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Correlating Defect Populations with Mechanical Performance in AM Tensile Samples of PH 17-4

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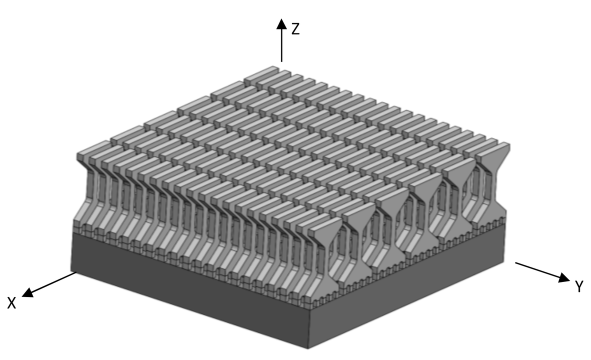

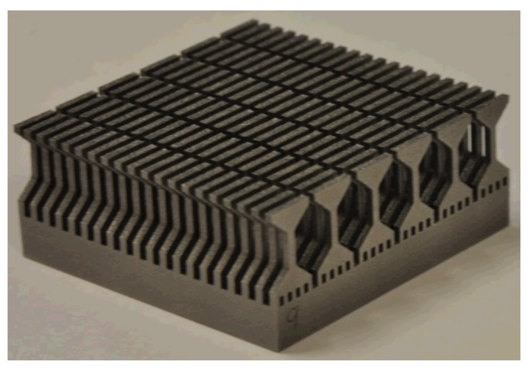

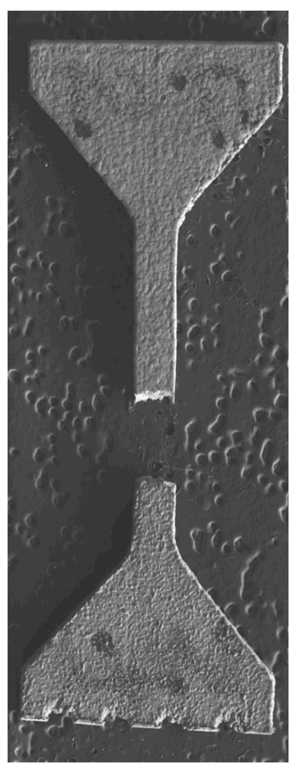

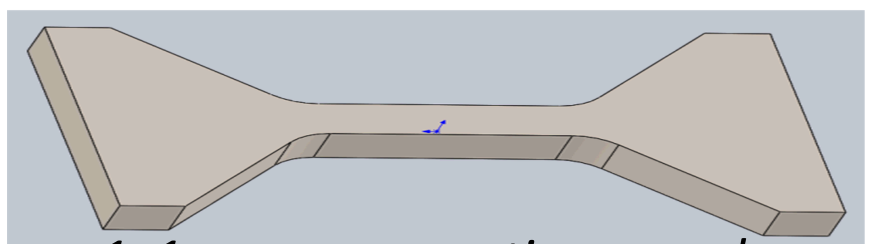

1x1 mm gage section sample

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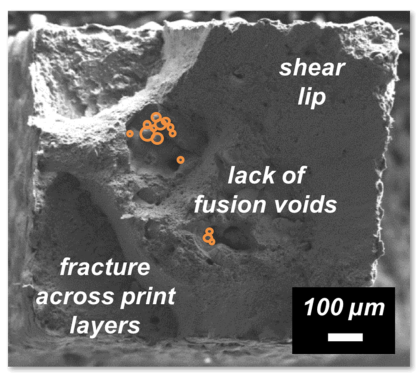
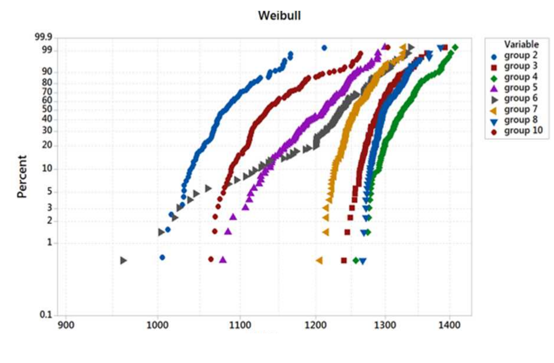
ABSTRACT

As a portion of a larger effort to relate AM microstructure to performance, micro-computed tomography is employed on a large ensemble set (100+) of precipitation hardened 17-4 stainless steel tensile samples having a resolution of 10.2 microns per cubic voxel edge. Micro-computed tomography allows for rapid identification and measurement of internal defect populations where porosity and lack of fusion are the primary features of interest. Distributions of defect size, shape and spatial arrangement are measured, evaluated and reported in terms of their statistical presence across the entire build. Correlations in observed defect presence will be shown and their potential relation to high-throughput mechanical testing results will also be highlighted.

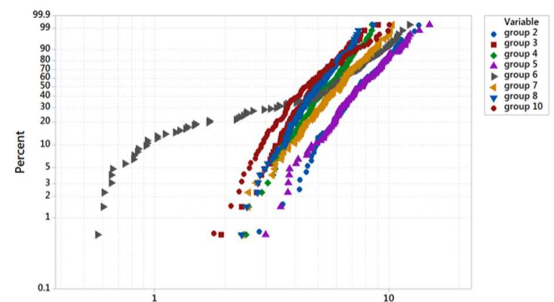
BACKGROUND



17-4PH dogbone fracture surface



Ultimate Tensile Strength (MPa)

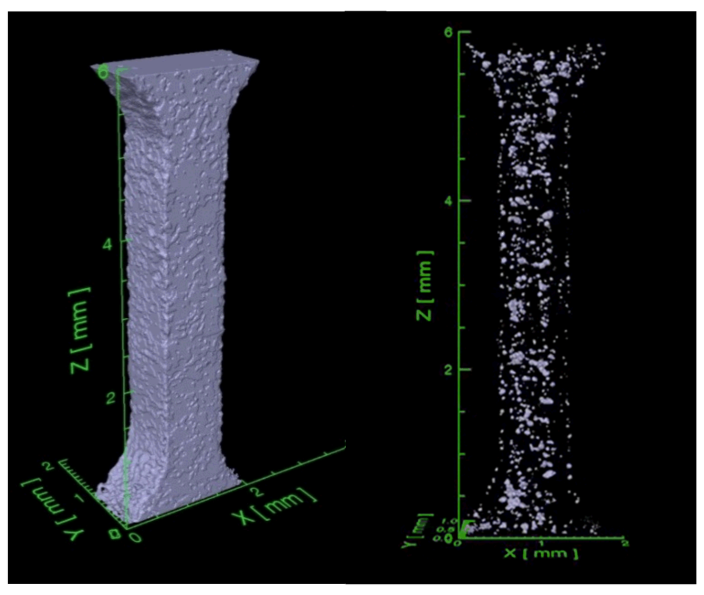


Elongation (%)

Using high throughput mechanical tensile testing, a statistically significant amount of mechanical tensile tests were performed on multiple builds of AM fabricated 17-4 precipitation-hardened stainless steel. One predominately recurring observation included lack of fusion voids and unsolidified powder at the fracture surfaces. These defects were also observed to collocate in regions of fracture across multiple print layers, shear lips and other locations of failure.

EXPERIMENTAL

Northstar X50 CT cabinet system



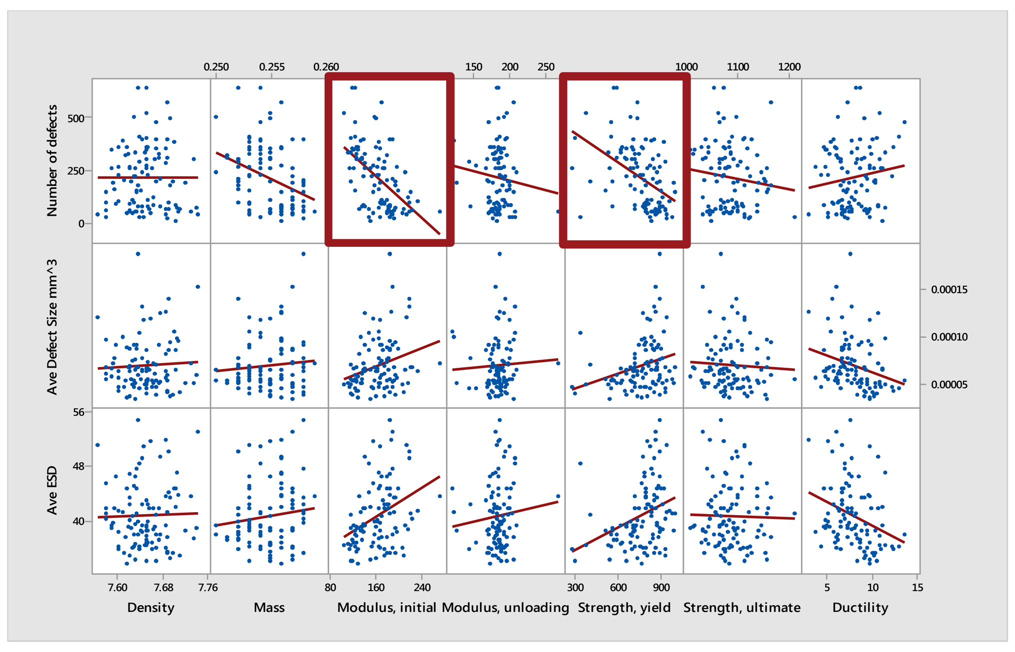
17-4PH dogbone CT surface (left) & porosity (right)

Using a North Star Imaging© Inc. X50 cabinet system and an Xray Works© 1500 uA table top system, both operating near 160kV, micro-computed tomography was performed on 100+ tensile bars from the Group 2, AM build. Effective pixel size for all samples ranged from 6.5 – 10.2 um per voxel edge.

Quantification of defects were then performed, including an assessment of equivalent spherical diameters, maximum defect size, defect quantity, defect frequency and local reduction in cross-sectional area due to defect presence.

Statistical relationships were then investigated for correlation between defect presence and global mechanical response as observed by high-throughput mechanical testing. In this regard the primary metrics of interest include density, modulus, yield strength, ultimate strength and ductility.

RESULTS

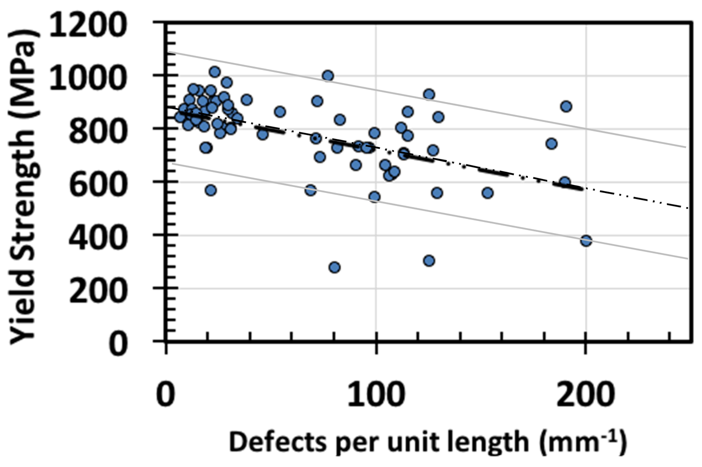


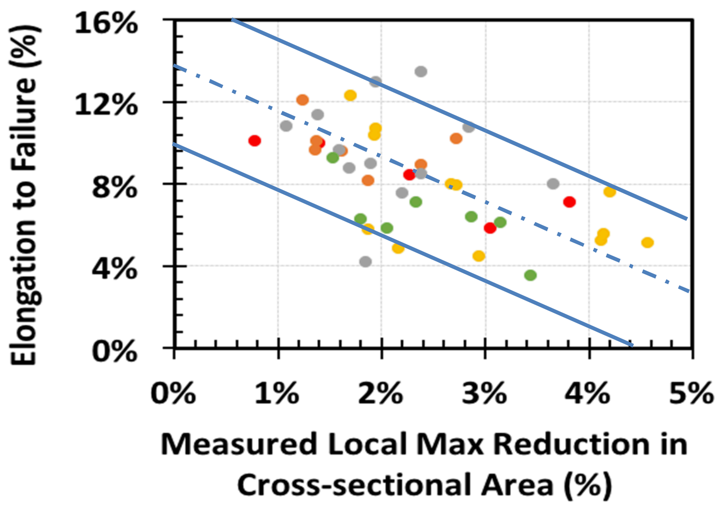
Correlation Table

	Density	Mass	Modulus, initial	Modulus, unloading	Strength, yield	Strength, ultimate	Ductility
Density	1.000						
Mass	0.235	1.000					
Modulus, initial	0.061	0.356	1.000				
Modulus, unloading	0.008	-0.014	0.146	1.000			
Strength, yield	0.015	0.305	0.757	-0.291	1.000		
Strength, ultimate	0.006	0.065	0.317	0.349	0.150	1.000	
Ductility	0.144	0.205	-0.293	-0.047	-0.294	0.164	1.000
Number of defects	-0.002	-0.349	-0.538	-0.106	-0.450	-0.129	0.146
Ave Defect Size mm^3	0.062	0.101	0.290	0.048	0.285	-0.058	-0.283
Ave ESD mm	0.026	0.117	0.364	0.092	0.337	-0.020	-0.310

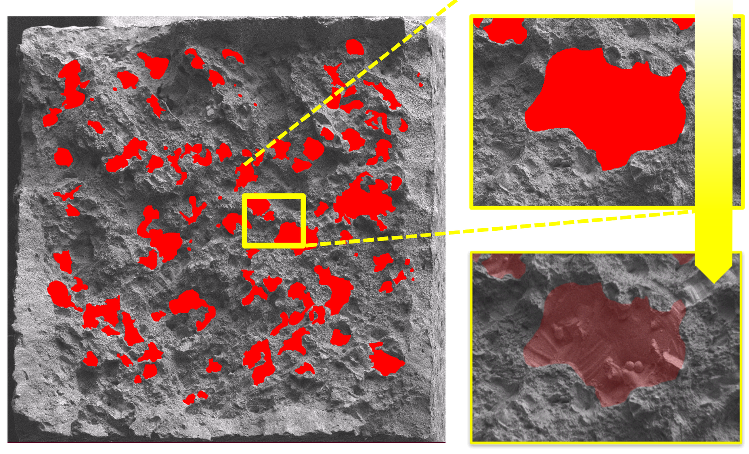
When considering the total quantity of defects, their average size (in voxels) and their equivalent spherical diameters (ESD), from the group 2 build, it is hard to identify many clear global correlations with respect to density, modulus, YS, UTS or ductility. The greatest correlation observed for global measures exists between initial modulus and YS for number of defects with a correlation factor of -0.538 and -0.450, respectively.

However, when interrogating the three-dimensional volumes from the group 2 build more closely, YS is observed to decrease with increasing frequency of voids (along the sample length) and maximum reductions in local cross-sectional area on the order of 5% (perpendicular to loading) show a notable decrease in elongation to failure.

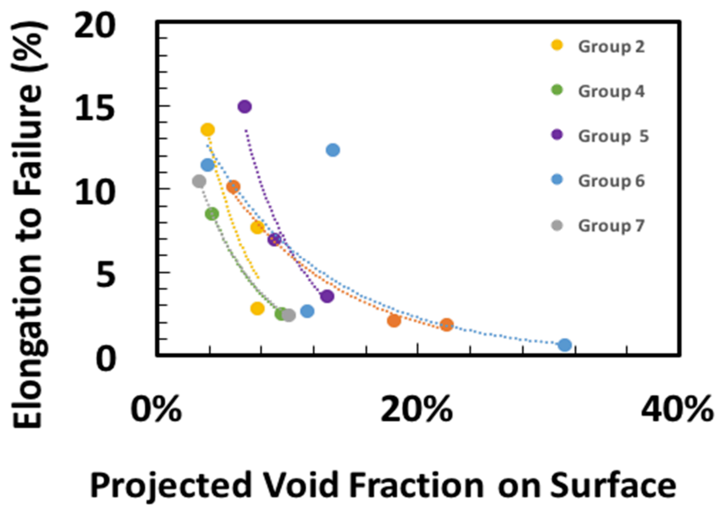




When considering local projected void fractions at fracture surfaces across multiple build groups, a relatively consistent post-mortem confirmation of the relationship between void fraction and elongation to failure is seen.



17-4PH dogbone fracture surface with highlighted void fractions



CONCLUSIONS

Utilizing micro-computed tomography in conjunction with high-throughput testing, large amounts of statistically significant data, relevant to lack of fusion defects and mechanical performance, can be obtained and interrogated. In this study, it was observed that the quantity of defects correlate notably with both initial modulus and yield strength with a correlation factor of approximately 0.5. Furthermore, local reductions in cross-sectional area were seen to correspond with decreases in elongation to failure. This observation was additionally observed post-mortem on a variety of fracture surfaces across multiple additively manufactured builds of precipitation-hardened 17-4 stainless steel.

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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