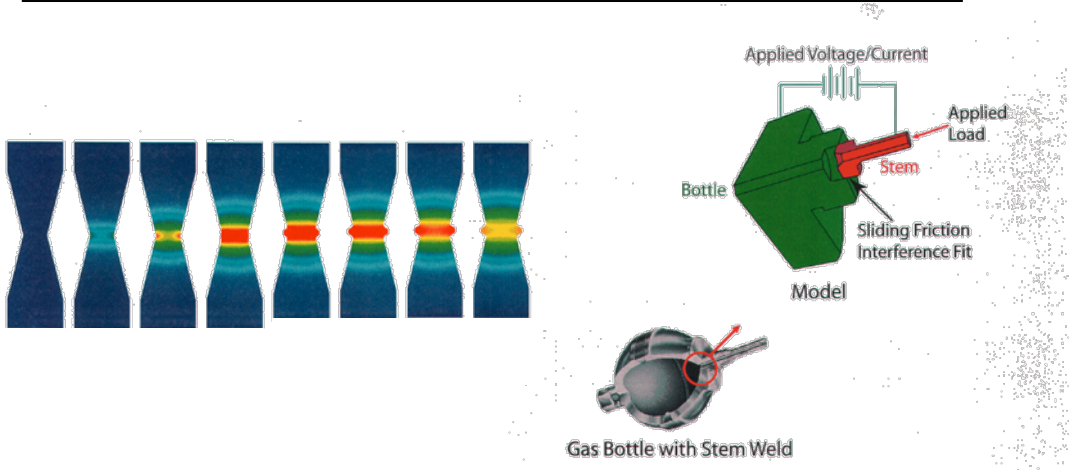
- Background
  - Weld Applicability to SNL
  - Effect of Porosity
- Laser-Welds
  - Process & Challenges
- Characterization Results
  - μComputed Tomography
  - Interfacial Shape Distributions
  - Interfacial Normal Distributions
- Implications to Processing
- Summary

Weld Applicability to SNL

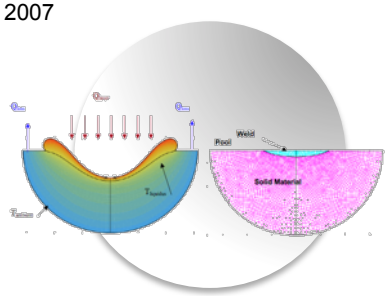


A. Bentley, **SAND1991-8201** : Feedback Control of Arc Welding Using Quantitative Feedback Theory, February 1991



W. Winters, A. Brown, D. Bammann, J. Foulk III, A. Ortega, **SAND2005-3000:** Progress Report for the ASCI AD Resistance Weld Process Modeling Project AD2003-15, May 2005

- M. Cieslak, A. Ritter, "Precipitate Formation in Austenitic Stainless Steel Welds," **Scripta Met**., Vol. 19, Issue 2, (1985) pp. 165-168
- J. Jellison, M. Cieslak, *Laser Materials Processing at Sandia National Laboratories,* presented at Applications of Lasers and Electro-Optics, Orlando FL, October 1994
- J. Knorovsky, M. Kanouff, P. Fuerschbach, D. Noble, P. Schunk, D. MacCallum, Hooper, *Calculated versus experimental heat inputs in laser spot welding,* presented at The American Welding Society, Chicago IL, April 2000
- C. Robino, A. Hall, J. Brooks, T. Headley, R. Roach, **SAND2002-4014** : Solidification Diagnostics for Joining and Microstructural Simulations, January 2003
- V. Semak, G. Knorovsky, D. MacCallum, R. Roach, "Effect of Surface Tension on Melt Pool Dynamics During Laser Pulse Interaction," **J. Phys. D: Appl. Phys.** Vol. 39, (2006) pp. 590-595
- *Boyce, Reu & Robino, The Constitutive Behavior of Laser Welds in 304L Stainless Steel Determined by Digital Image Correlation, **Met Trans A,** Vol. 37A (2006) pp. 2481-2492*
- J. Norris, M. Perricone, R. Roach, K. Faraone & C. Ellison, **SAND2007-1051** : Evaluation of Weld Porosity in Laser Beam Seam Welds: Optimizing Continuous Wave and Square Wave Modulated Processes, February 2007



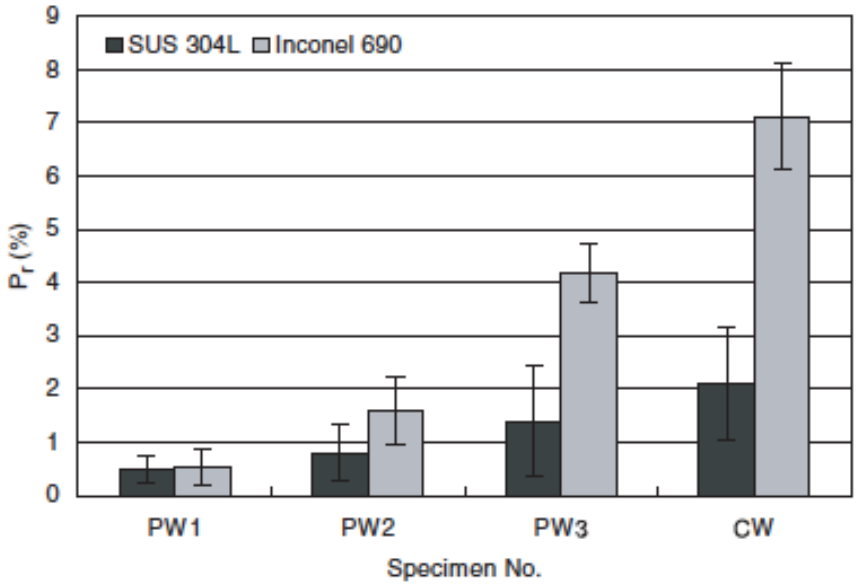
Porosity & Mechanical Response

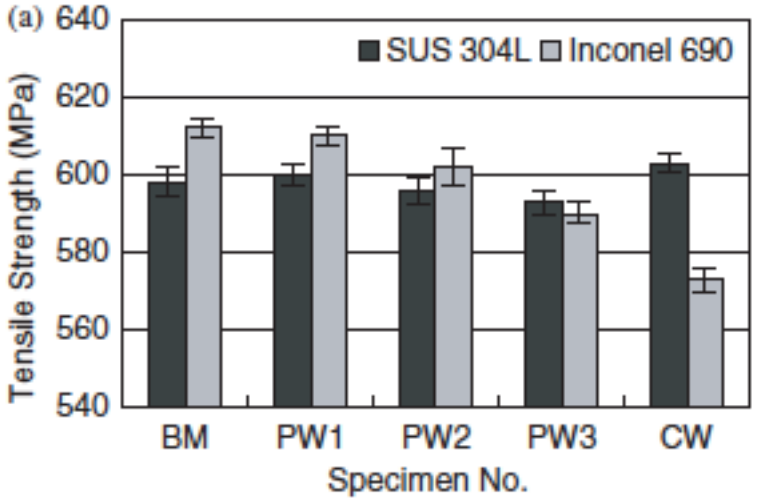
Mechanical Testing

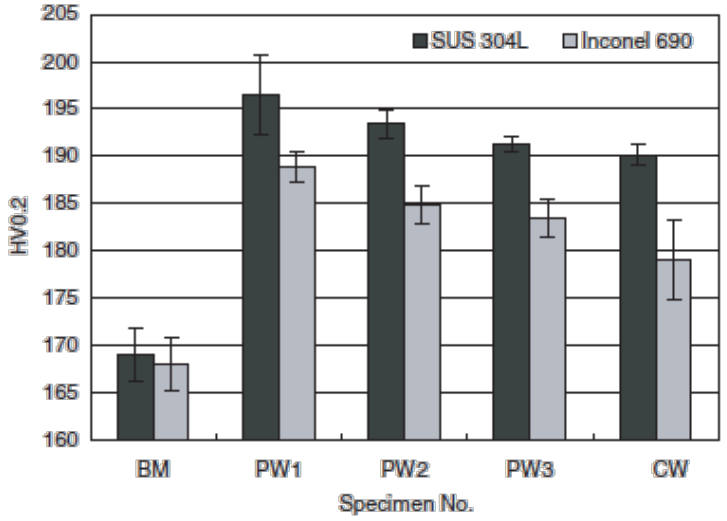
INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. **38** (2005) 722–728 — doi:10.1088/0022-3727/38/5/009

Porosity reduction in Nd–YAG laser welding of stainless steel and inconel alloy by using a pulsed wave

T Y Kuo[1] and S L Jeng[2]





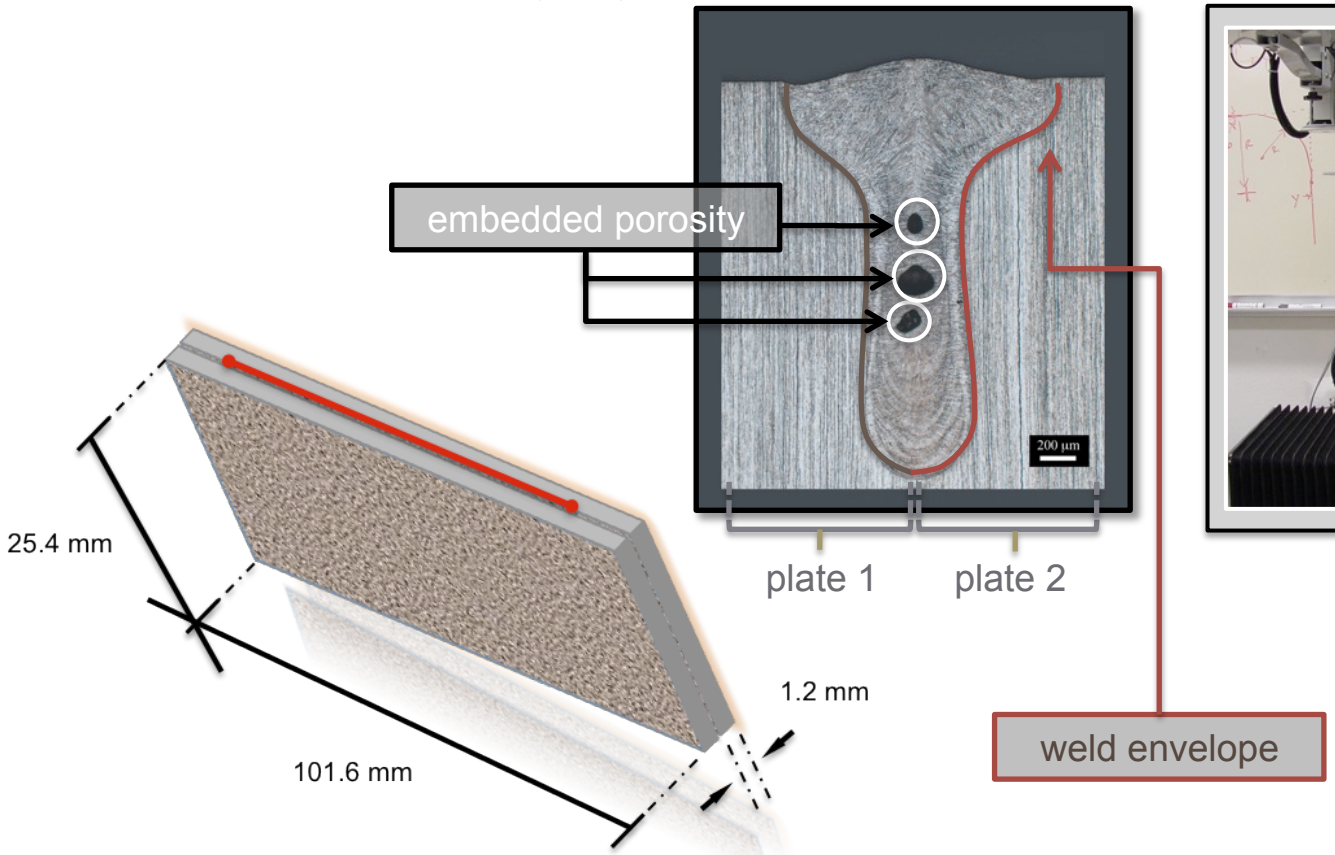


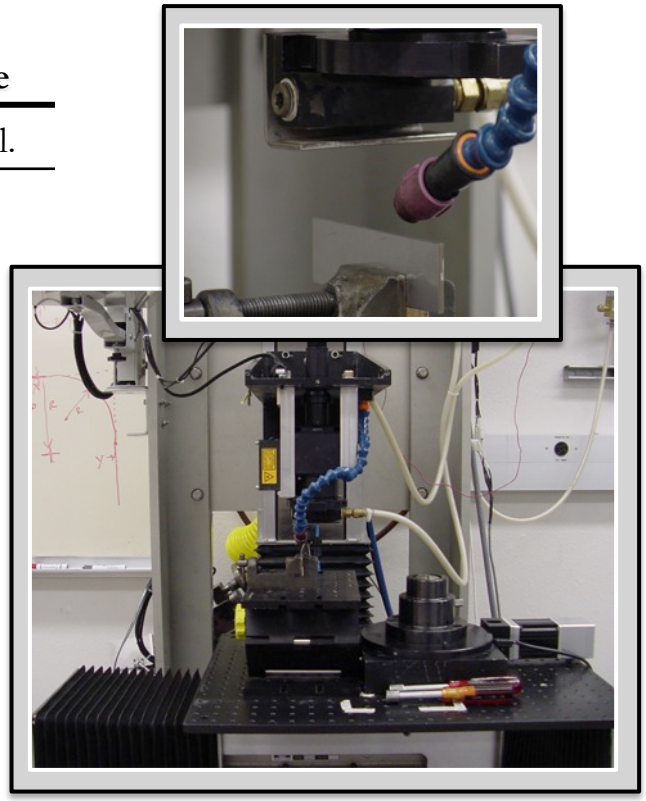
Kuo and Jeng, Porosity Reduction in Nd-YAG Laser Welding of Stainless Steel and Inconel Alloy by Using a Pulsed Wave, ***J. Phys. D: Appl. Phys.,*** *Vol. 38 (2005) pp. 722-728*

Laser Welding

C	Cr	Cu	Mn	Mo	Ni	N	P	S	Si	Fe
0.03	18.09	0.2	1.73	0.16	8.57	0.06	0.024	0.001	0.36	bal.

304L Stainless Steel (wt%)





ROFIN SINAR Nd:YAG
- 3-axis stage
- Constant speed
- Ar shielding gas
- CW or PW

μ-Computed Tomography

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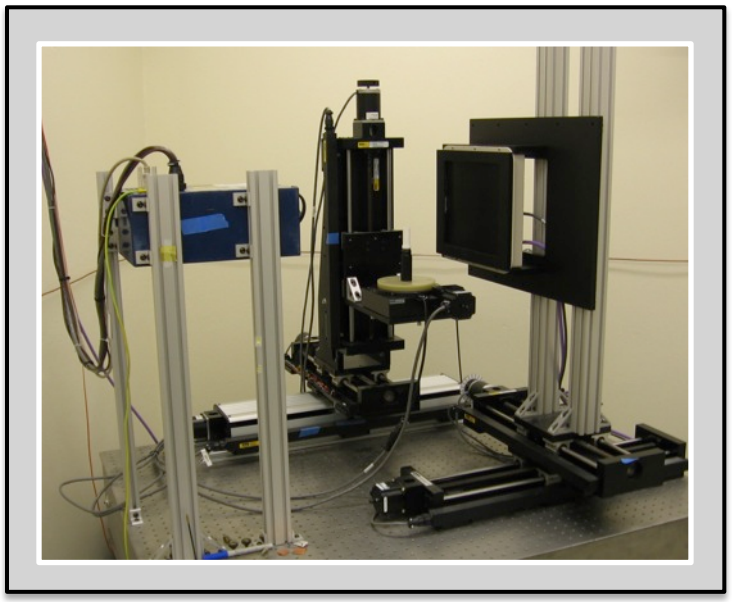
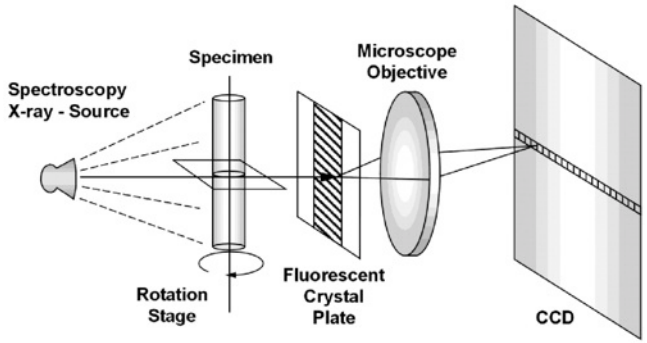
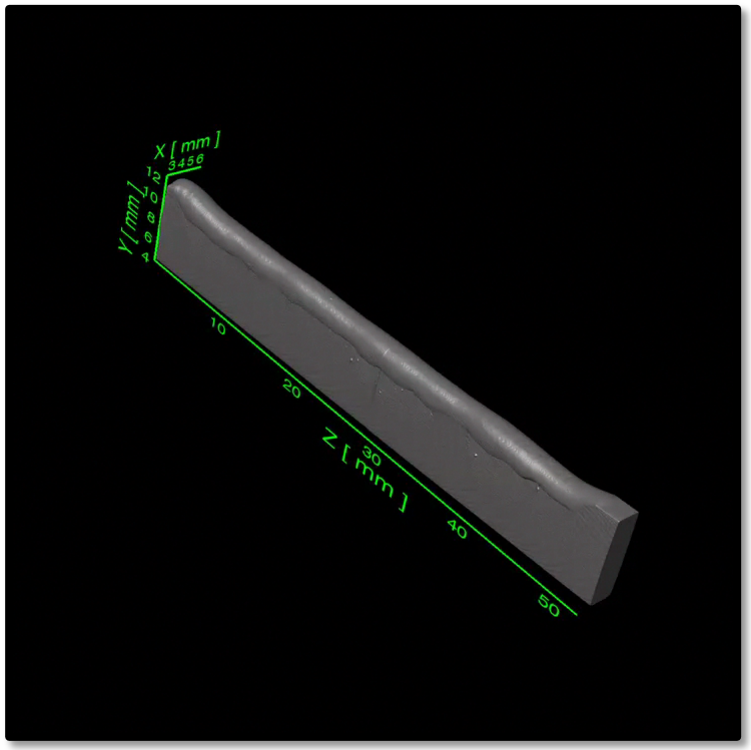


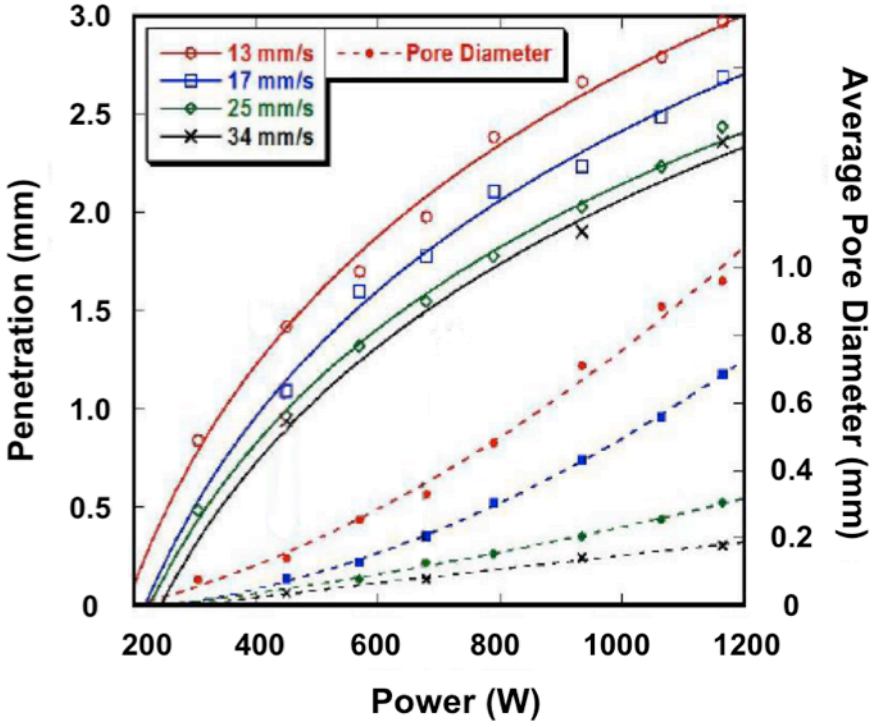


M.D. Bentley, et al. *Am. J. Physiol. Regul. Integr. Comp. Physiol.*,vol. 282, no. 5 (2002)

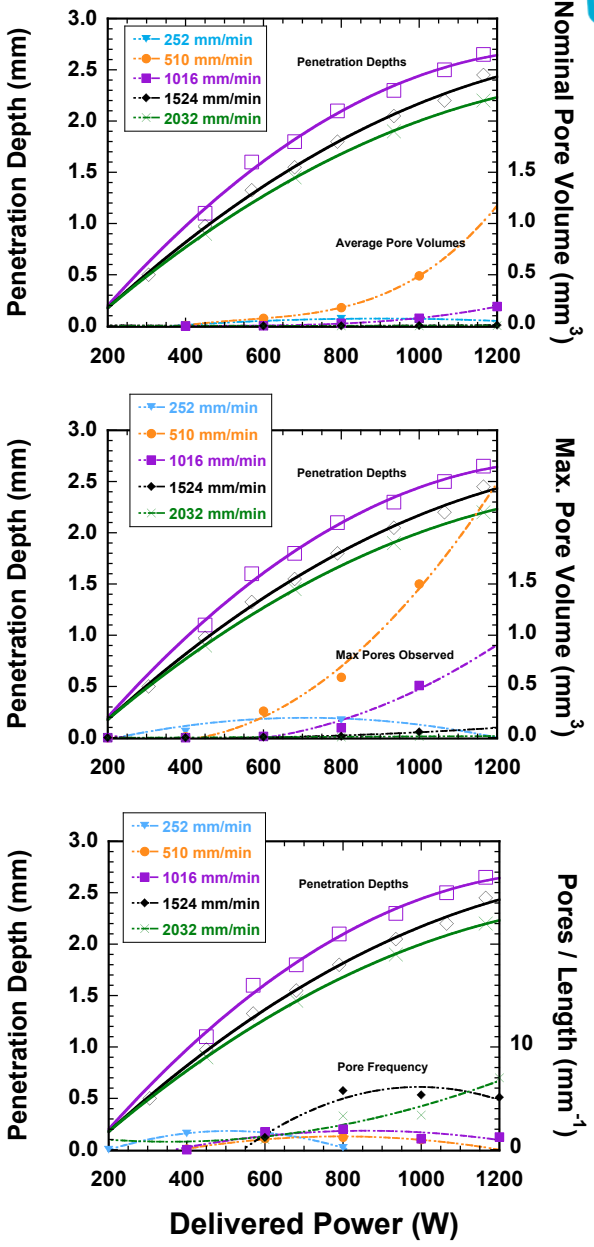


- Rotation occurs counter clock-wise in front of a fluorescent cesium iodide plate
- Magnification lenses determine effective pixel size
- Energy is set to 130KV and 250uA yielding a spot size on the order of 27 um

Process - Parameter Map



J. Norris, et al. Evaluation of Weld Porosity in Laser Beam Seam Welds: Optimizing Continuous Wave and Square Wave Modulated Processes. ***SANDIA REPORT*** *SAND2007-1051 (2007)*



Porosity Trends

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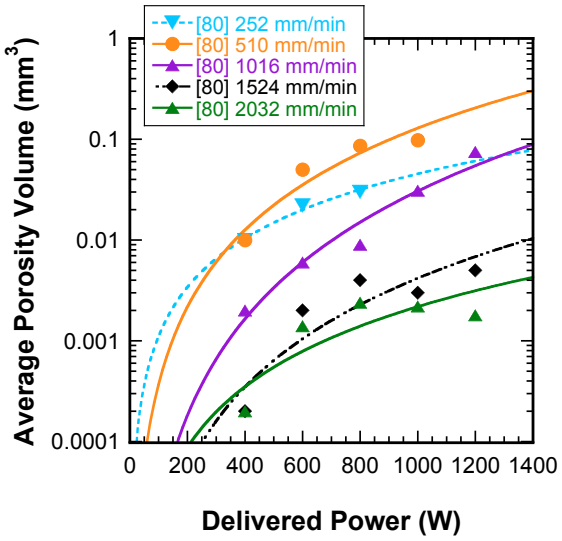
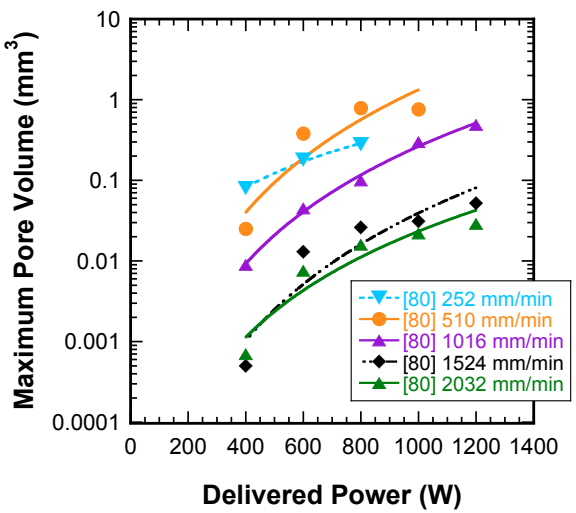
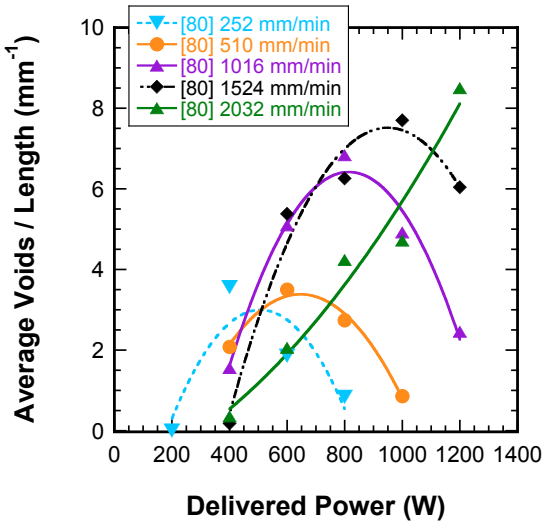
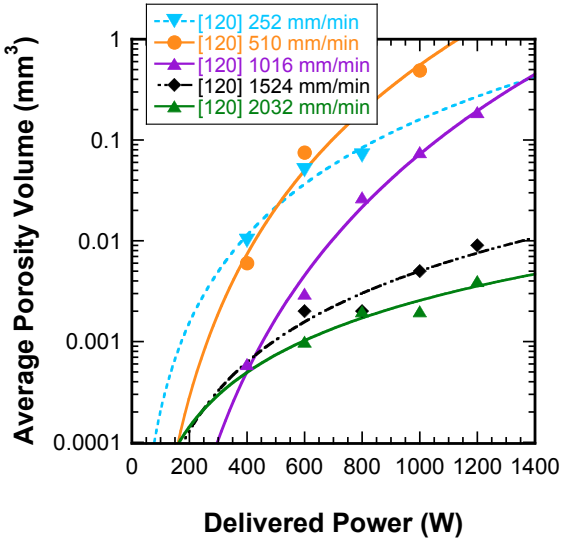
80 mm lens

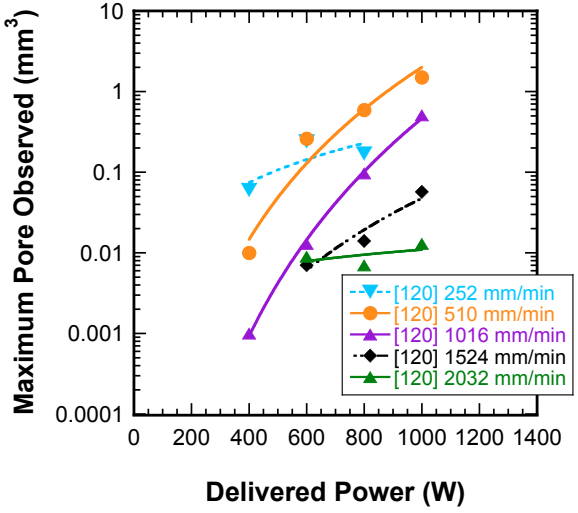


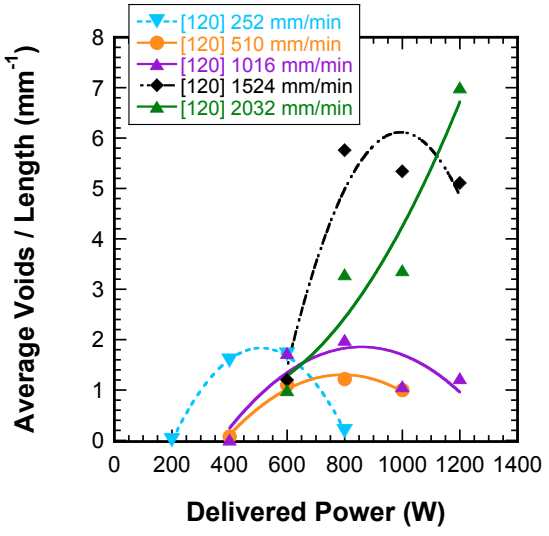




120 mm lens







Porosity Distributions

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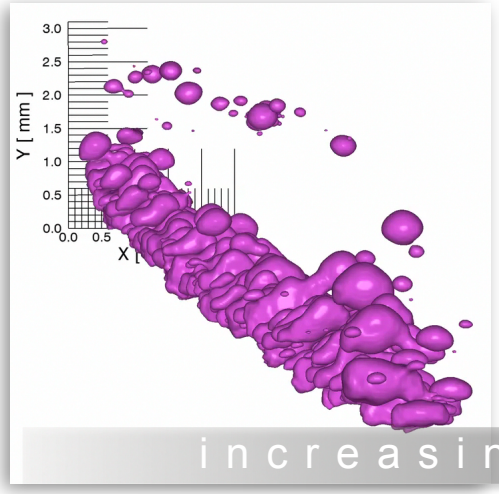
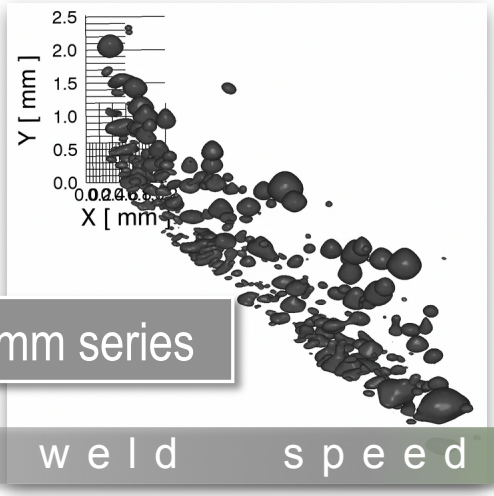
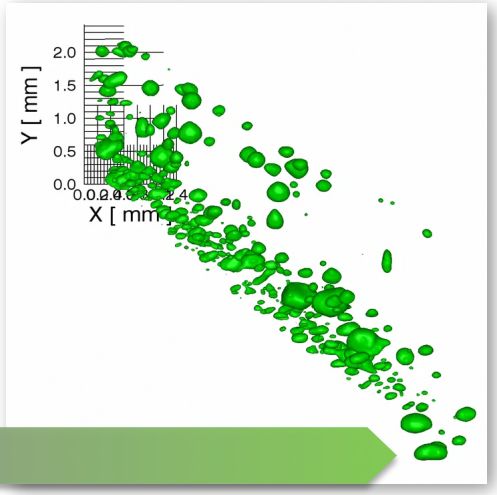
1016 mm/min



1524 mm/min

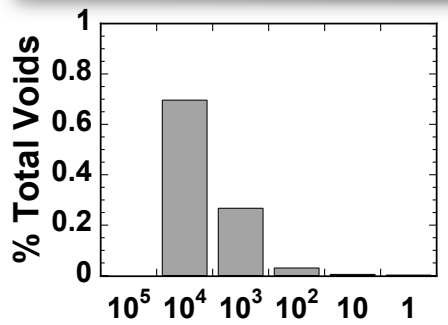


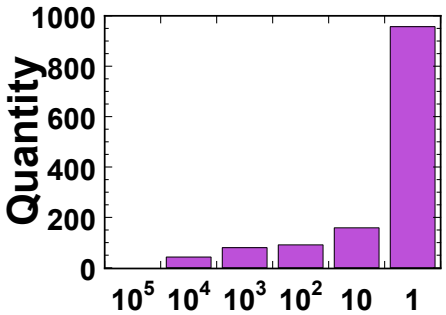
2032 mm/min

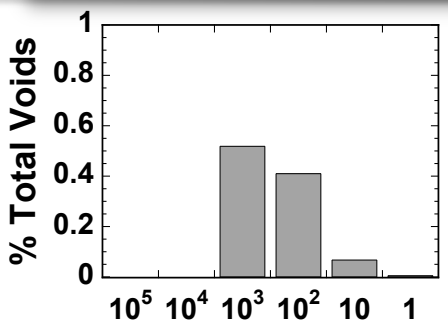


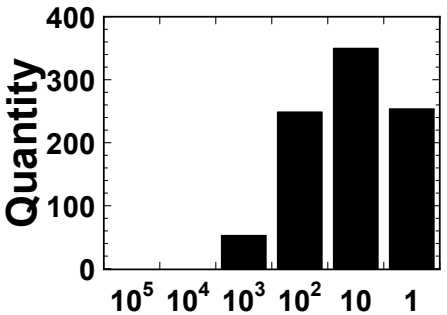
80 mm series

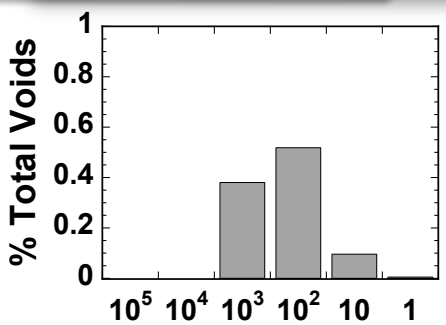
increasing weld speed

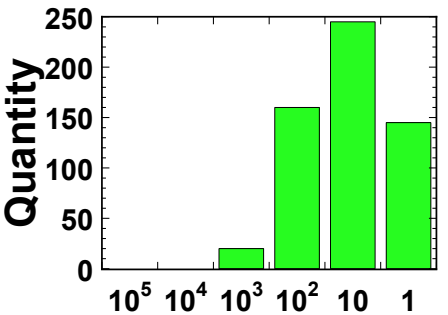




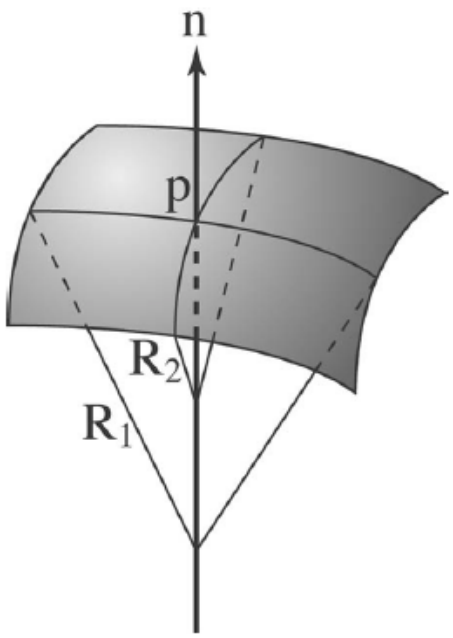








Interfacial Measures



$$H = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$ Mean Curvature

ISD

$$K = \left(\frac{1}{R_1 R_2}\right)$$ Gaussian Curvature

$$\kappa_1 = H - \sqrt{H^2 - K}$$

$$\kappa_2 = H + \sqrt{H^2 - K}$$

Two Principle Curvatures

IND

Kammer & Voorhees, The Morphological Evolution of Dendritic Microstructures During Coarsening, ***Acta Mater.,*** *54, (2006) pp. 1549-1558*
Kammer & Voorhees, Analysis of Complex Microstructures: Serial Sectioning and Phase-Field Simulations, ***MRS Bull.,*** *33, (2008) pp. 603-610*

Mendoza, Alkemper & Voorhees, ***Met Trans A,***
Vol. 34A (2003) pp. 481-489

Interfacial Measures

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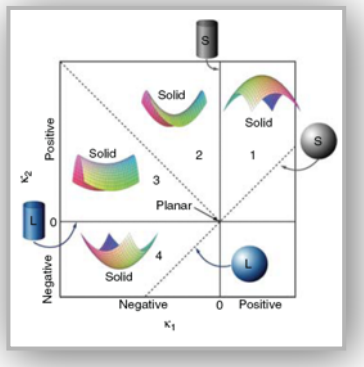
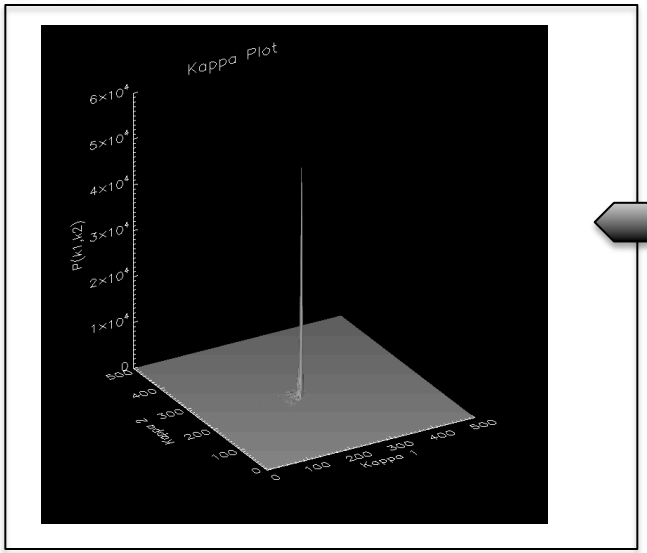
ISD



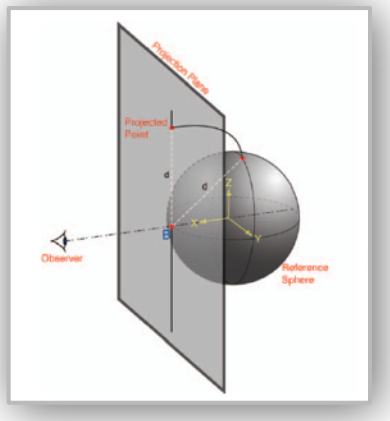
Mendoza, Alkemper & Voorhees, ***Met Trans A,*** *Vol. 34A (2003) pp. 481-489*



$P(\kappa_1, \kappa_2)$

$P(n)$

IND



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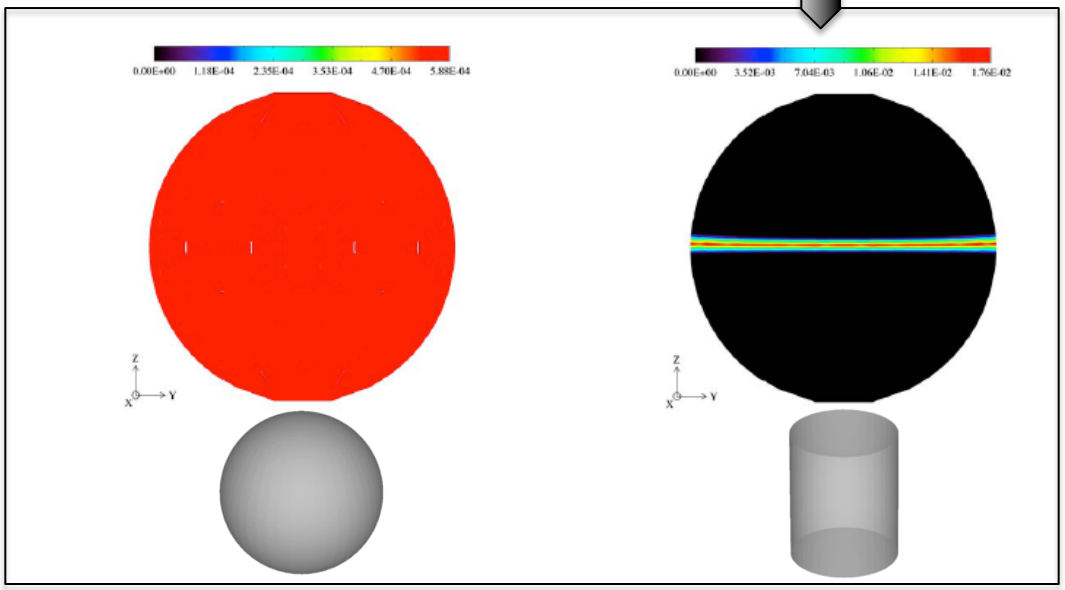

Interfacial Shape Distribution

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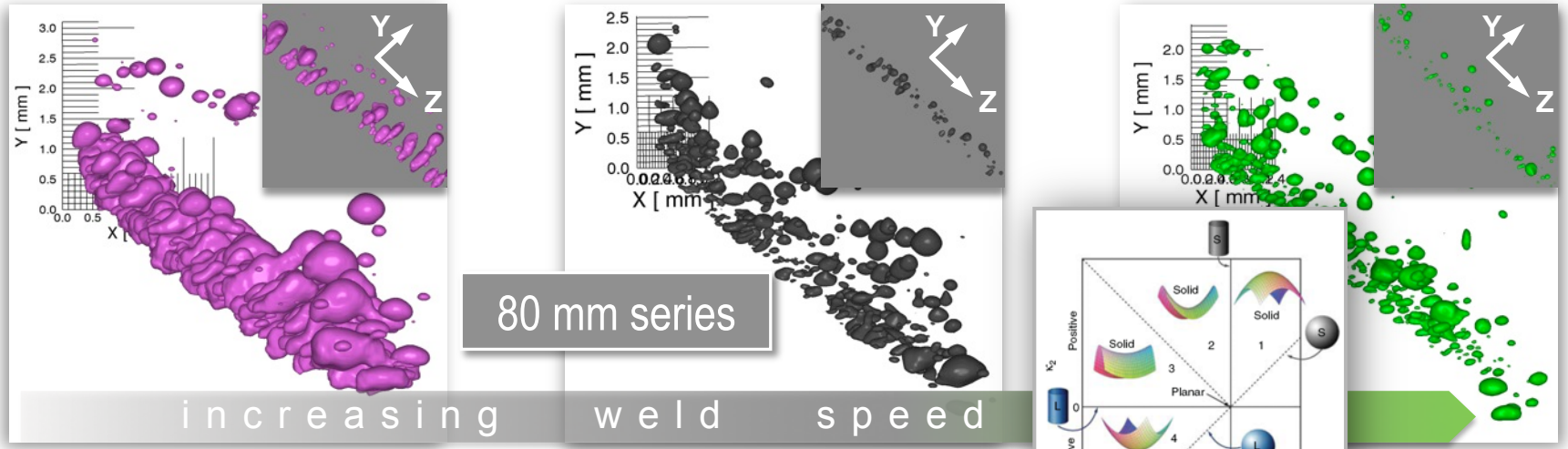
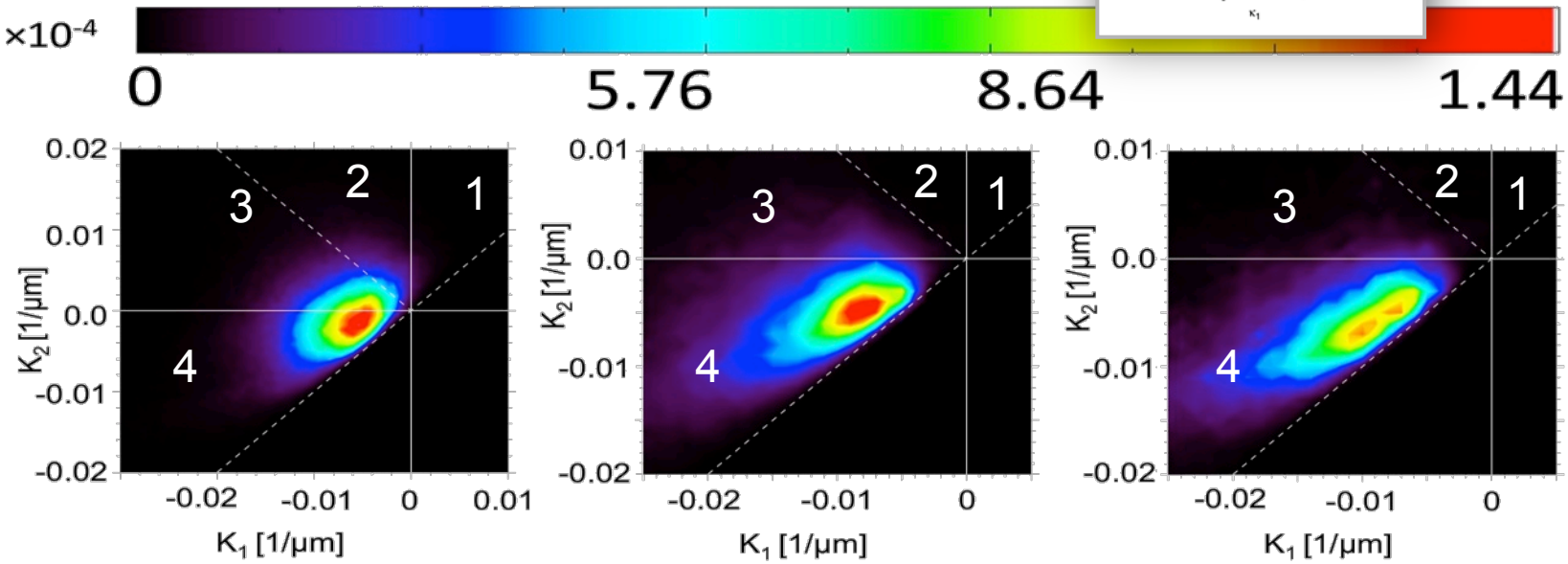
1016 mm/min **1524 mm/min** **2032 mm/min**

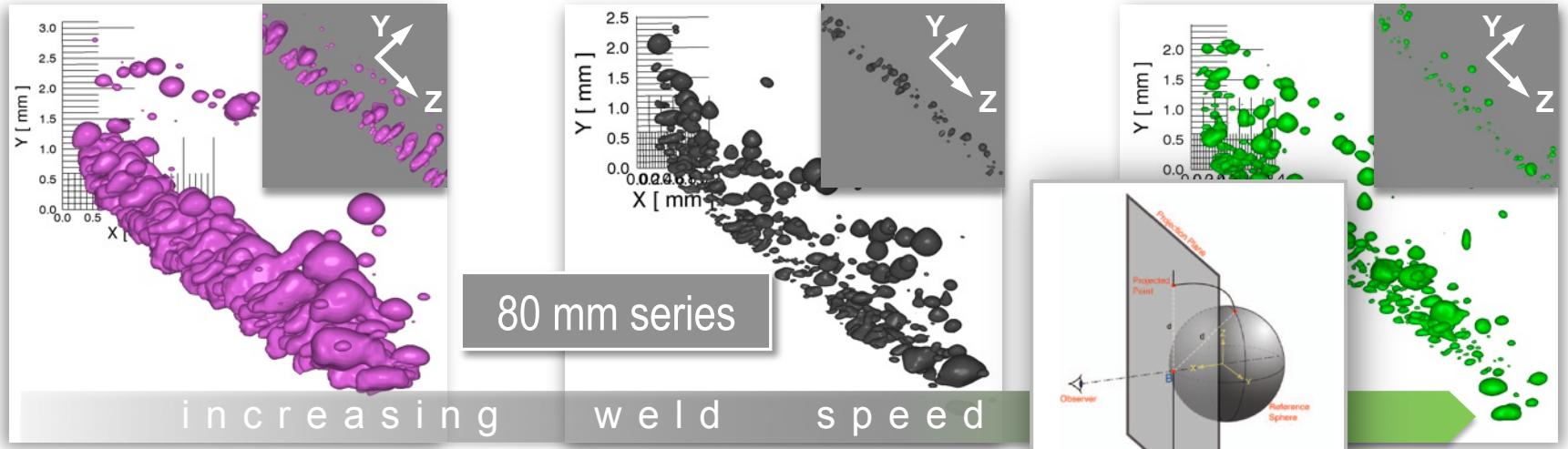


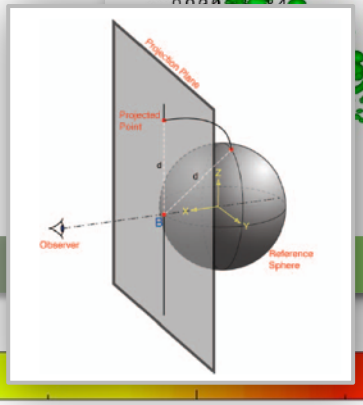


Interfacial Normal Distribution

Sandia National Laboratories

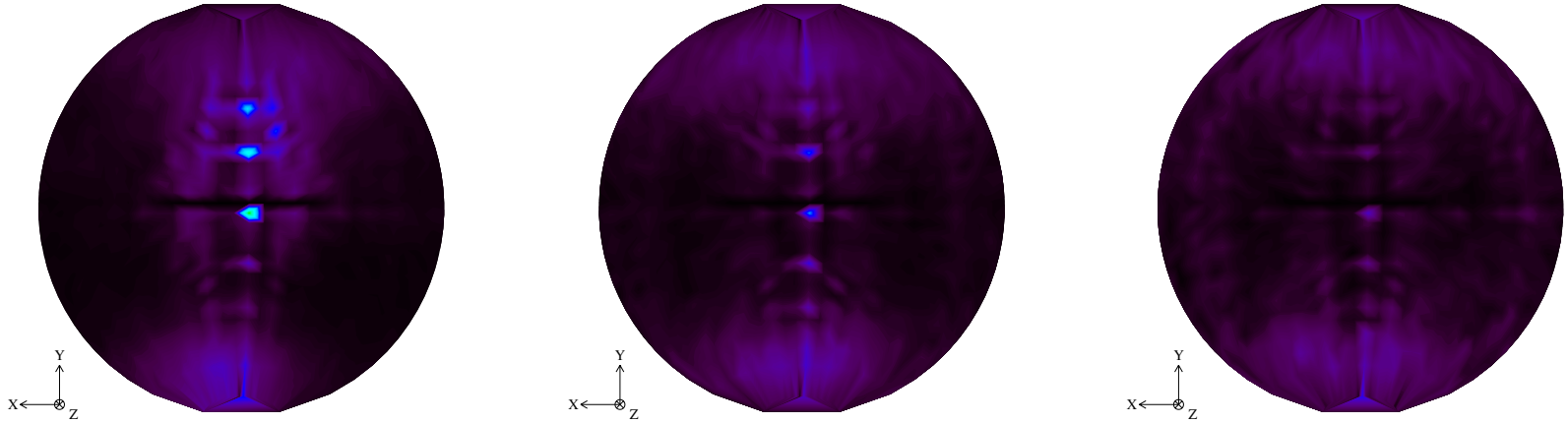
1016 mm/min **1524 mm/min** **2032 mm/min**





$\times 10^{-2}$

0 4.80 7.20 1.20



Shape Anisotropy

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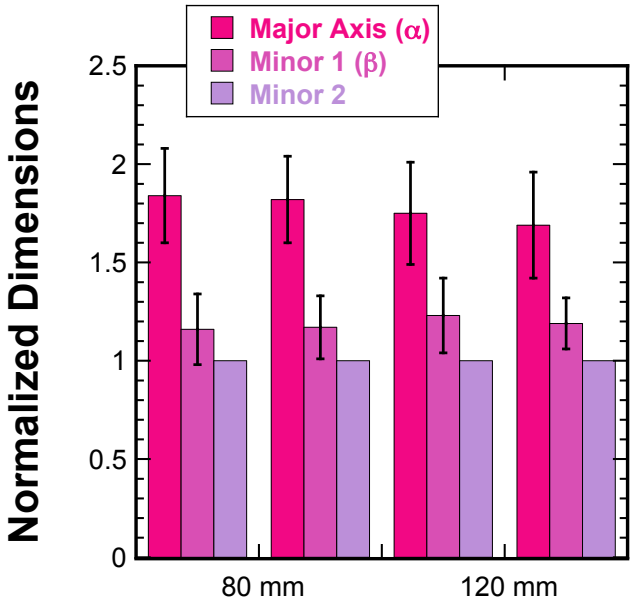
1016 mm/min

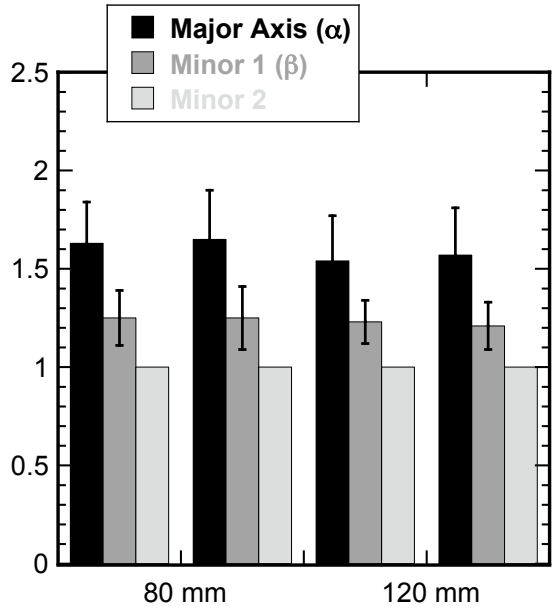


1016 mm/min

α = 1.69 – 1.85

β = 1.19 – 1.23

1524 mm/min

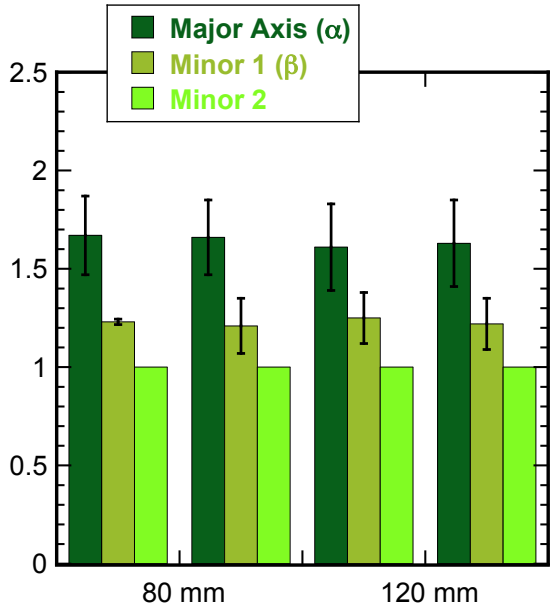


1524 mm/min

α = 1.54 – 1.65

β = 1.21 – 1.25

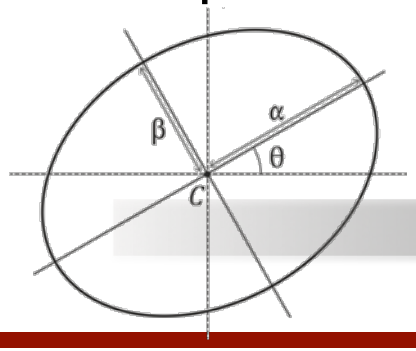
2032 mm/min



2032 mm/min

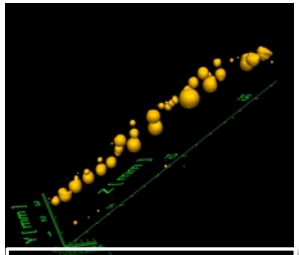
α = 1.61 – 1.67

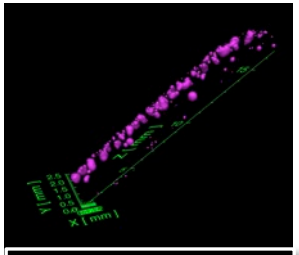
β = 1.21 – 1.25



increasing weld speed

INCREASING POWER DELIVERED


80-1000-20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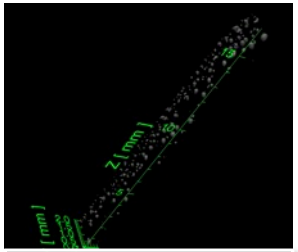
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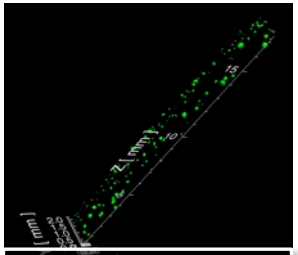
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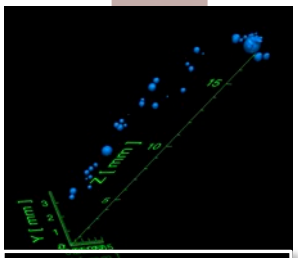
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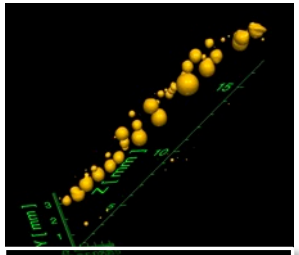
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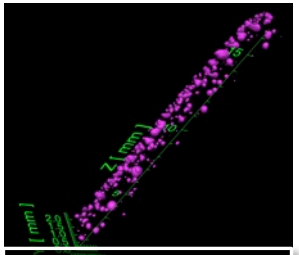
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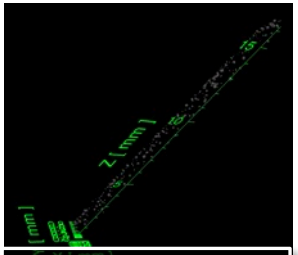
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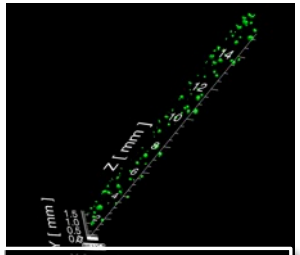
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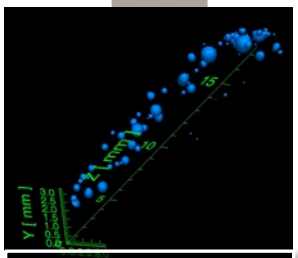
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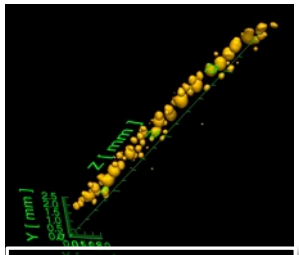
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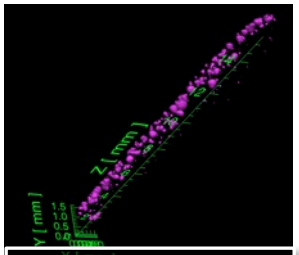
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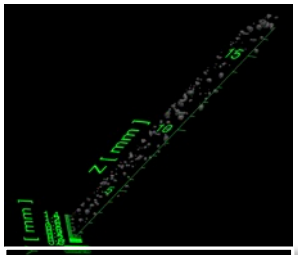
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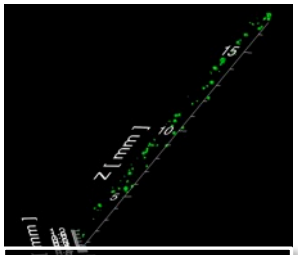
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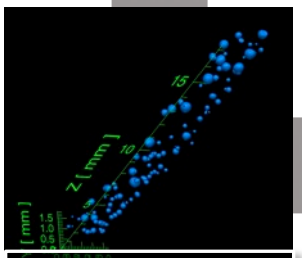
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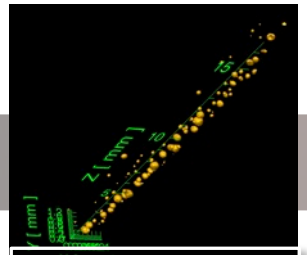
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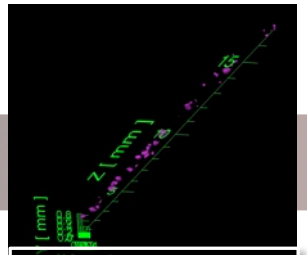
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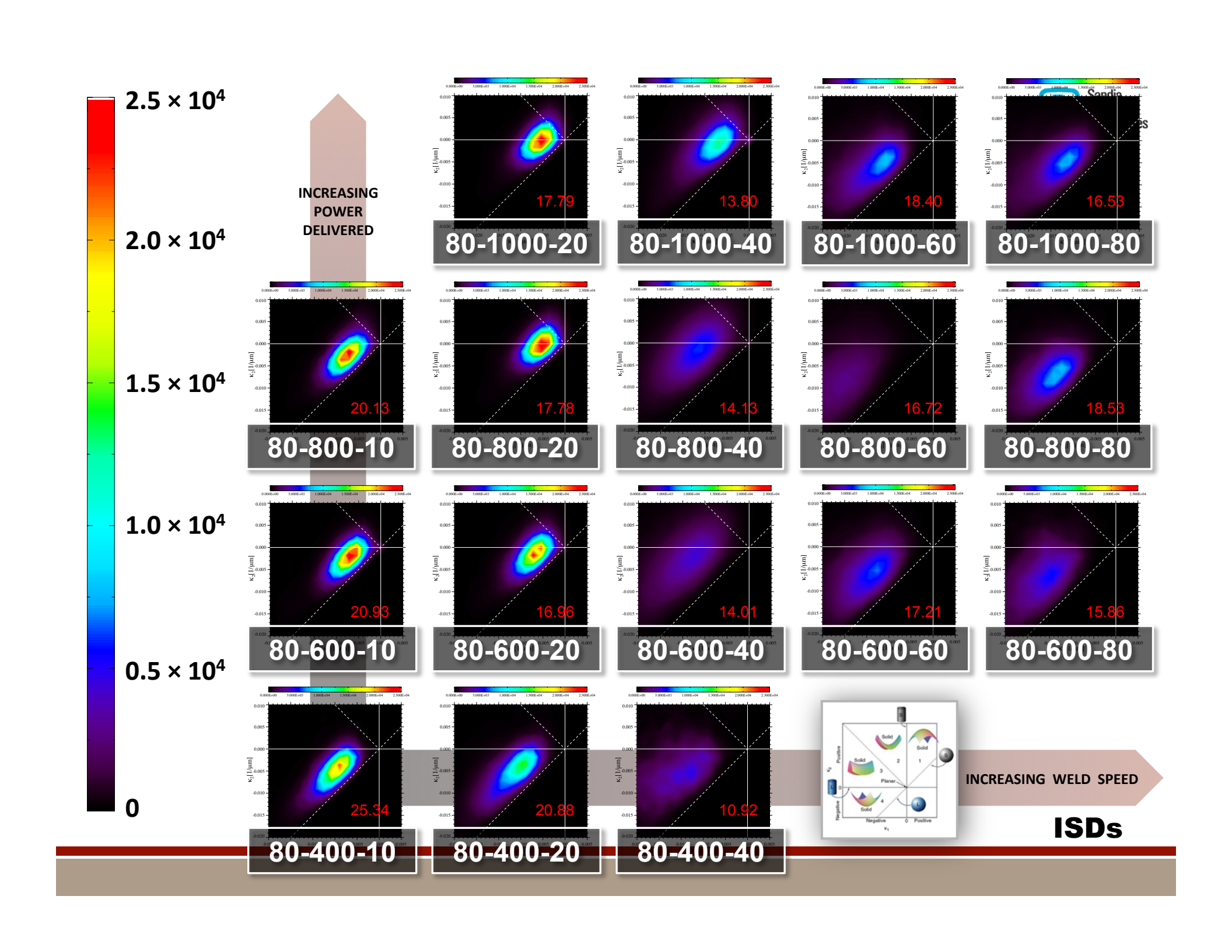
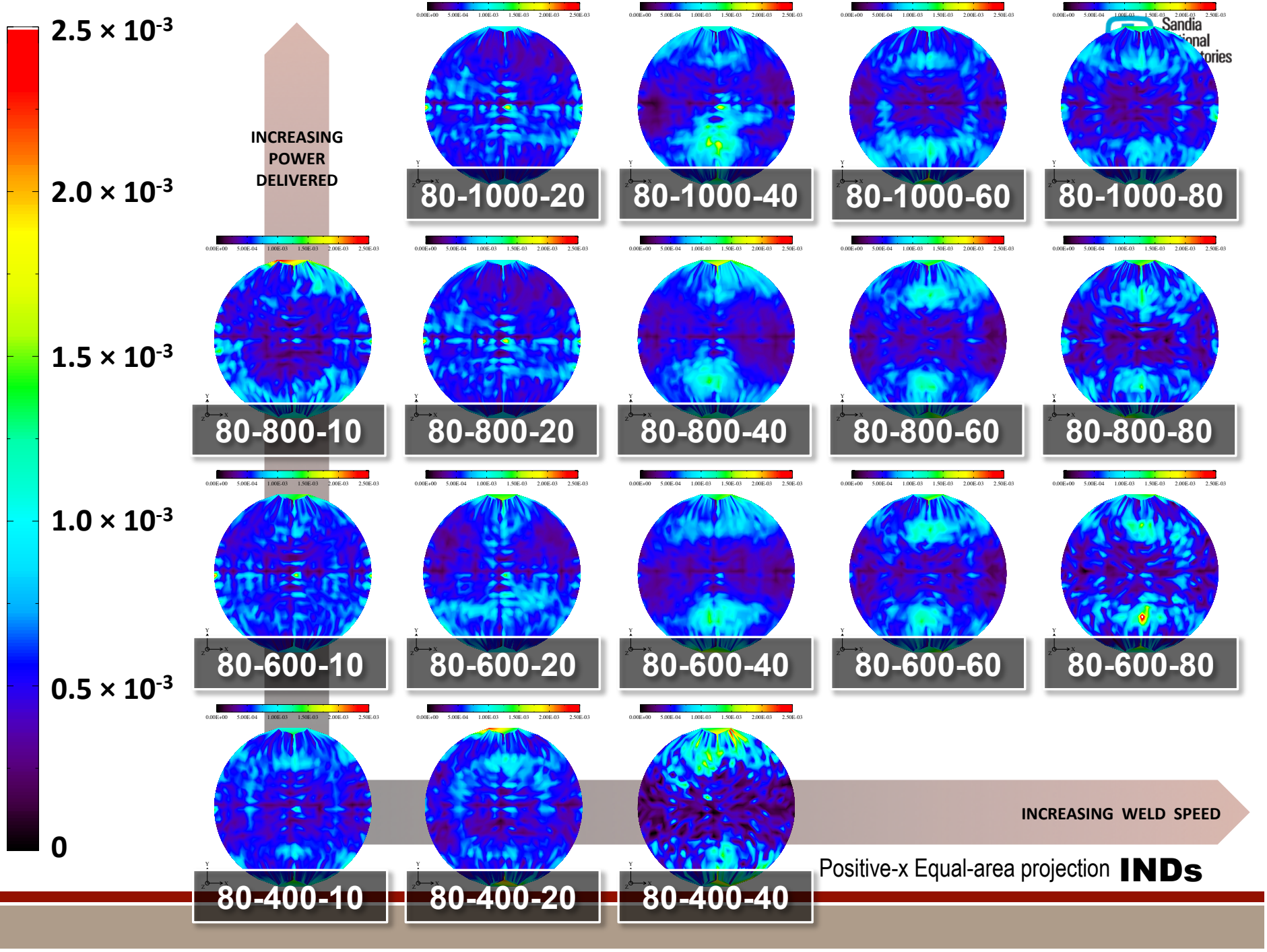
INCREASING WELD SPEED

3D Reconstructions


2.5 × 10^4
2.0 × 10^4
1.5 × 10^4
1.0 × 10^4
0.5 × 10^4
0
INCREASING POWER DELIVERED
17.79
80-1000-20
13.80
80-1000-40
18.40
80-1000-60
16.53
80-1000-80
20.13
80-800-10
17.78
80-800-20
14.13
80-800-40
16.72
80-800-60
18.53
80-800-80
20.93
80-600-10
16.96
80-600-20
14.01
80-600-40
17.21
80-600-60
15.86
80-600-80
25.34
80-400-10
20.88
80-400-20
10.92
80-400-40
Solid
Solid
Solid
Planar
Solid
Positive
Negative
Negative
Positive
INCREASING WELD SPEED
ISDs


2.5 × 10-3
2.0 × 10-3
1.5 × 10-3
1.0 × 10-3
0.5 × 10-3
0
INCREASING POWER DELIVERED
80-1000-20
80-1000-40
80-1000-60
80-1000-80
80-800-10
80-800-20
80-800-40
80-800-60
80-800-80
80-600-10
80-600-20
80-600-40
80-600-60
80-600-80
80-400-10
80-400-20
80-400-40
INCREASING WELD SPEED
Positive-x Equal-area projection INDs

Summary

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- Across all welds examined, the most frequently occurring void sizes constitute less than 10% of the total porosity found in each weld
- Pore size increases with decreases in speed or increases in power delivered.
- Pore frequency displays an inverse parabolic relationship with increases in speed or power delivered.
- Like frequency, ISDs show the distribution of porosity shapes trend toward a high population of specific curvature pairs at low welding speeds, become more distributed in shape with increases in speed and then trend back toward a higher population of specific curvature pairs at even higher speeds.
- INDs demonstrate that variation in anisotropy of pore orientation is similar regardless of power used.
- INDs also shows directional anisotropy of pores reach a maximum at 40”/min with anisotropy decreasing with increases or decreases in welding speed.

Questions

Sandia National Laboratories

J. Madison, L. K. Aagesen, *"Quantitative Characterization of Porosity in Laser Welds of Stainless Steel"* **SCRIPTA MATERIALIA (2012),** vol. 67, pp. 783-786

J. Madison, L. K. Aagesen, Porosity in Millimeter-Scale Welds of Stainless Steel: Three-Dimensional Characterization SANDIA REPORT, **SAND2012-4474**, (2012) *issued by* Sandia National Laboratories, operated for the U.S. DoE by Sandia Corporation