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The Effects of Annealing Treatments on AM 316L Stainless Steel

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Abstract

Additively manufactured austenitic stainless steel often exhibits high strength due to a refined microstructure (fine scale solidification substructure) and sometimes finely dispersed oxides. In many applications, however, the tradeoff between strength and ductility must be considered, i.e. maximize toughness. In this work, 316L stainless steel was deposited with a ProX 300 laser powder bed system and the deposits were annealed with the objectives of decreasing residual stress and increasing ductility and toughness. Tensile testing was performed on the as-deposited material, while hardness testing and microstructural characterization were used to determine the effects of annealing. In the as-deposited condition, Rockwell B hardness was 94-95 HRB, which is somewhat higher than typical annealed 316L. After annealing in the 600-1100°C range, only a moderate decrease in hardness was obtained. It was not until 1200°C that significant reductions in hardness and concomitant recrystallization/grain growth were observed. The results were compared to the case of highly cold-worked austenitic stainless steel (high dislocation density), which responds dramatically to heat treatments as low as 700°C.

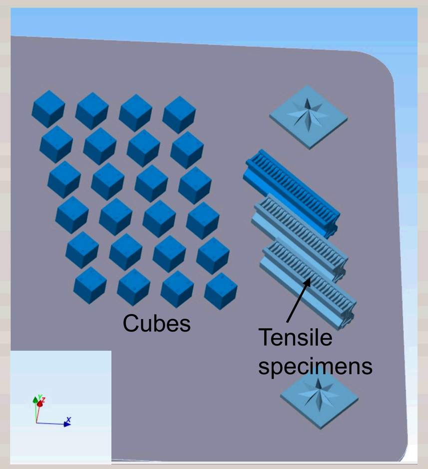
Materials & Methods

Powder Bed Additive Manufactur

ProX 300 laser powder bed machine, 3D System

- 316L stainless steel powder
- Cube shaped samples, 1cm across, built wi alternating laser path directions; cross-hatch pattern
- Tensile bars also produced using same proc

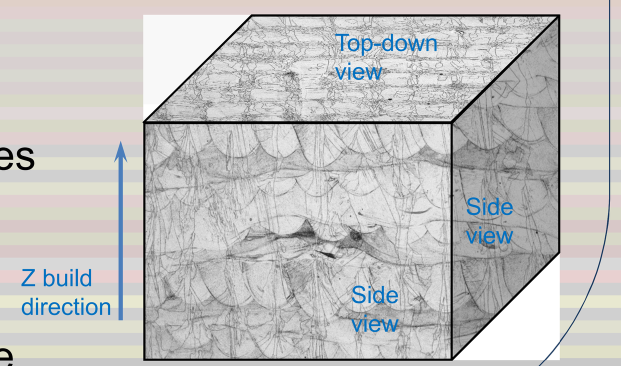
Heat Treatment and Characterization



Annealing treatments applied to investigate recrystallization and grain growth regimes

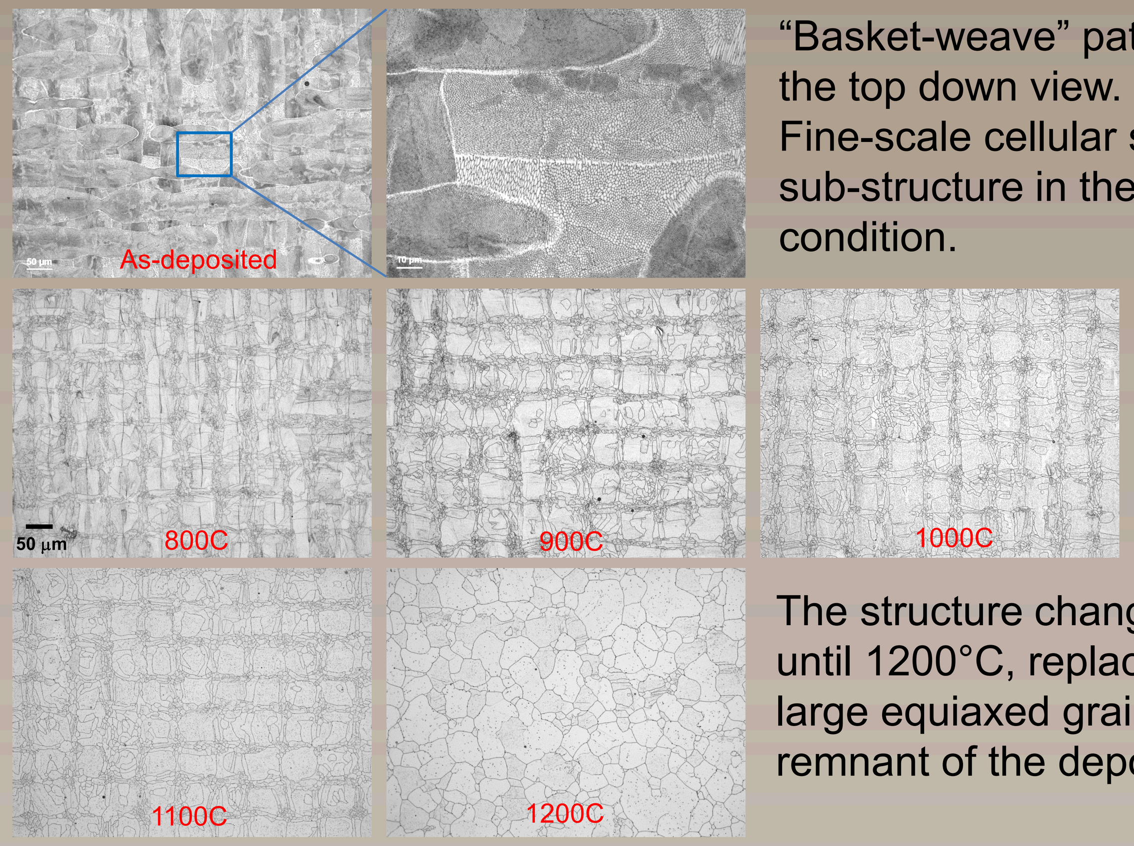
- Temperatures 600-1200°C, vacuum atmosphere
- Annealing time held constant at 2 hrs.
- Rockwell hardness indentation performed in the "top-down" and "side" directions
- Comparison to highly cold-worked & annealed stainless steel
- 50 tensile bars tested to develop statistical data

- High-throughput tensile technique
- Metallography and optical microscopy in both orientations
- As-deposited and annealed microstructures analyzed in etched condition (60/40 Nitric acid/H_2O, electrolytic)
- Chemistry of both powder and builds measured using inert gas fusion technique



Microstructure of AM Deposited and Post-AM Annealed 316L Stainless Steel

Microstructure in the top-down (z) orientation



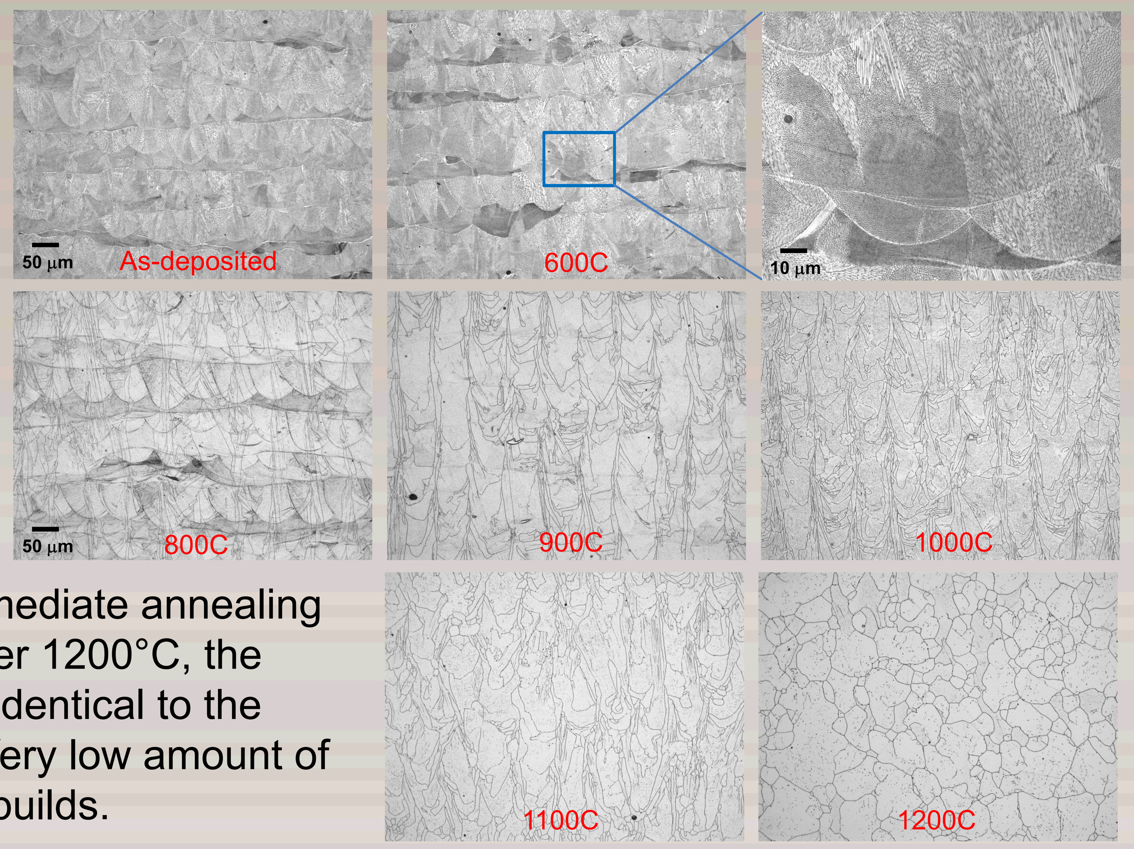
"Basket-weave" pattern visible in the top down view.
Fine-scale cellular solidification sub-structure in the as-deposited condition.

Unusual square shaped grains dominate this view, with finer grains in between.

The structure changes only slightly until 1200°C, replaced by relatively large equiaxed grains with no remnant of the deposited structure.

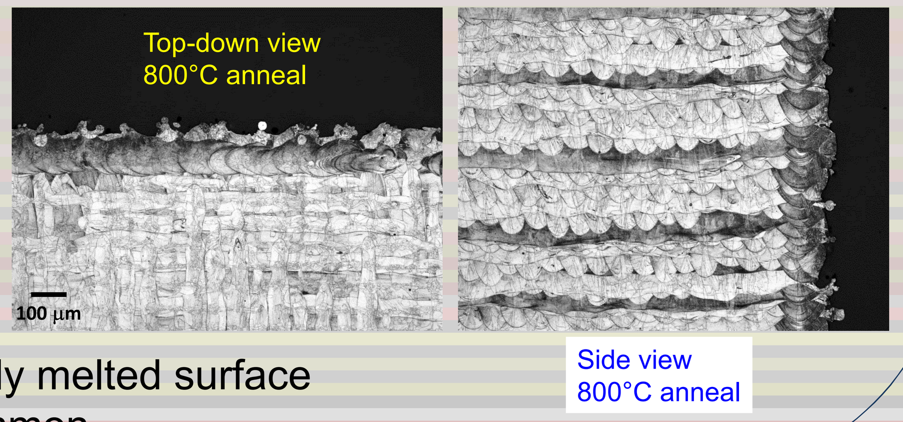
Microstructure in the side-view orientation

Layers of overlapping laser welds are visible. Fine-scale cellular structure is annealed out between 700 and 800°C. A roughly columnar grain structure develops at intermediate annealing temperatures. After 1200°C, the microstructure is identical to the top-down view. Very low amount of porosity in these builds.



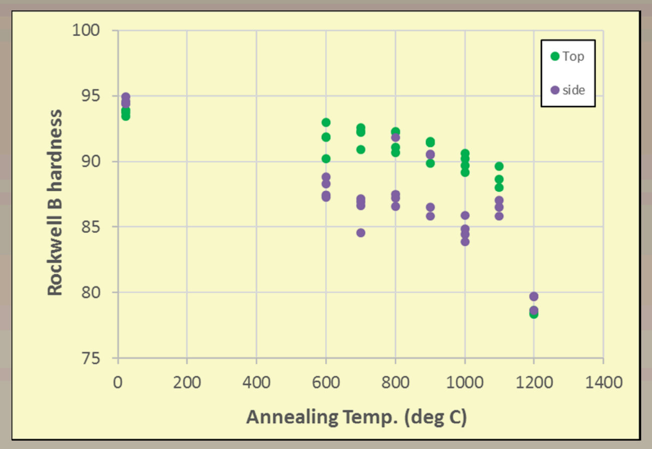
Microstructure of contour pass (edge effect) regions

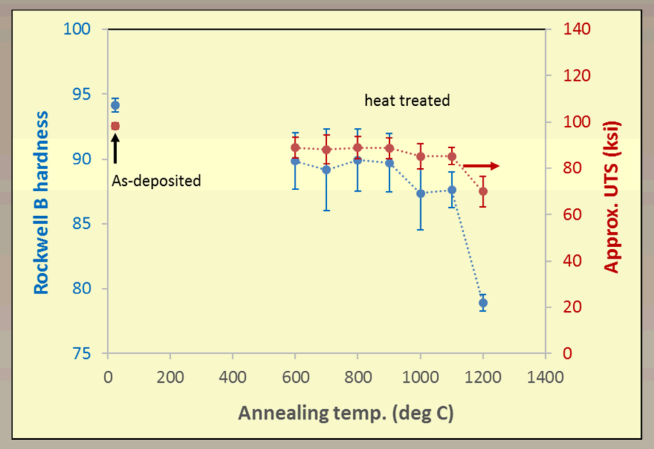
Surface contour passes employed different parameters than the interior passes. The contour passes appear wider, mainly due to absence of overlap effects. Unmelted/partially melted surface particles are common.



Hardness and Strength Results; Effects of Heat treatment

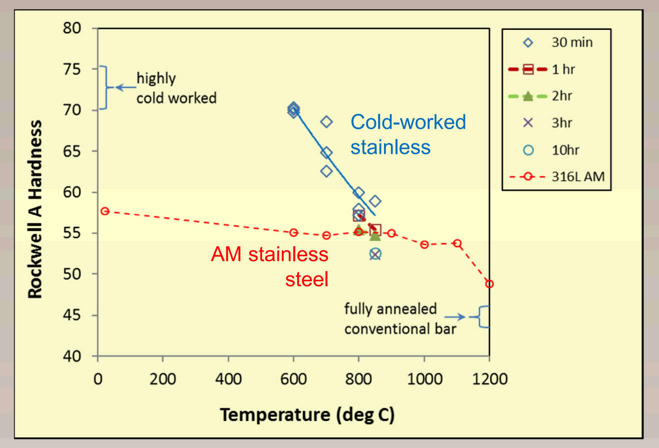
Effects of orientation and heat treatment on hardness





Hardness in the top-down direction was slightly, but consistently, higher than hardness measured on the side of the build. This was true for the (anisotropic) columnar grain structures produced at intermediate anneal temperatures. The as-deposited material and the 1200°C annealed samples were isotropic in both microstructure and hardness.

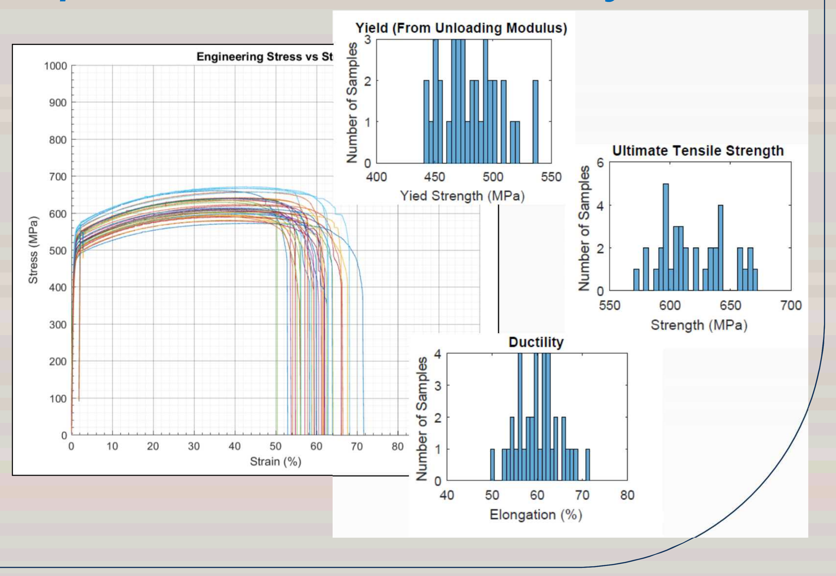
Overall, the hardness decreased only moderately up to 1200°C where a larger drop was exhibited due to recrystallization and growth of equiaxed grains. Although the as-deposited hardness is somewhat higher than annealed 316L due to fine-scale microstructure, it does not contain high amounts of deformation (dislocation density not very high). Therefore, it does not exhibit a dramatic annealing response.



In comparison, highly cold-worked (flowformed) tube shows a significant annealing response as low as 700°C.

Tensile test results: as-deposited condition only

Ultimate strength correlates well to the hardness results. Ductility is comparable to wrought material, although with somewhat more scatter in strain-to-failure. The range 50-70% ductility is still quite good for AM material and highlights the low defect concentration in this material.



Summary & Future Work

The microstructure of AM 316L, built with the ProX 300 system, shows low porosity and a fine solidification substructure in the as-deposited condition. With annealing treatments, slight anisotropy develops due to differences in microstructure – columnar grains in the side view and large "square" grains in the top-down view separated by a fine grain network. The material properties are only moderately affected up to about 1200°C.

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NNSA National Nuclear Security Administration
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