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QUANTITATIVE CHARACTERIZATION OF LASER WELDS IN 304L STAINLESS STEEL

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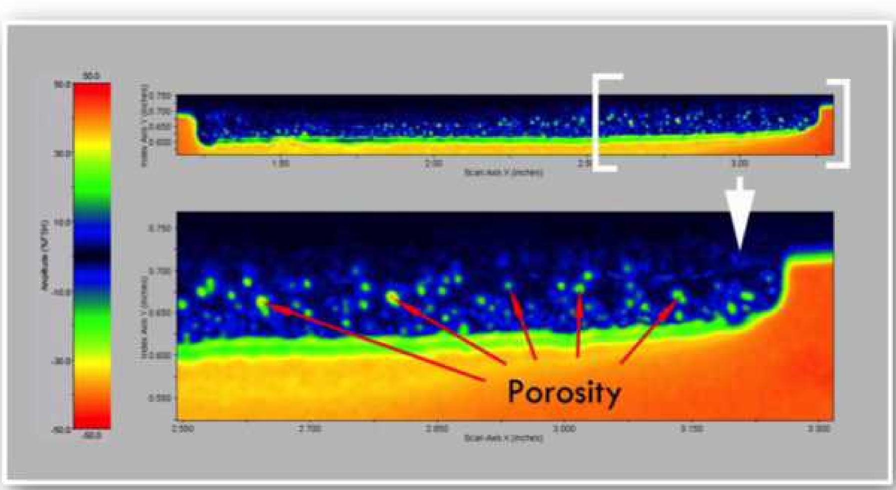
ABSTRACT

Sandia National Laboratories is responsible for the quality and well-being of welds and brazes throughout the DOE & NNSA complex with applications ranging from nuclear weapons and nuclear energy to waste storage and renewable energy technologies. As such, the development of advanced qualitative and quantitative evaluations in addition to three-dimensional metrics for the assessment and characterization of weld microstructures is both useful and of extreme value. Here, high rate solidification events such as laser welds are examined for exploration of the linkage between processing and resultant microstructure. This is done by means of three-dimensional reconstruction and characterization among a matrix of weld joints. The presence, variability and distribution of micro-structural features such as porosity are examined and will later be used for determination of effects on joint stability, integrity and spatial composition. Presently, the goal is to begin by relating such variability to processing parameters such as weld speed, weld power and modulation.

CHARACTERIZATION – Ultrasonic Scan

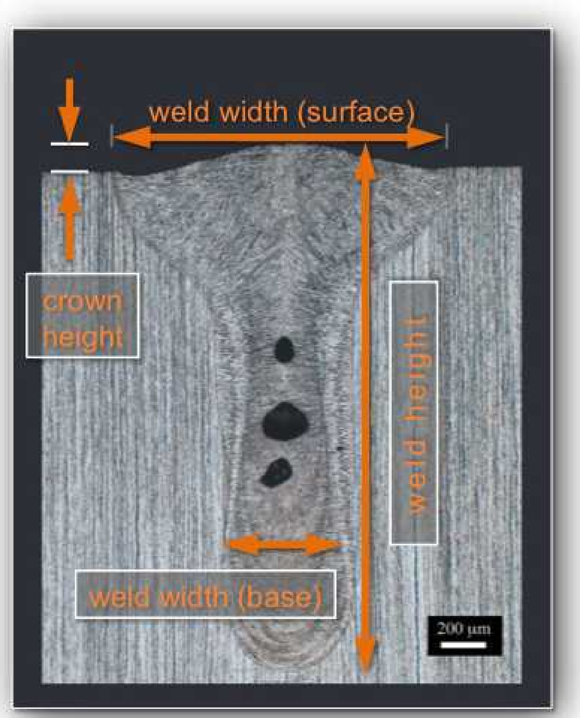


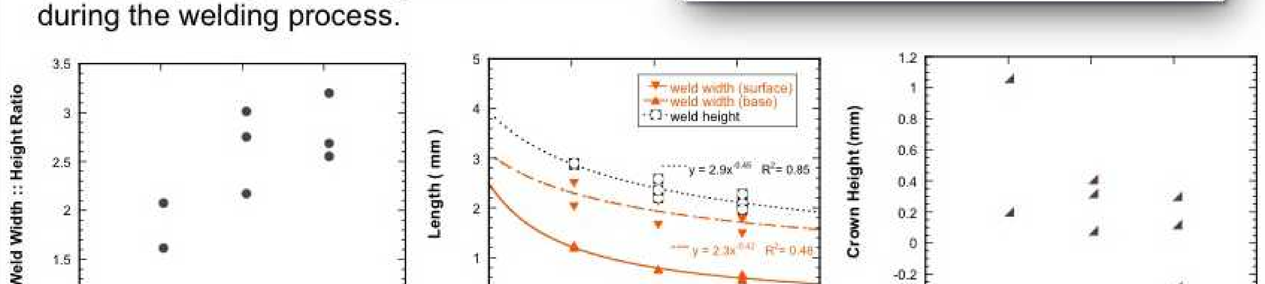
Full Wave Form Capture (FWFC) Ultrasonic scans of the welded region allow for reflected sound signals to be converted into a 2-dimensional image by plotting reflected signal amplitude at a given time over a volume of interest.

Sound waves travel uninterrupted across well bonded interfaces but are reflected and produce high amplitude signals when interacting with poorly bonded or porous regions. Conversely, surface defects ultimately deflect the transmitted sound waves before passing through the sample resulting in weakened or absent reflected signals in the region of the defect. Intense surface curvatures of the sample can also produce similar deflections making this technique rather sensitive to the curvature and/or surface finish of the sample. Furthermore, this technique yields largely qualitative indications of internal volume characteristics as there is little ability to discern in-plane and through thickness porosity when multiple regions exist along the same line of sight.

CHARACTERIZATION – Metallography

Although inherently destructive, here, traditional metallography provides a straight-forward opportunity for visual inspection of weld microstructure not obtainable by imaging variations in phase or density. Multiple sections from each weld case were prepared and imaged to ascertain weld pool width, depth, void diameters and heat affected zone widths. Decreases in weld height as well as width at the surface and base correspond with increasing weld speed while the width to height ratio doubles over the range of welding speeds investigated. Furthermore the crown heights exhibit a trend toward decreasing height to the point of height decrease at the weld centerline suggesting an inflection point in resultant surface tension expelling or drawing molten material during the welding process.



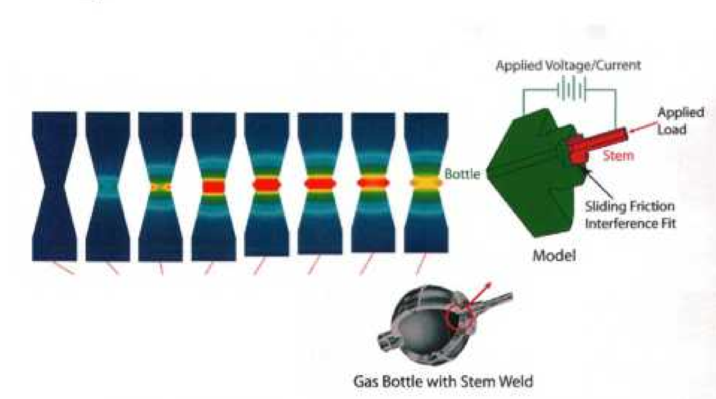


CONCLUSIONS

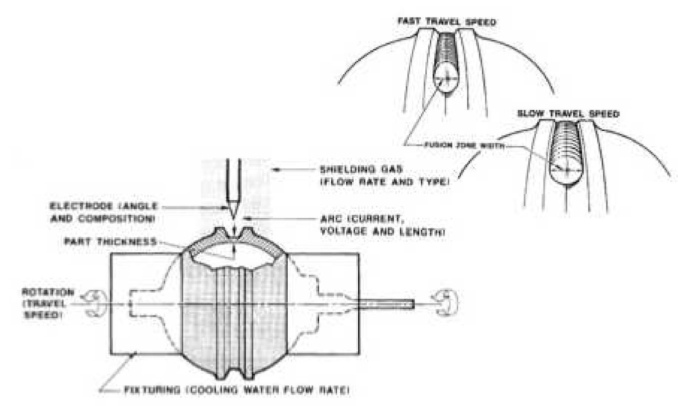
- Ultrasonic scans are useful in identifying bonding gaps, depths of penetration as well providing a qualitative estimate of the overall porosity content in a weld while traditional metallography provides useful information about the size, shape and relative dimensions of the weld that can be directly correlated to the processing parameters.
- Over the range of parameters examined, increases in weld speed result in an increase in the weld width :: weld depth ratio but a decrease in the individual widths, heights and resultant crown heights.
- Micro-computed tomography (µ-CT) provides a non-destructive and relatively rapid means to gain full three dimensional evaluations of weld porosity which can be evaluated both qualitatively and quantitatively with voxel resolution down to 27 µm^3.
- With increasing weld speed the amount of voids per length increases by a factor of 4 while nominal void size decreases by 2 orders of magnitude over the same range.
- Across all welds examined, the most frequently occurring void sizes do not constitute even 10% of the total voided space suggesting even numerous individual metallographic sections may underestimate the total porosity content and/or the total void distribution.
- At increasing weld speeds, characteristic curvatures of the porosity present transition from flat–plate ellipsoids to smaller more-rounded spheres with fewer ellipsoids present.

BACKGROUND

A large number of components found among the DOE & NNSA complex utilize welds, many of which occur partially or entirely in steels. As such the process :: quality relation has been explored widely through collaboration and principle investigations at Sandia National Laboratories over the past 25 years.[1,2,3] These studies have resulted in many practical engineering correlations as well as improved radiation and heat transfer models in various joining geometries with particular emphasis on welds.[4,5] These efforts have also improved material response models based on multiple weld parameters as well.[6] Many of these investigations however, have focused primarily on macro-scale studies beyond the level of the microstructure and have been largely phenomenological and process-driven in scope.[7,8]

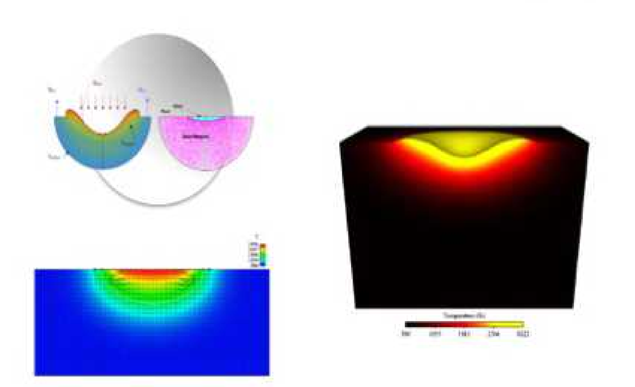


W. Winters, A. Brown, D. Bammann, J. Foulk III, A. Ortega, **SAND2005-3000** : Progress Report for the ASCI AD Resistance Weld Process Modeling Project AD2003-15, May 2005



A. Bentley, **SAND2002-4014** : Feedback Control of Arc Welding Using Quantitative Feedback Theory, February 1991

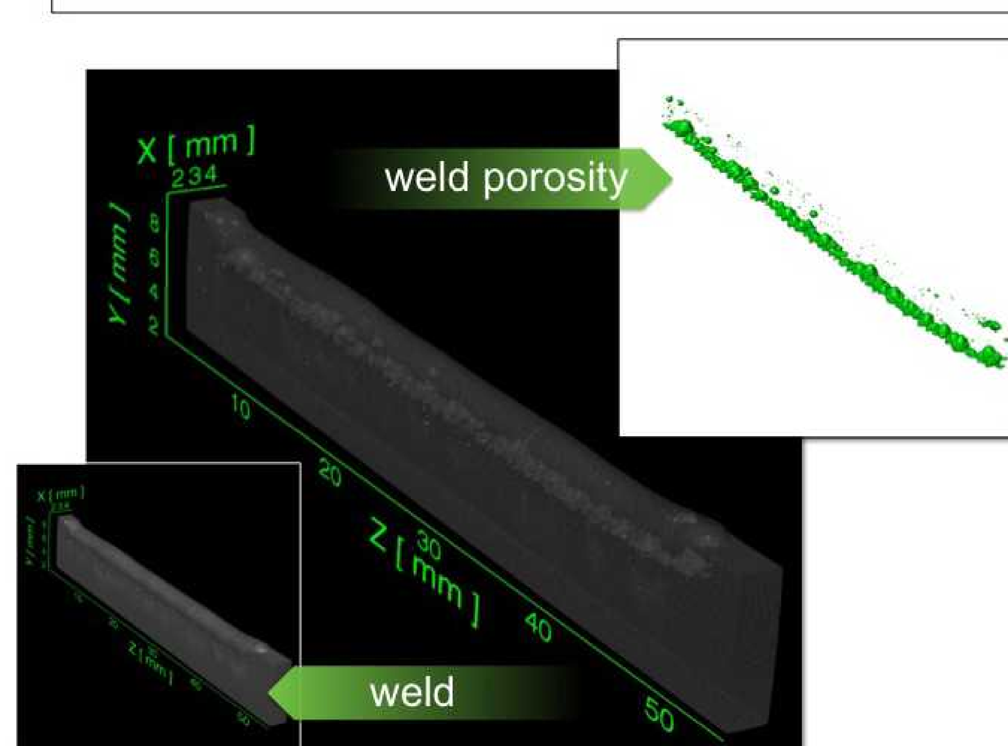
A basic phenomenological understanding of the process :: resultant microstructure is lacking, so in an effort to address this gap, this program investigates the effect of processing on microstructure and what specifically is the combined role of high rate solidification on the resulting microstructure on the weld and distribution of features such as porosity.

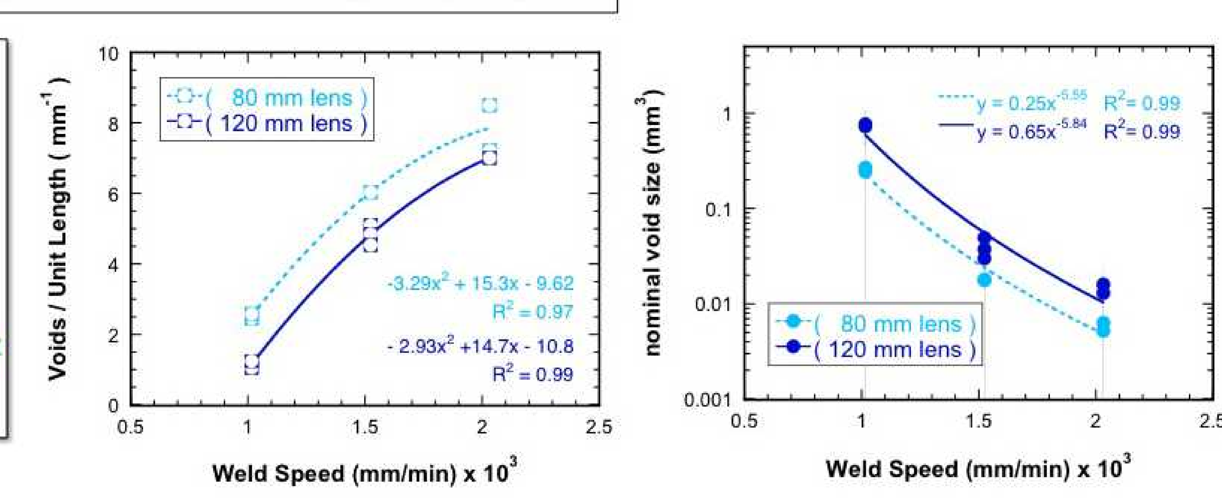


P. Notz, D. Noble, M. Martinez, A. Kraynik, **SAND2007-5870** : Use of Aria to Simulate Laser Weld Pool Dynamics for Neutron Generator Production-12, September 2007

1. A. Bentley, I. Horowitz, Y. Chait, J. Rodrigues, **SAND94-0795** : Control of Resistance Plug Welding Using Quantitative Feedback Theory, December 1996
2. J. Jellison, M. Cieslak, *Laser Materials Processing at Sandia National Laboratories*, presented at Applications of Lasers and Electro-Optics, Orlando FL, October, 17-20, 1994
3. M. Cieslak, A. Ritter, "Precipitate Formation in Austenitic Stainless Steel Welds," Scripta Met., Vol. 19, Issue 2, (1985) pp. 165-168
4. 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
5. C. Robino, A. Hall, J. Brooks, T. Headley, R. Roach, **SAND2002-4014** : Solidification Diagnostics for Joining and Microstructural Simulations, January 2003
6. 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
7. 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
8. P. Notz, D. Noble, M. Martinez, A. Kraynik, **SAND2007-5870** : Use of Aria to Simulate Laser Weld Pool Dynamics for Neutron Generator Production-12, September 2007

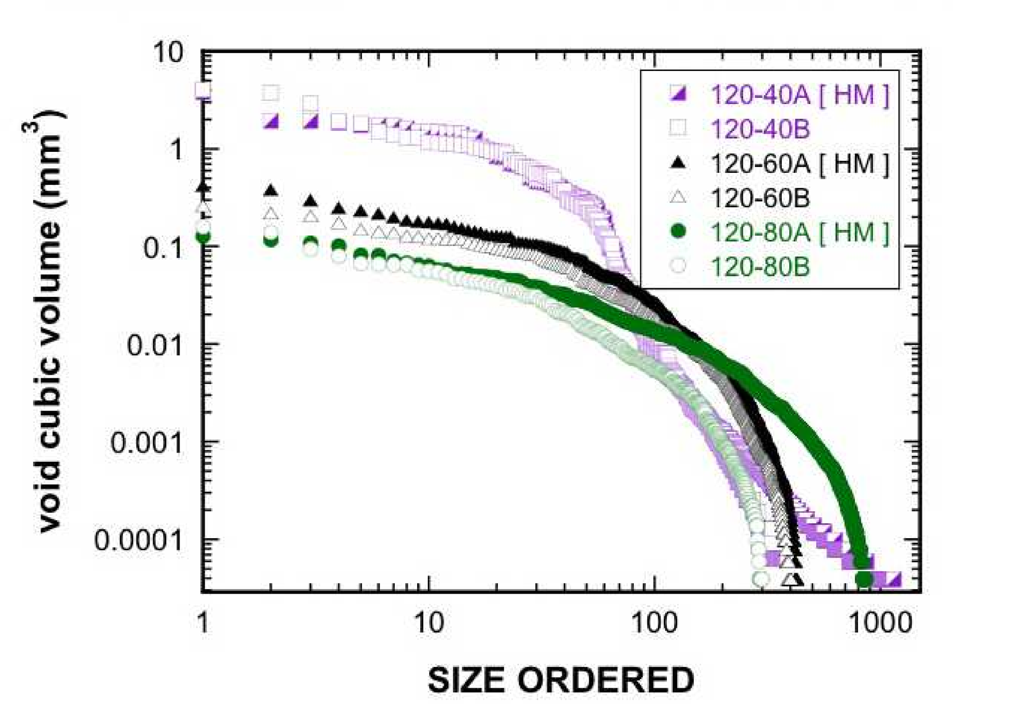
CHARACTERIZATION – µ Computed Tomography

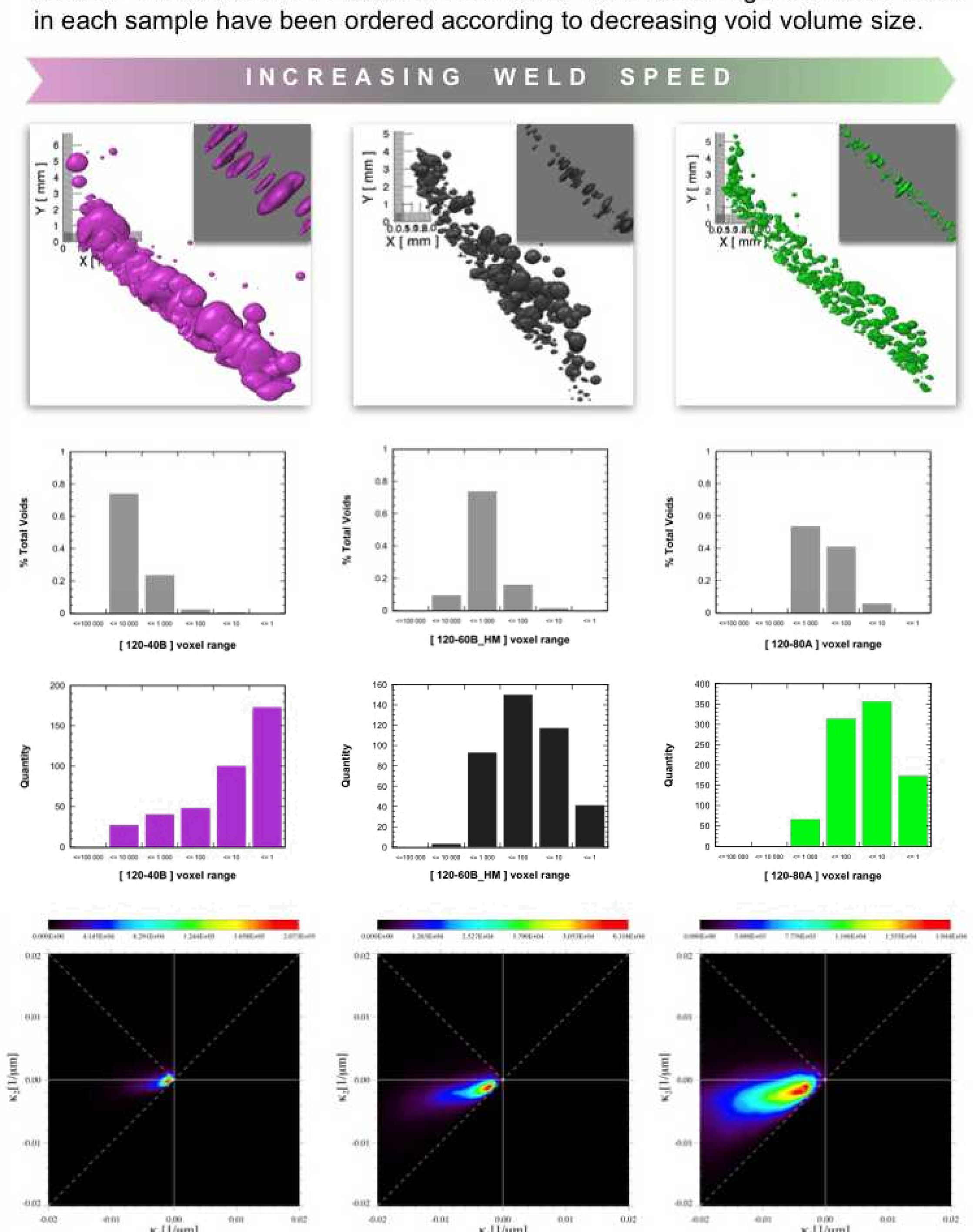




Using micro-computed tomography (µCT) full 3-dimensional reconstructions of weld porosity in a matrix of welds at varying speed and power were examined. This allows for the creation of process-parameter maps in which welding conditions can be related to the porosity present. At right are two such maps which show voids per unit length and nominal void size, both as functions of weld speed respectively.

Additionally, since the full spatial arrangement of voids in each sample is known, the size distributions of all voids can be traced as shown at right where all voids in each sample have been ordered according to decreasing void volume size.

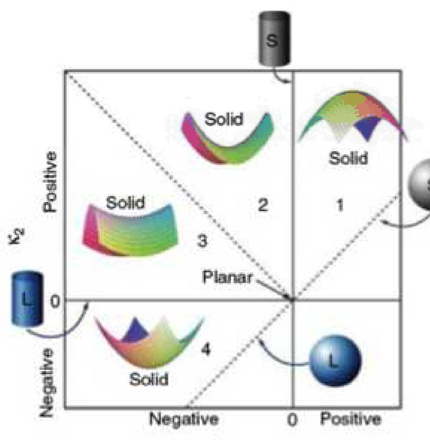




Histograms detailing the quantity of pores present in each weld with bins corresponding to voxel magnitude are shown at left. Voxel magnitude bins range from 1 to 1×10^5. Furthermore, the contribution of each voxel bin to the total porosity in each weld seam has been determined and is also shown.

For increasing weld speeds, average void size decreases as the presence of smaller voids increases. However across all cases, the top-most contributors to the total porosity are never the voxel magnitude bins of greatest population. In fact, voxel bins possessing 10 or fewer voxels/void contribute less than 7% to the total porosity in each case. As a result, the term "nominal void size" has been adopted, as shown in the plot above, such that the average void size for voxel bins contributing 90% or more to the total voided regions are reported.

Interfacial shape distributions (ISDs) for porosity were also performed to characterize the morphologies produced with increasing weld speed. Each map represents a population distribution of principle curvature pairings K_1 and K_2 in which the colors presented indicate quantity and their location in the map indicate curvature according to the ISD legend developed by Voorhees *et al.*❖✪■★ as shown below. However, in this application, "L" most generally; liquid phase, corresponds to porosity in the instances presented here.



For minimum weld speeds, the majority of curvatures exist near the $K_2 = 0$ axis with a minor bias toward zone 4 indicating many cylindrical and saddle shape patches. With increases in weld speed, faster speeds produce more spherical voids as nearly the entire distribution occurs in zone 4 bound between cylindrical and spherical void asymptotes.

❖ J. Alkemper, P. Voorhees, Acta Mat., Vol. 49 (2001) pp. 897-902
✪ R. Mendoza, J. Alkemper, P. Voorhees, Met. Mat. Trans. A., vol. 34A (2003) pp. 481-489
■ D. Kammer, P. Voorhees, Acta. Mat., Vol. 54 (2006) pp. 1549-1558
★ D. Kammer, R. Mendoza, P. Voorhees, Scripta Mat., Vol. 55 (2006) pp. 17-22

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