Jet Propulsion Laboratory
California Institute of Technology

Fabrication and Property Development for a Functionally Graded Austenitic to Maraging Stainless Steel Component

R. Peter Dillon Ph.D., John Paul Borgonia, Ashley Reichardt**, Peter Hosemann Ph.D.**, Andrew A. Shapiro-Scharlotta Ph.D., and Bryan W McEnerney Ph.D.

** University of California, Berkeley, Department of Nuclear Engineering

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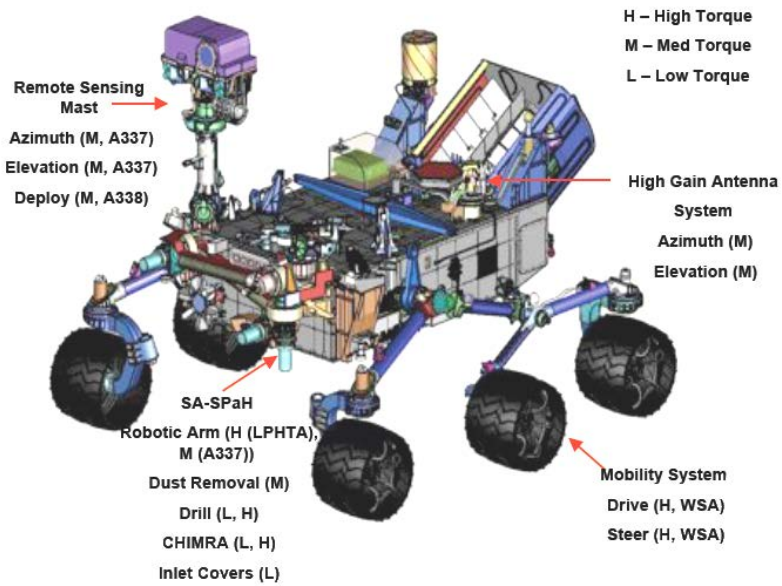
Agenda

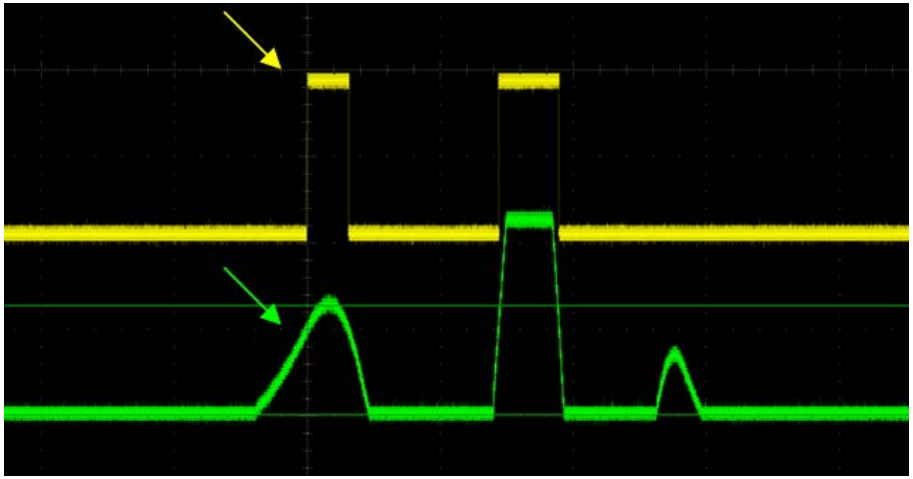
- Motivation for Functionally Graded Materials at JPL
- Mechanical Ground Support Equipment (MGSE) Test Article
  - Fabrication
  - Characterization
  - Testing
- Full Scale Fabrication
- Conclusions
- Future Work

Motivation: Mars Rover Actuators



The Curiosity Rover (or Mars Science Laboratory (MSL)):

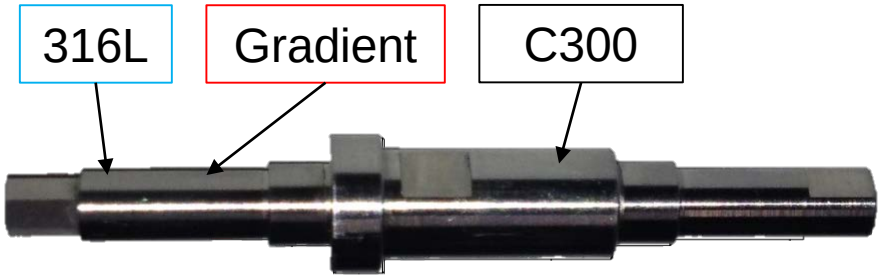
- There are 51 actuators on the rover
- Maraging steel shafts were used in the actuators
- Magnetic interactions between the motor, brake and encoder were observed
- The encoders can be magnetically sensitive



What if a non-magnetic material was used, but only in the vicinity of the encoder?

- MGSE shaft used to test magnetic interactions.
- C300: alloy currently used in actuator shafts
  - Keep in dynamic area for mechanical properties
- 316L: Austenitic SS alloy
  - Non-magnetic
  - Low martensite formation
- Fabricate posts (blanks) using laser deposition (LD)
  - -140/+325 Carpenter 316L
  - -100/+270 Carpenter Micro-Melt 1.2709 (C300)
- Machine MGSE from posts

MGSE Test Article



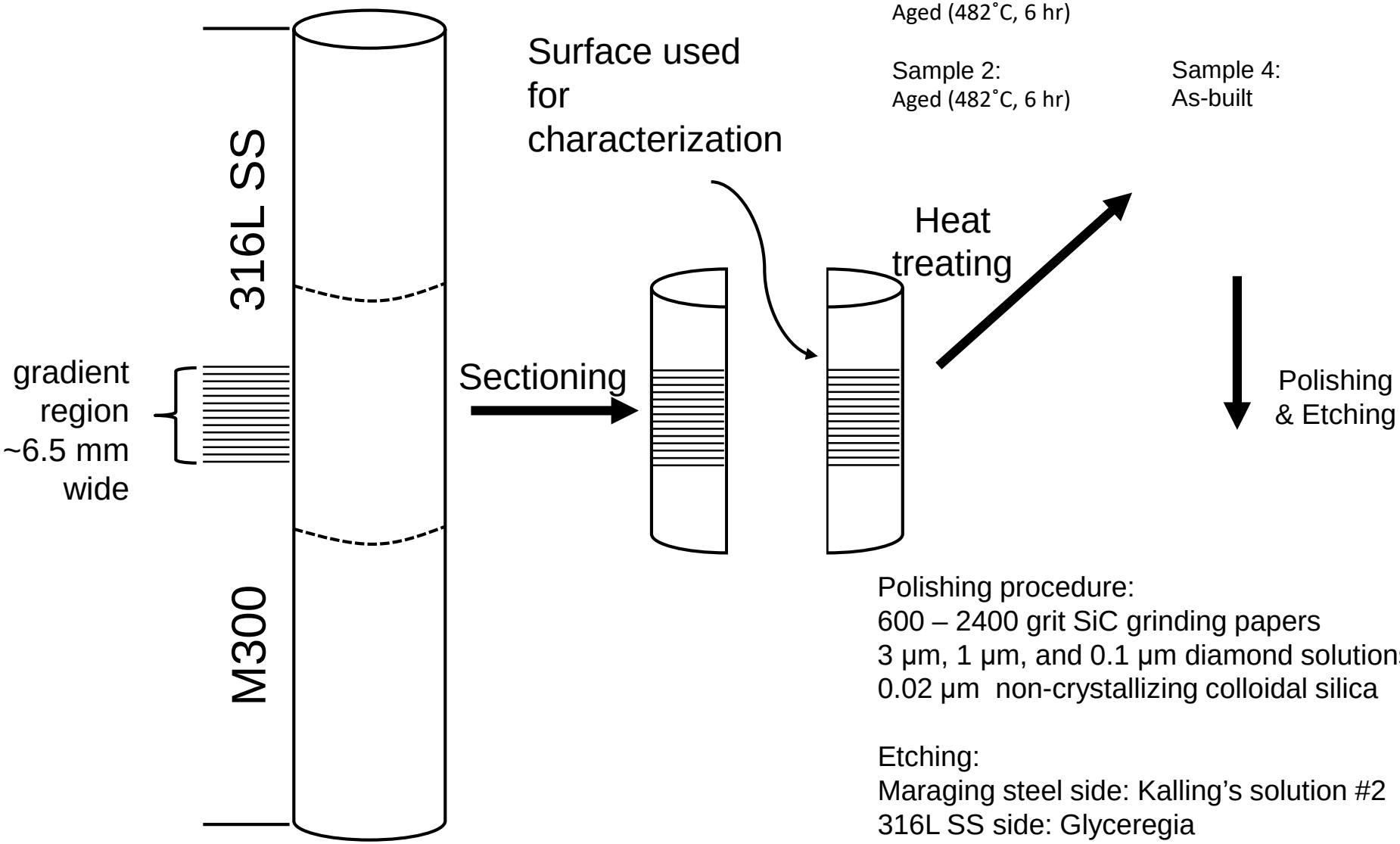
Sample preparation: Sectioning and heat treatment

Sample 1:
Annealed (815˚C, 1hr)
Aged (482˚C, 6 hr)

Sample 2:
Aged (482˚C, 6 hr)

Sample 3:
Annealed (815˚C, 1hr)

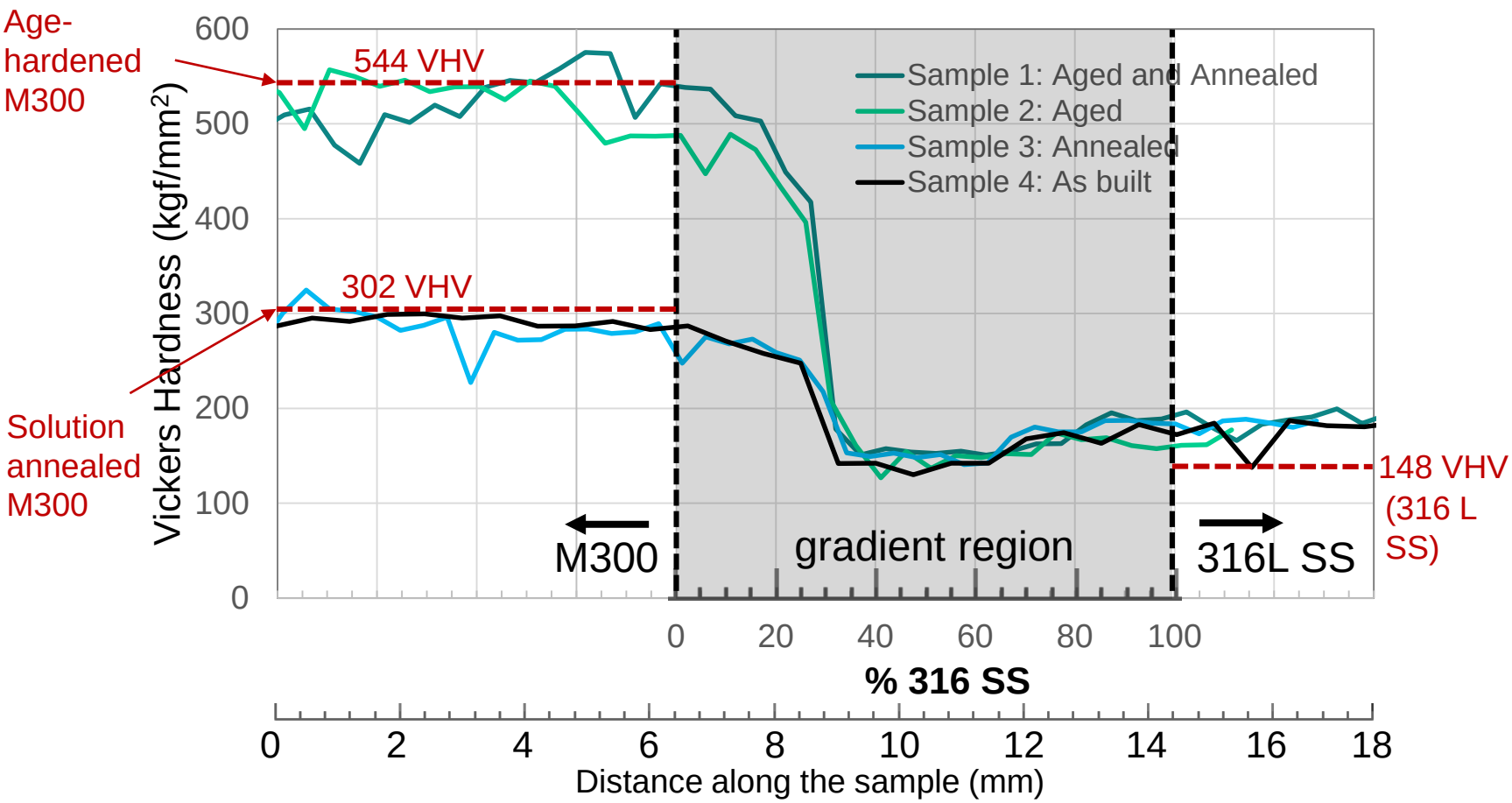
Sample 4:
As-built



Polishing procedure:
600 – 2400 grit SiC grinding papers
3 µm, 1 µm, and 0.1 µm diamond solutions
0.02 µm non-crystallizing colloidal silica

Etching:
Maraging steel side: Kalling's solution #2
316L SS side: Glyceregia

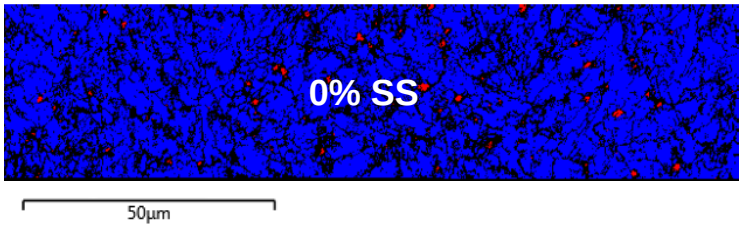
Gradient Hardness

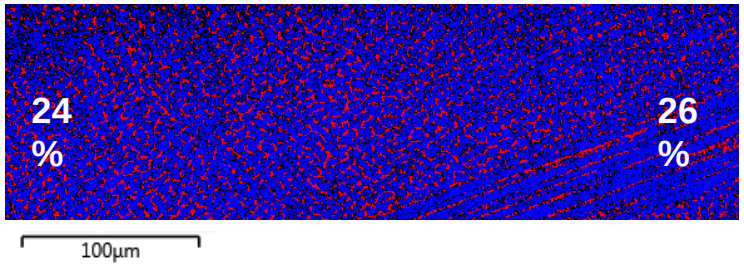


Load: 500 kgf
Indent spacing: 400 – 600 μm Values for the commercial wrought alloys are shown in red.

Age Hardening Effects on Phase Composition

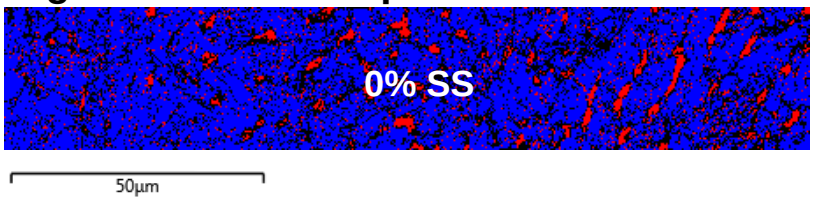
As-built component:



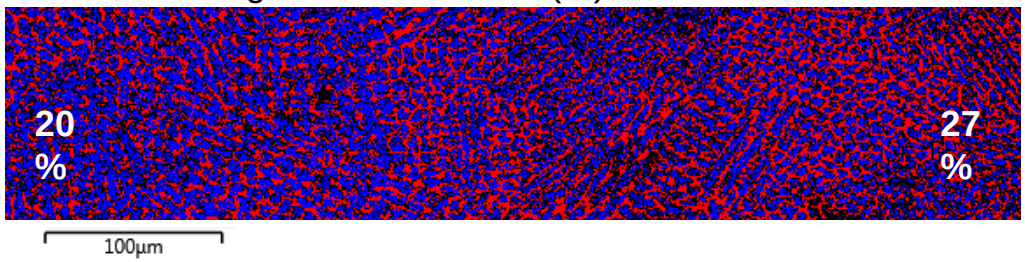


Fe FCC
Fe BCC

Age-hardened component:



Increasing 316L SS content (%) →

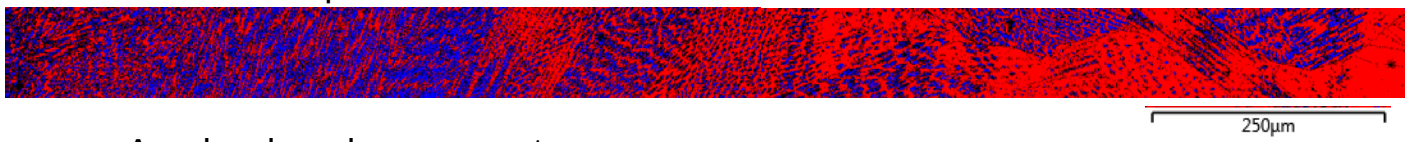


After age-hardening, a larger percentage of reverted austenite is present in the both the pure maraging steel and intermediate stainless steel compositions. Due to the increased time spent at elevated temperatures during fabrication (most likely during cyclic heating of previously deposited layers) Mo and Ti segregated into alloy-rich pools, which upon aging served as sites for austenite reversion.

Age Hardening Effects on Phase Composition

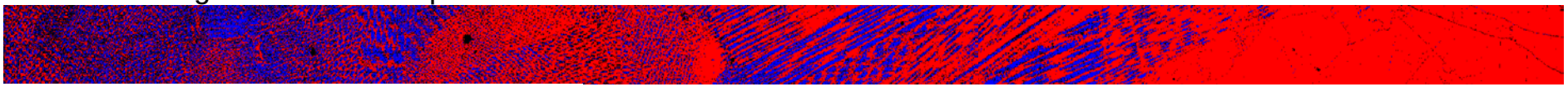
The transition to 100% austenite occurs at the same composition (~53-54% SS) regardless of age hardening.

As-built component:



Fe FCC
Fe BCC

Age-hardened component:



26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62

316L Stainless steel content (%)

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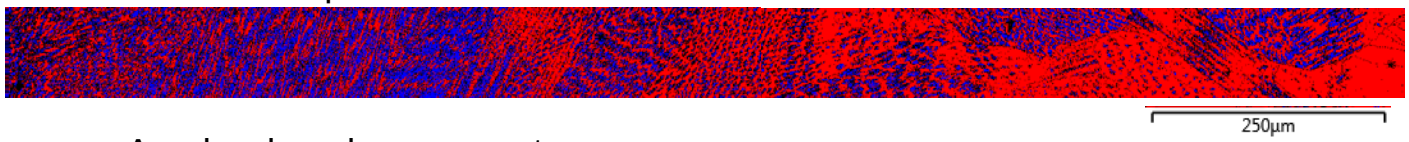

Fe FCC
Fe BCC

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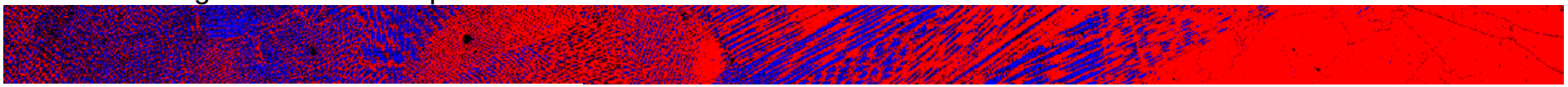

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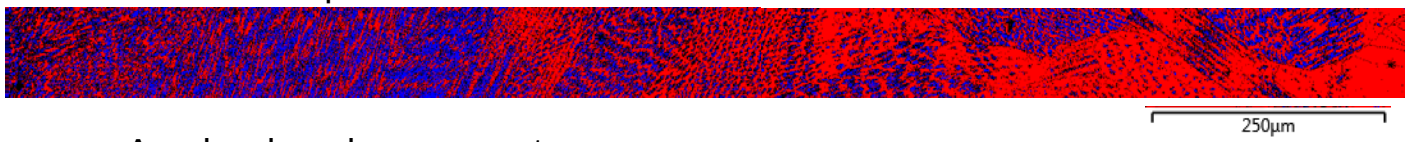

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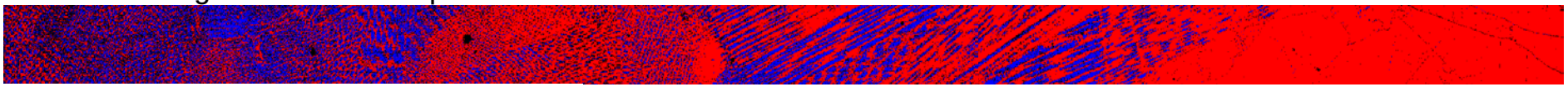
Fe BCC

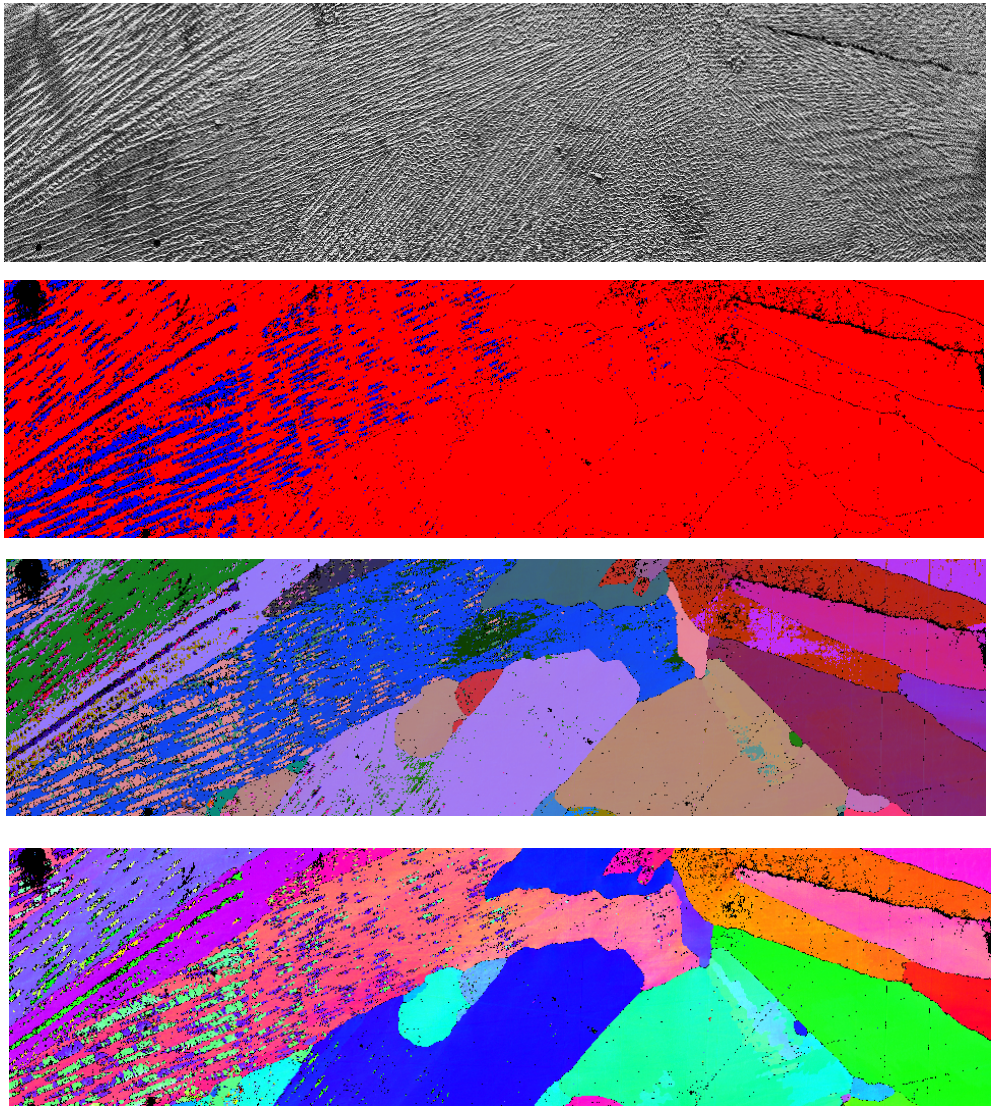
Age-hardened component:



26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62

316L Stainless steel content (%)

Age Hardening Effects on Phase Composition



crack

Transition to large FCC grains:

At roughly 53% SS content, the component transforms to 100% austenite in large 100-250 µm grains. The age hardened also exhibited increased porosity and occasional cracking along the grain boundaries in this composition range.

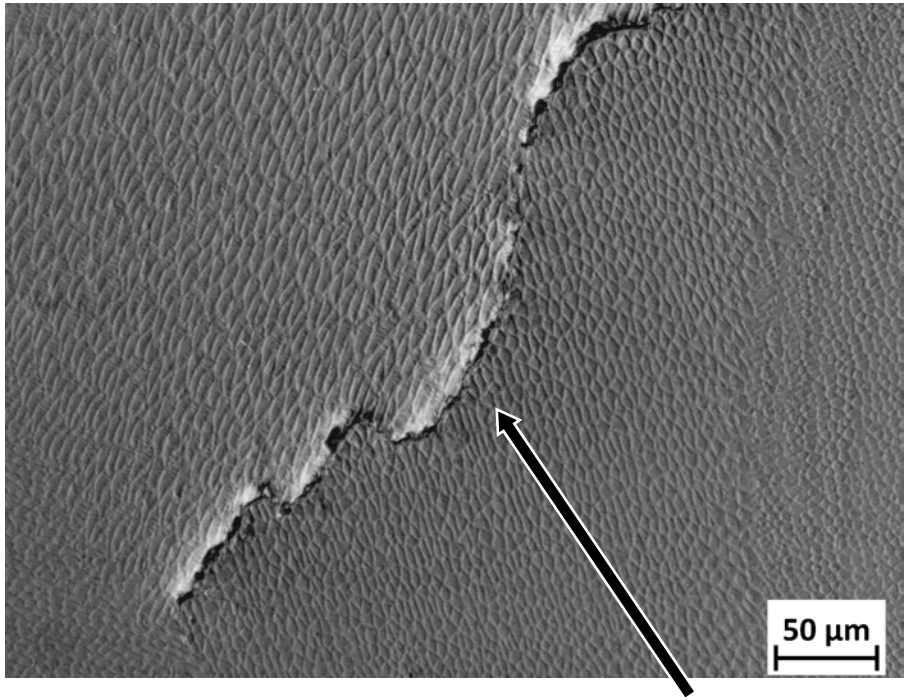
cracking occurs along GB

~44% SS

~62% SS

Cracking

The crack morphology is consistent with solidification cracking commonly observed in the welding of austenitic stainless steels when the **primary solidification mode is austenite**.

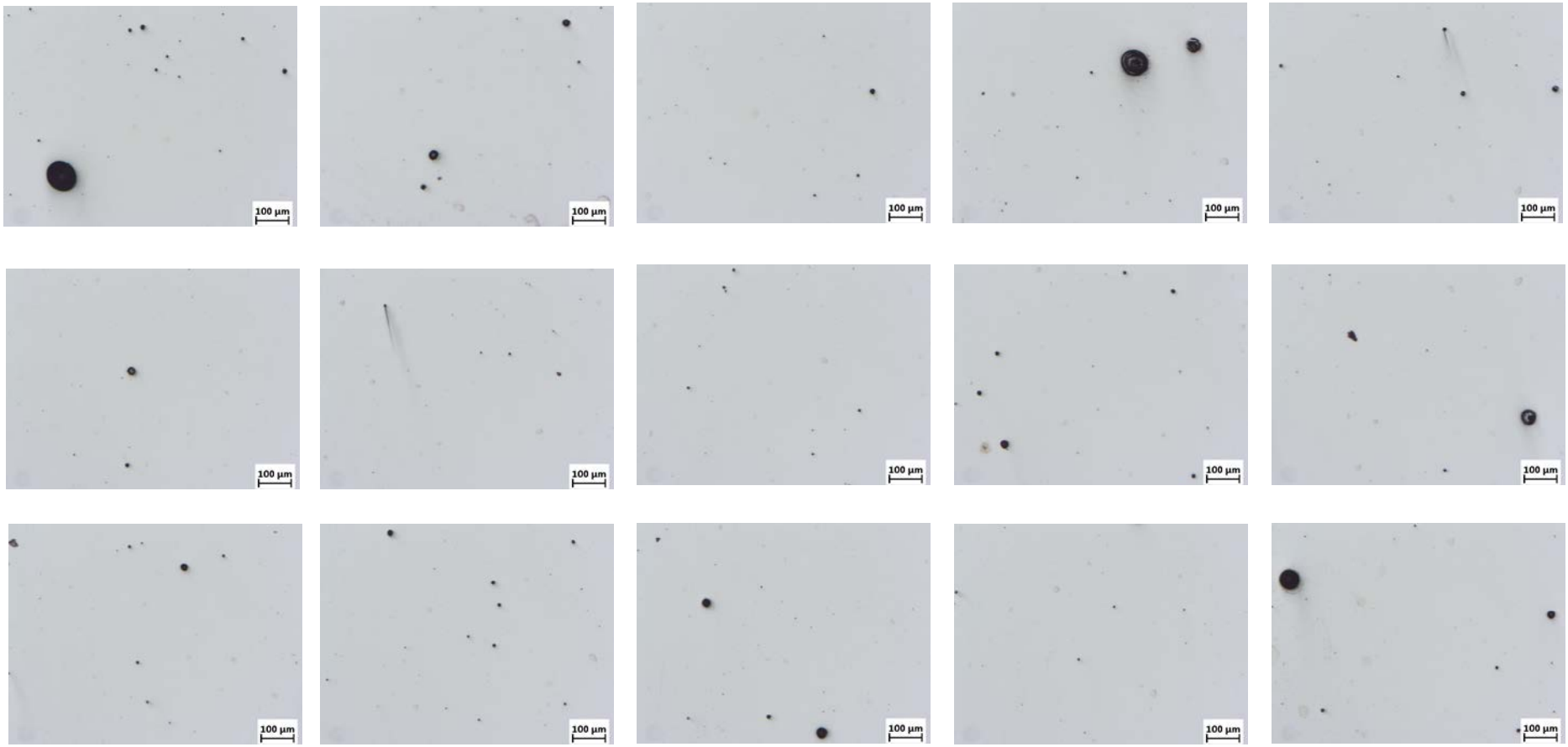


Crack located along solidification (grain) boundary in the SS-rich area of the aged component. Etching reveals the opposing solidification fronts.

Textbook example of a solidification crack. The fracture surface appears as an “eggcrate” from opposing cellular/dendritic fronts separating.

J. Lippold. Welding Metallurgy and Weldability. (2015).

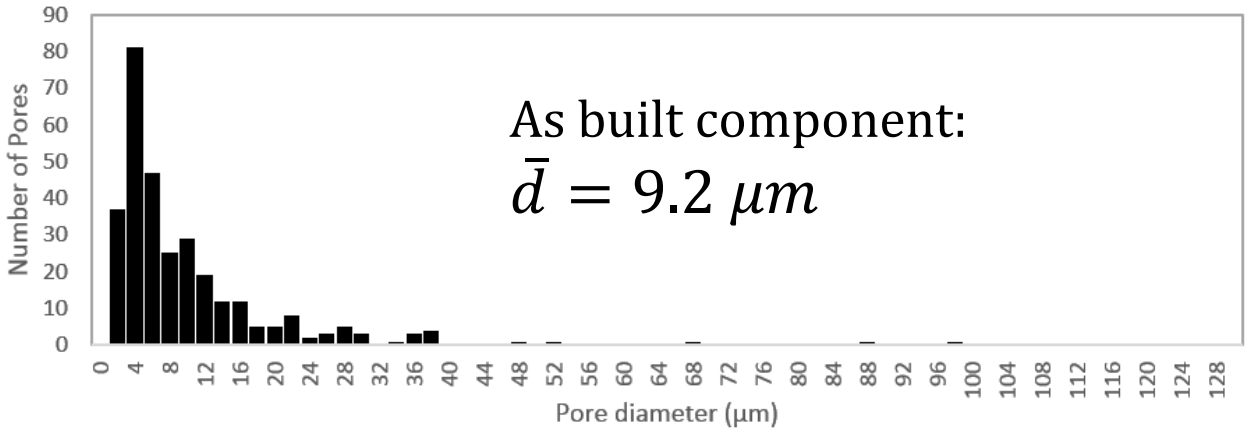
Porosity post-build (maraging)



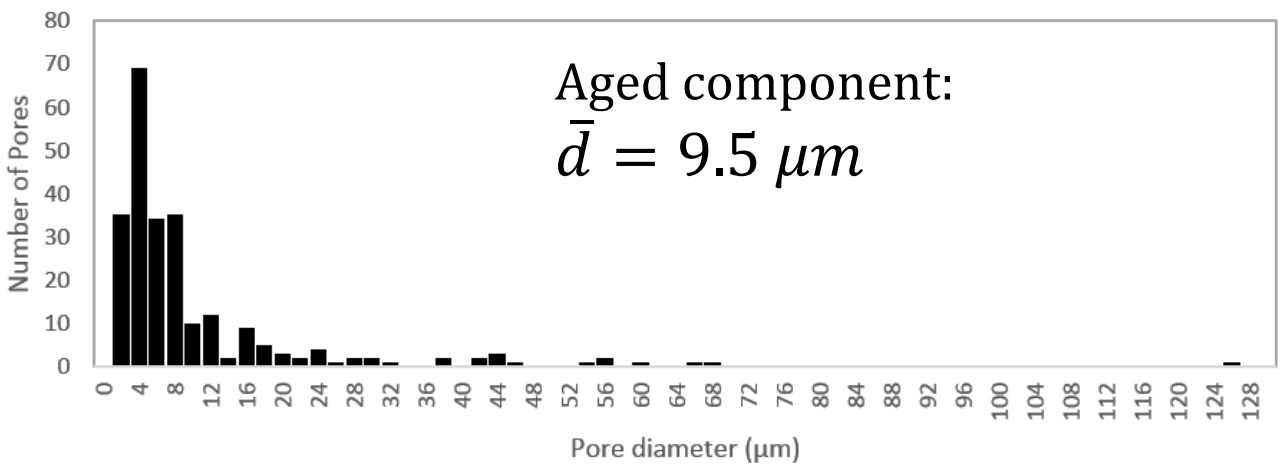
Typical porosity observed in as-built and aged samples
Minimum of 30 micrographs per condition for imaging and pore size analysis
Porosity between sub-micrometer and 150 µm (observed)

Porosity analysis

Note that the average pore size is actually much smaller due to the limitations of this method in measuring pores of diameter d < 2 µm.



The distribution of pores is similar in the as built and aged components, as expected.



Total porosity

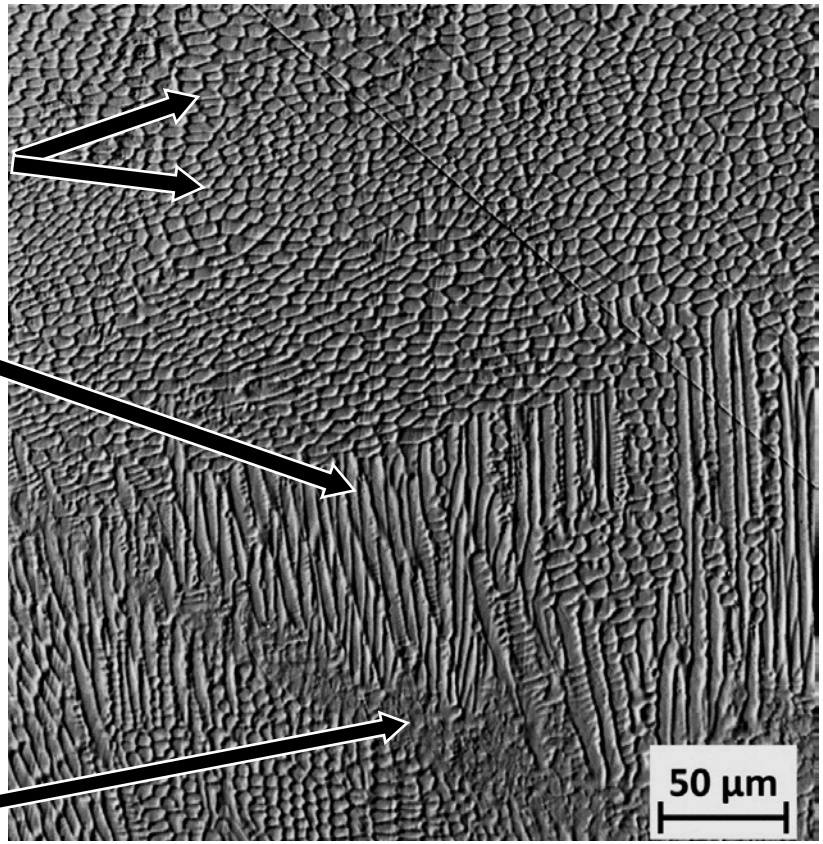
	As built component	Aged component
Total area of pores	0.051 mm^2	0.054 mm^2
Total surface area surveyed	18.34 mm^2	18.63 mm^2
Porosity area fraction	0.00277	0.00288
Estimated porosity volume fraction	0.00277	0.00288
Porosity percentage	0.28 %	0.29 %
Density	99.72 %	99.71 %

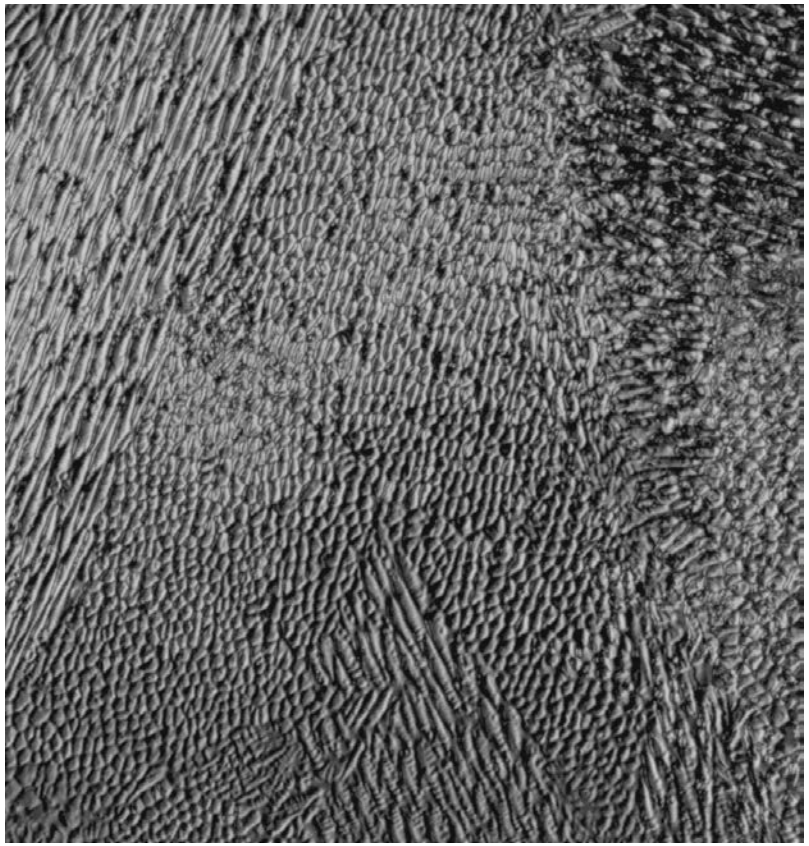
Solidifed microstructure

Solidification subgrain boundaries

Solidification grain boundary

Melt bead boundary



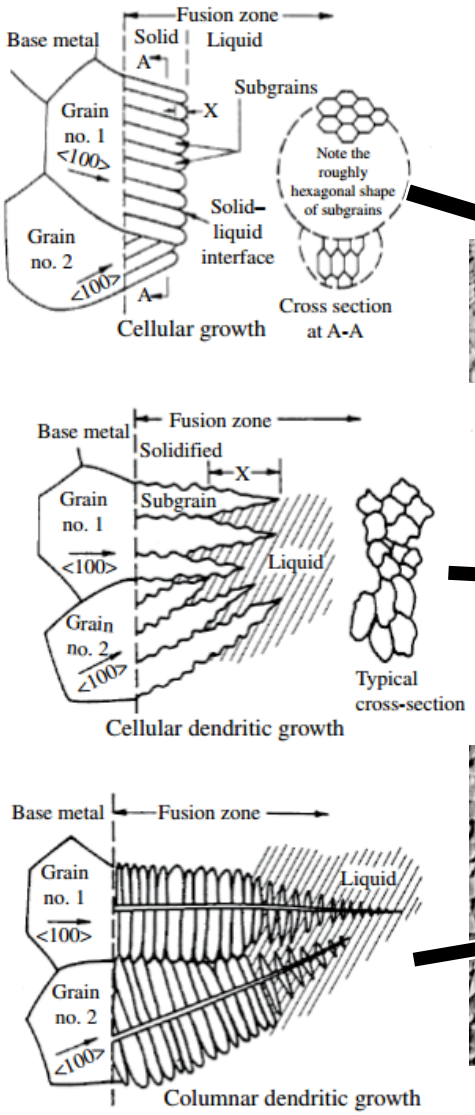


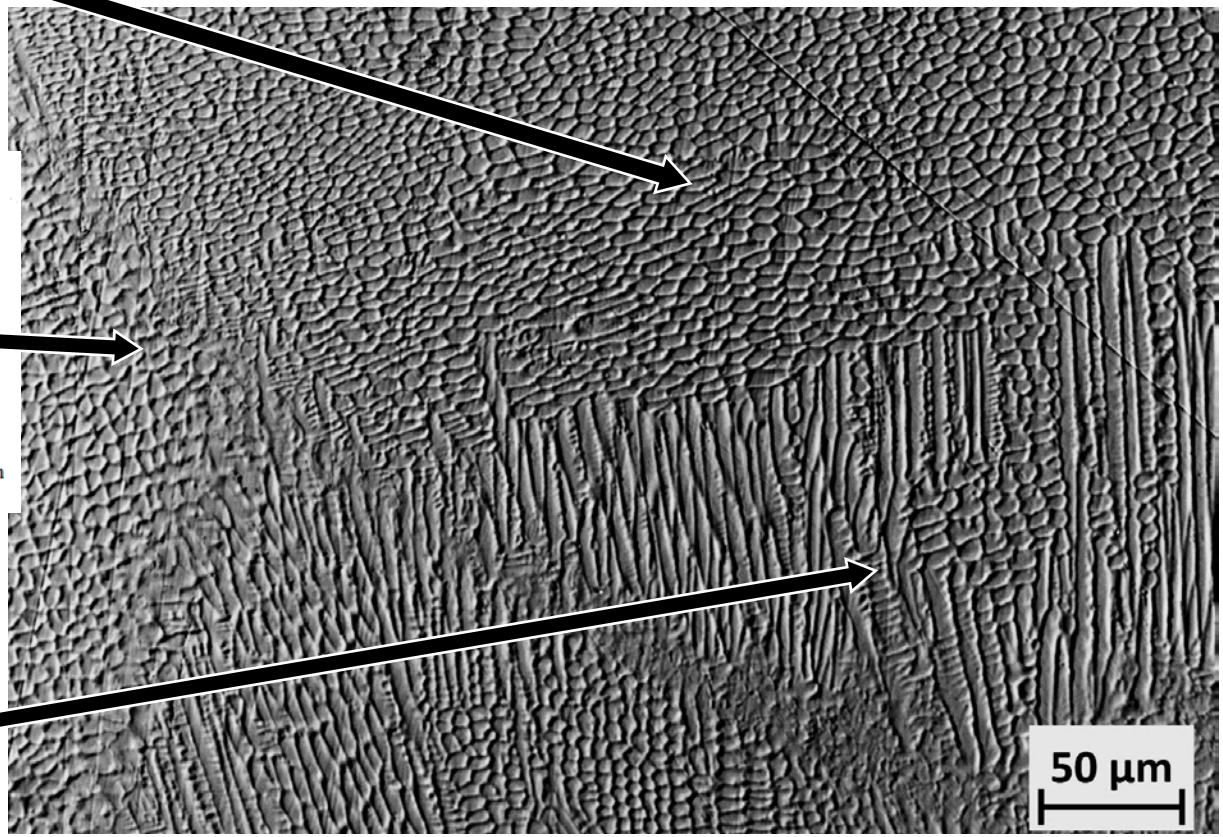
Microstructure at 100% 316L SS
(known to be large austenite grains)

Microstructure at ~16% 316L SS
(known to be a mix of fine FCC + BCC grains)

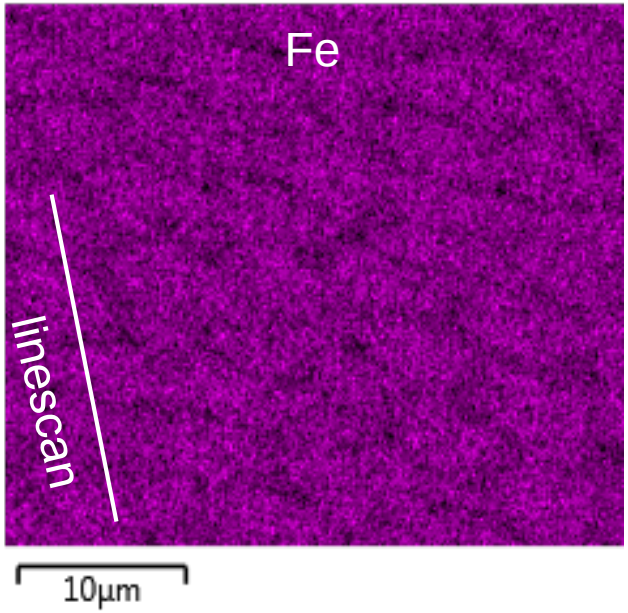
Solidifaction mode (cont.)

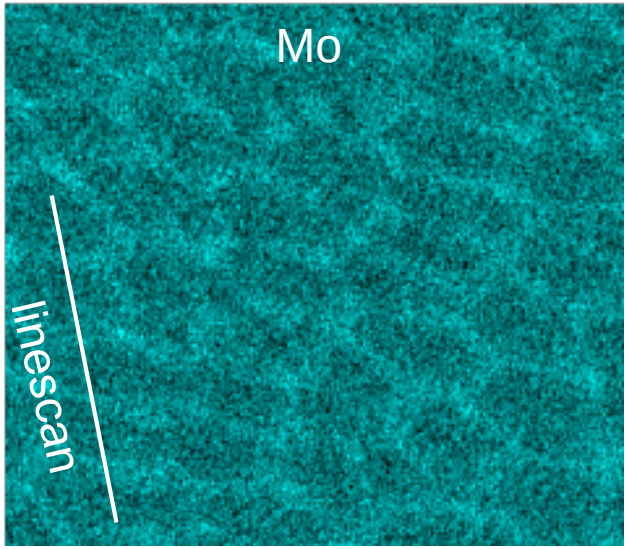
Pure 316L SS side:
Solidification mode = mix of **cellular**, **cellular dendritic** and **dendritic** growth

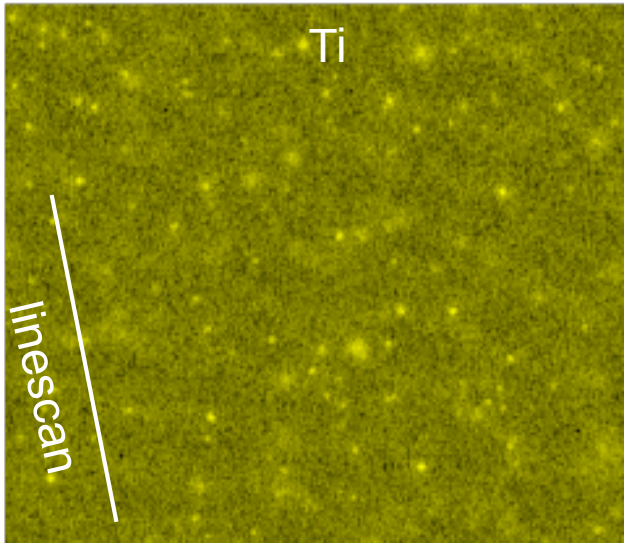




Solute behavior

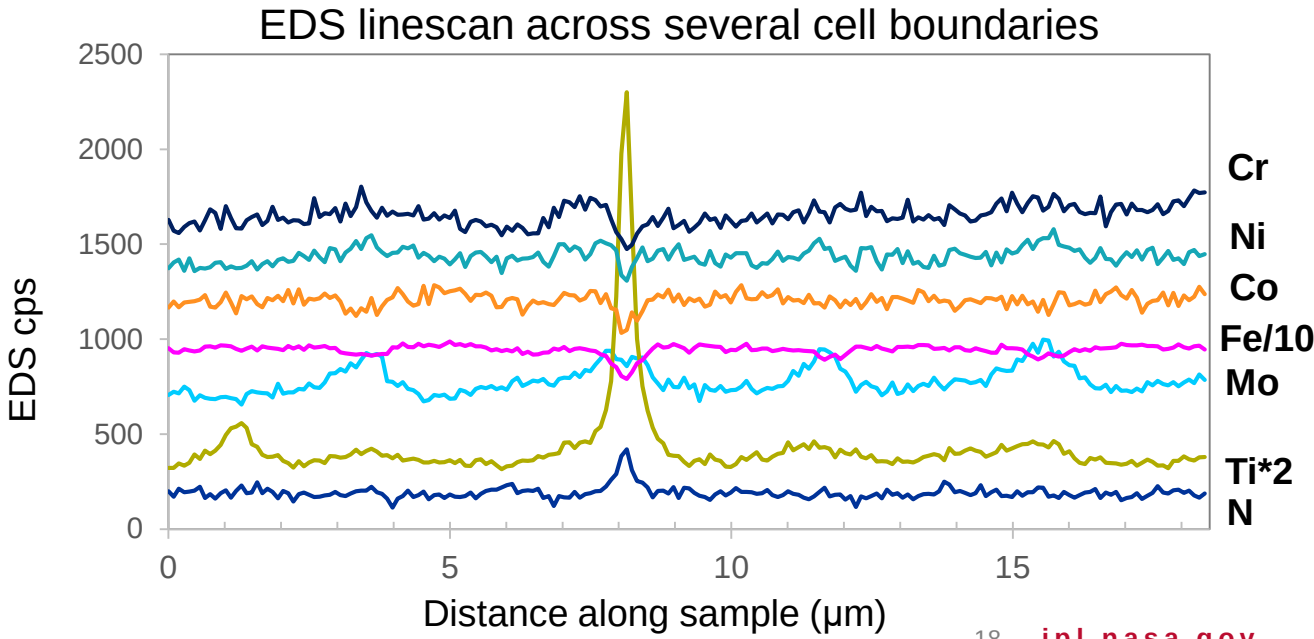






Dual-phase region at ~40% SS where FCC is present at cell boundaries and BCC forms within cells:

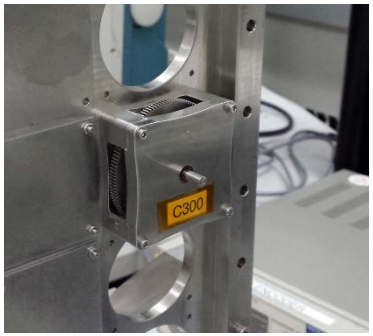
Due to microscopic solute redistribution, the solidification cell boundaries become rich in alloying elements, Mo, Ti, & Ni, and slightly depleted in Fe.



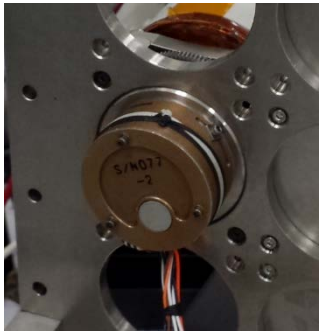
MGSE Magnetic Interaction Testing

- Shaft assembled in test gearbox
  - Assembly tested with drive and brake
  - Measure effect on encoder

MGSE Test Bed



MGSE Gearbox



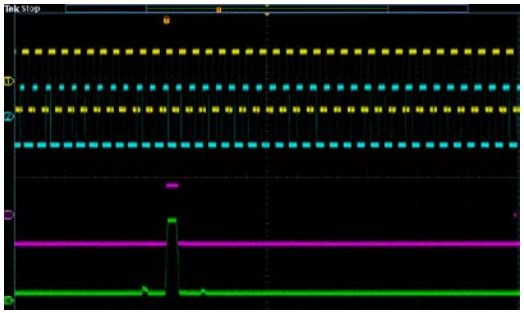
Encoder

Magnetic brake

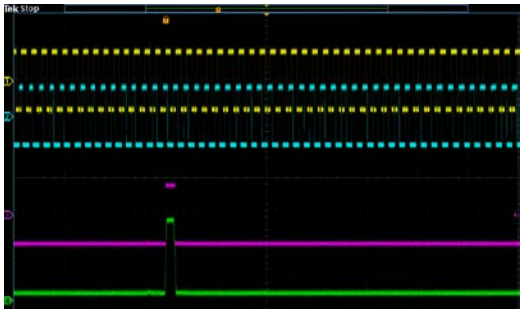
MGSE Magnetic Interaction Test Results

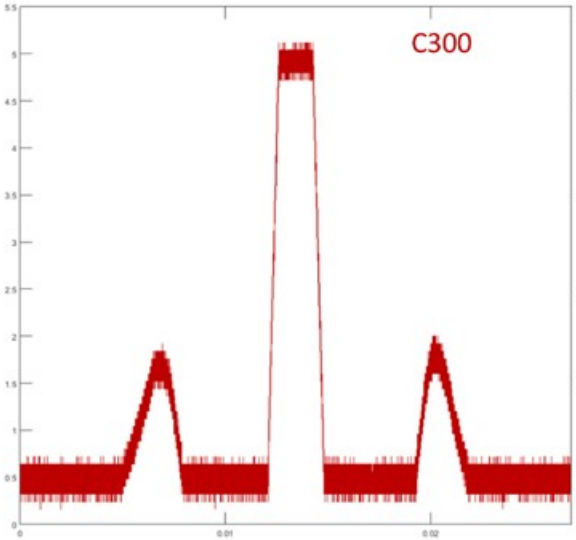
C300

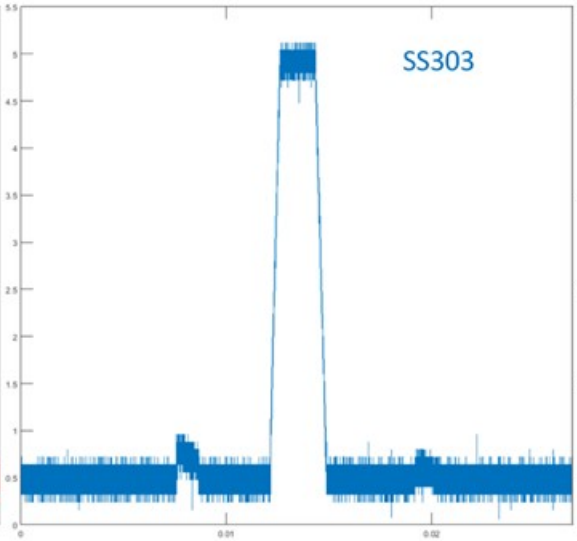
SS303

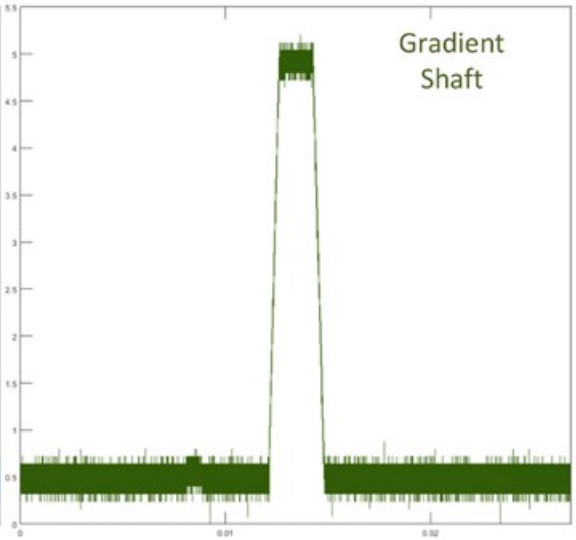


316L-C300 Gradient

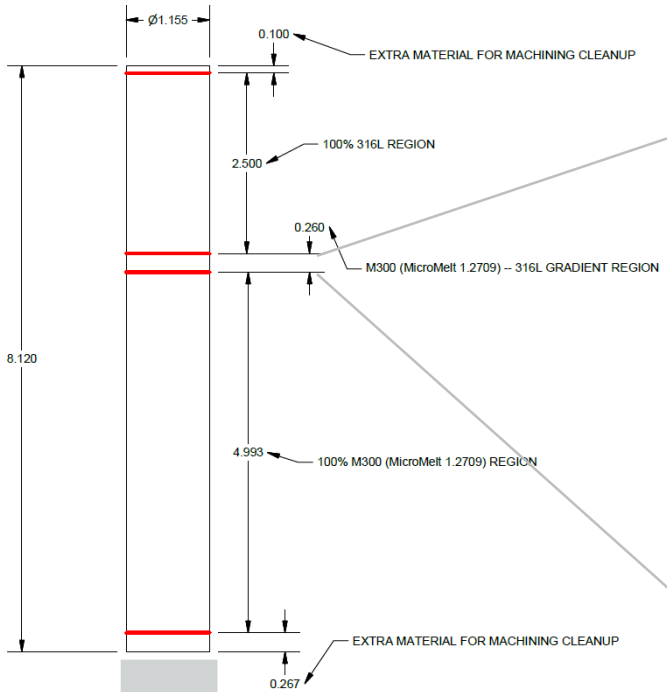




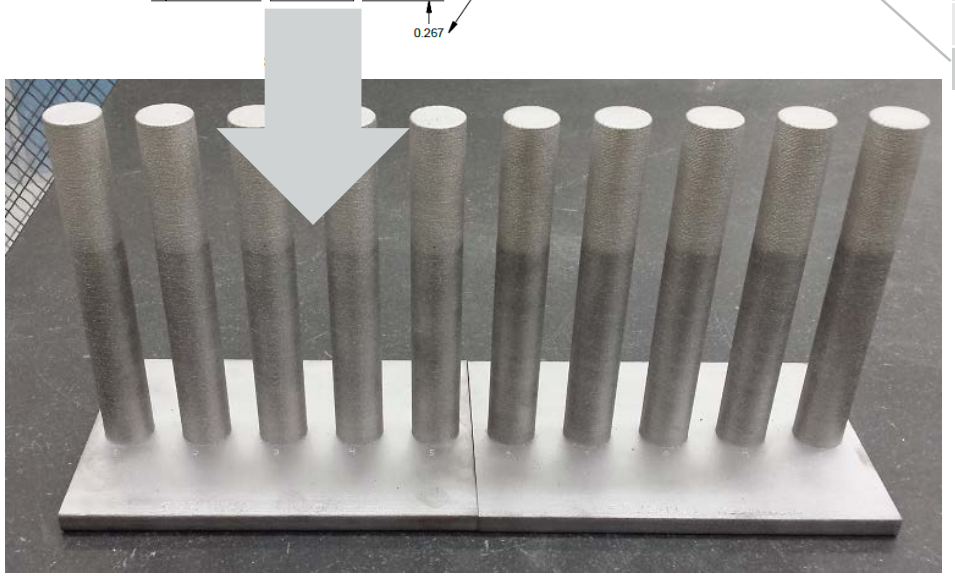




Full Scale Fabrication of Blanks



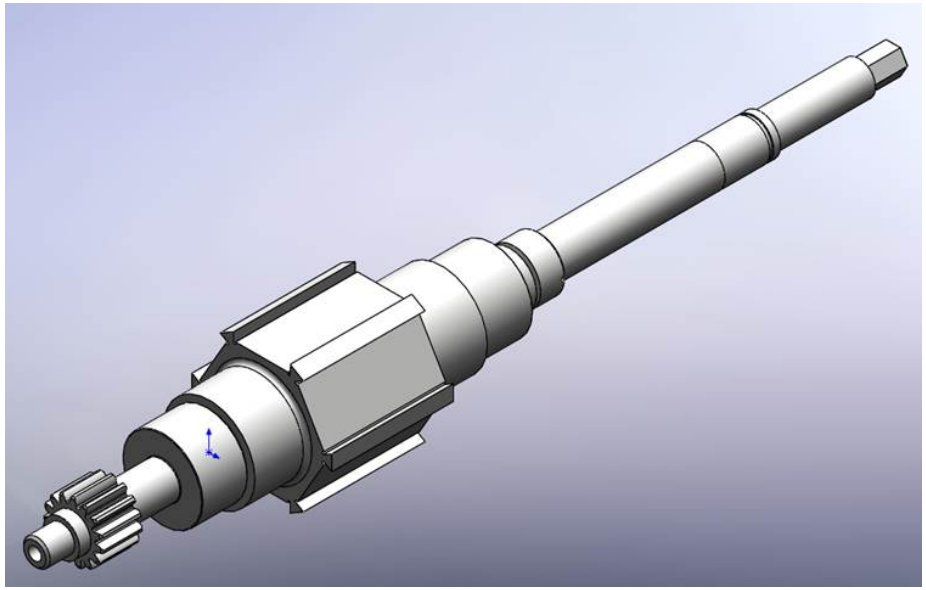
Start Layer	End Layer	Vol % C300	Vol % 316L
0	99	100.000	0.000
100	100	92.857	7.143
101	101	85.714	14.286
102	102	78.571	21.429
103	103	71.429	28.571
104	104	64.286	35.714
105	105	57.143	42.857
106	106	50.000	50.000
107	107	42.857	57.143
108	108	35.714	64.286
109	109	28.571	71.429
110	110	21.429	78.571
111	111	14.286	85.714
112	112	7.143	92.857
113	213	0.000	100.000

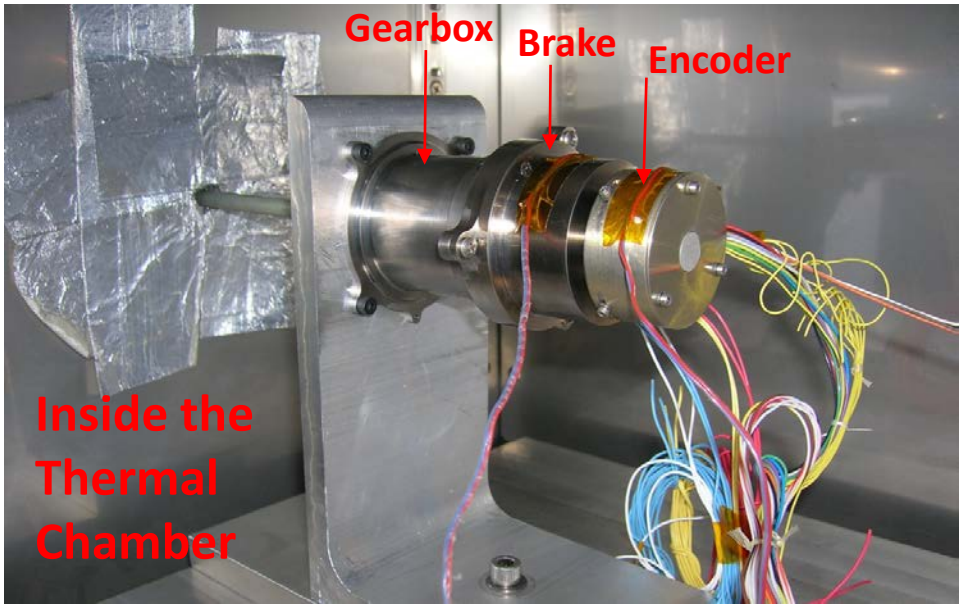


Selected fabrication parameters:
Nominal laser power: 990 W
Layer thickness: ~0.5 mm (0.02 in)
Hatch travel speed: 76.2 mm/min (30 in/min)

Future Work

- Complete Machining of Full Scale Gradient Shaft
- Integrate into actuator
- RT and thermal test of gradient alloy encoder shaft with actuator
  - Operate -90 to +105 °C
  - Survive: -135 to +120 °C
- Optimize heat treatment
- Complete mechanical testing
- Qualify for flight





Conclusions

1. A gradient between C300 maraging steel and 316L stainless steel was successfully incorporated into an actuator component using laser deposition and traditional machining.
2. The magnetic properties were tailored in a monolithic structure through the use of additive manufacturing, specifically laser deposition.
3. The resultant magnetic properties appear to reduce, to an acceptable level, magnetic interactions between a motor, brake, and encoder.

Acknowledgements

- Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration
- Dr. Jong-ook Suh, Dr. Scott Roberts, Tien Nguyen, James Morcos, Gerald Lung, and Luis Dominguez, Jet Propulsion Laboratory
- RPM Innovations

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