Microstructure & Mechanical Properties of Direct Metal Laser Sintered (DMLS) SS316L in the As-Printed and Heat Treated Condition

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Shashidhara S	Tensile Tests
Sandeep, Ananth Prof. A S ShetraBalan	AIMIL (Particle Size Distribution) VIT (Surface Roughness)

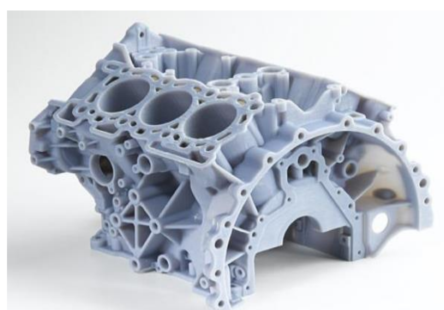
Background on Additive Manufacturing

Additive Manufacturing technology is seen as an emerging technology for repair as well as new make (near net shape) applications. The advantages of the process are in being able to result in near net shape, complex parts, with weight savings

Additive Manufacturing Applications

Aerospace

Healthcare



Automotive Parts

Background – SS316L

Stainless Steel alloy 316/316L is a chromium-nickel molybdenum austenitic stainless steel developed to provide improved corrosion resistance to Alloy 304/304L in corrosive environments.
Grade 316L, the low carbon version of 316 and is immune from sensitisation (grain boundary carbide precipitation). Thus it is extensively used in heavy gauge welded components (over about 6mm).
Post-weld annealing is not required when welding thin sections.
The addition of molybdenum improves general corrosion and chloride pitting resistance. It also provides higher creep, stress-to-rupture and tensile strength at elevated temperatures.
It is readily used in a variety of parts for applications in the industrial, architectural, and transportation fields.

Objective – Characterization of DMLS SS316L

- To optimize parameters for dense part in the As-Printed sample without any Hot Isostatic Pressing (HIPing).
- To characterize DMLS SS316L (Stainless Steel 316L) and evaluate its suitability for orthopedic implant materials.

Properties of SS316L

1) High Tensile Strength
2) Resistance to corrosion
3) Biocompatibility
4) Excellent welding characteristics.

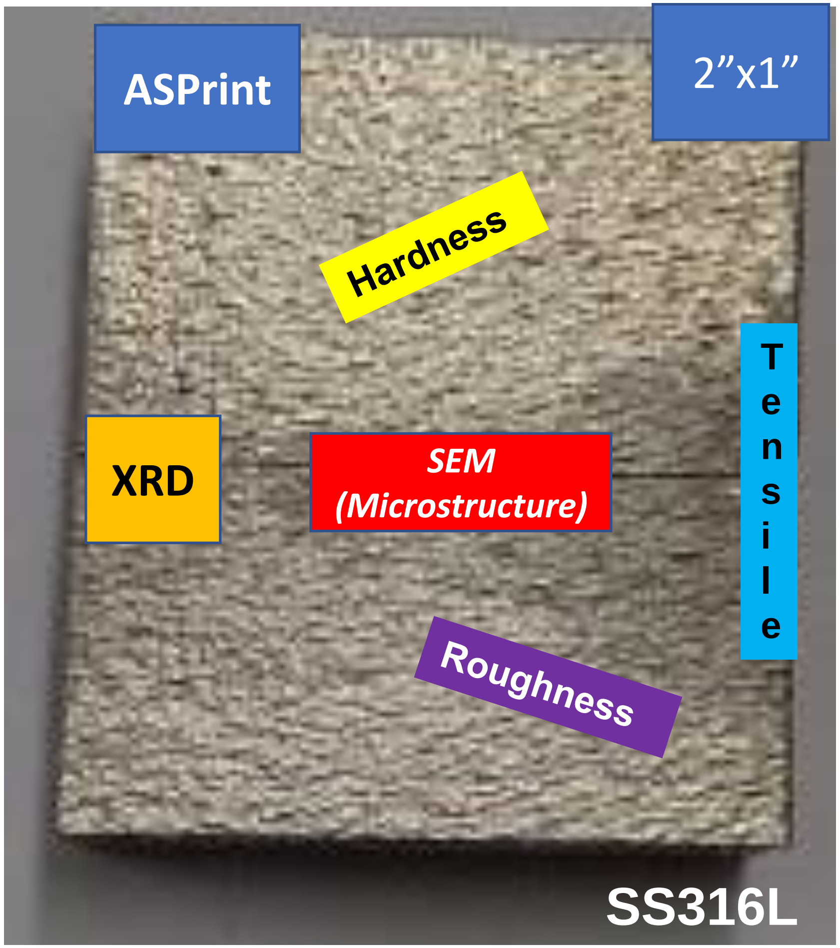
The objective of this analysis is to characterize DMLS SS316L in the as printed and heat treated condition, for mixed powder (Praxair & Oerlikon) and bulk sample (Praxair)

a. Roughness
b. Hardness
c. Microstructure (porosity, particle size analysis, chemistry and phases)
d. X-ray diffraction (phase analysis)
d. Tensile strength (Room Temperature) - small scale testing

in order to serve as a baseline for building various products

Characterization DOE

Particle Size Analyser	•Malvern 3000; Dry Method; Size Range (10nm to 3.5mm)
Surface Roughness	• Mahr MarSurf GD 120
Microstructure	•Zeiss Axiocam HRc with Axiovision & ImageJ software
Microhardness	•Future Tech FM 800 Tester Load=300gf; Vickers Method
SEM	•FEI Quanta200 •ThermoFisher EDS
X-Ray Diffraction	•Xpert PRO PANAnalytica Cu K_{α} λ=1.54 Å ; Angle Range (20-100) deg, Step Size: 0.033, Step Time: 118.5 sec
Tensile Strength	• Instron 5987, 2 KN, Strain Rate: 0.006mm/s
Heat treatment	• No Heat Treatment tests were done on SS316L



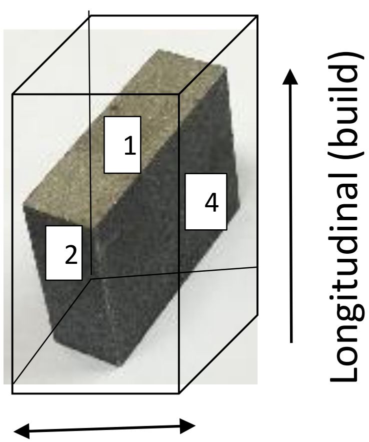
Etchant for SS316L As-Printed

Glyceregia: (15cc HCl, 10cc HNO3, 5 drops of glycerine); Dip for 10-15 seconds

Nominal Composition of SS316L (wt%) *from EOS Data Sheet*

Element	Fe	Cr	Ni	Mo	Mn	Si	Cu	P	S	N
Percentage	62-64	17-19	13-15	2.25-3	2	0.75	0.5	0.025	0.01	0.1

Process Parameters for DMLS sample	May not be accurate
Laser Power	250-300W
Beam Diameter	80µm
Layer Thickness	20-80µm
Hatch Distance	80-120µm
Scan Speed	800-1000mm/s
Powder Size	35µm



Transverse direction

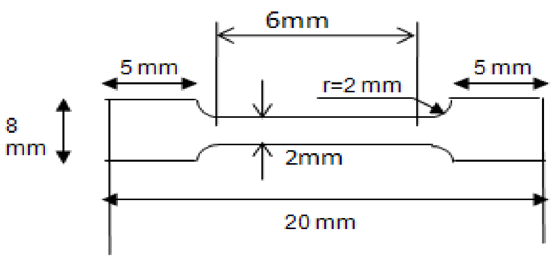
Legend: Cube

1 Top surface (where name/code is)

2 Transverse surface used

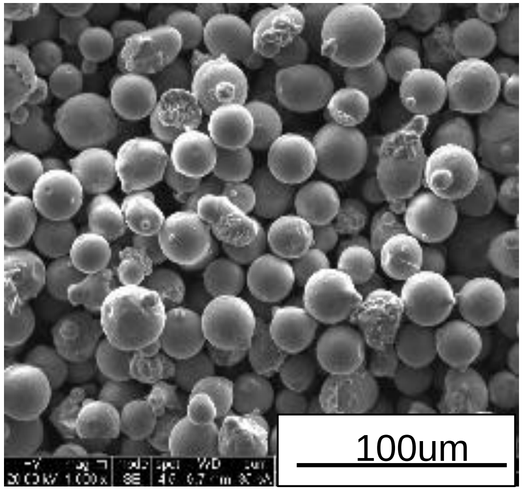
4- Side surface (Any side can be Longitudinal)

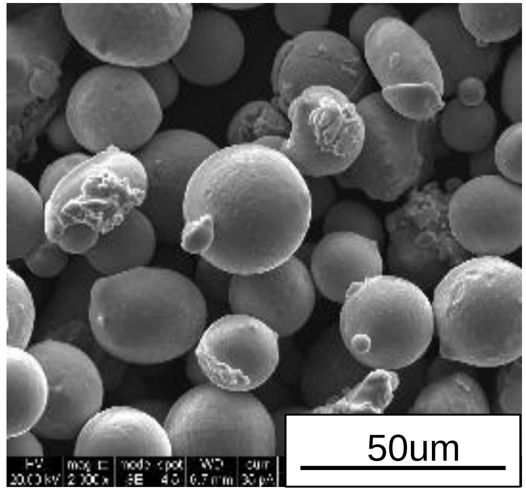
Tensile Sample



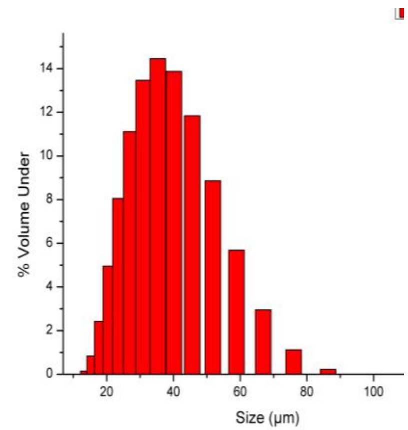
GaugeLength:	**6mm**
Thickness:	**0.5mm**
StrainRate:	**0.006 mm/s**

Powder Characterization



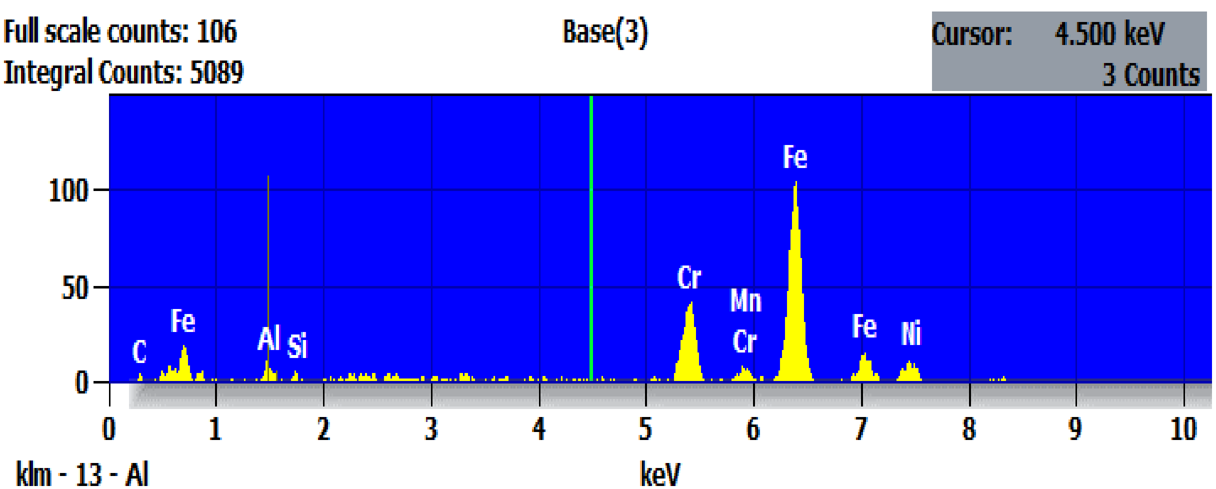


Particle Size Distribution



Particle Range	Avg.Size µm
Dv10	21.77
Dv50	33.676
Dv90	51.802

Energy Dispersive Spectroscopy (EDS)



Composition of SS316L (wt%)

Fe	66.54
Cr	18.32
Ni	11.63
Mn	2.04
Si	0.99

Average Particle Size was found to be approx : 34 µm

Surface Roughness

Glass Bead Blasting Conditions

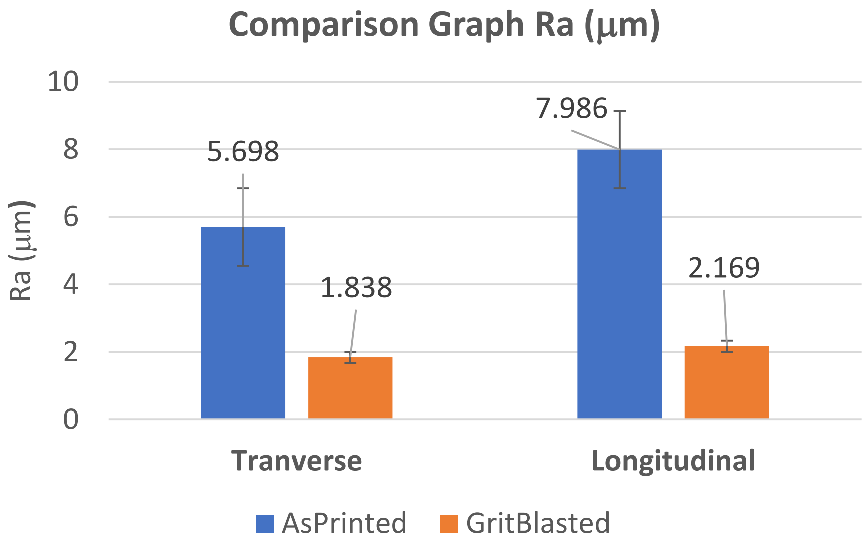
Pressure	7.5 bar
Time	5 min
Distance bw gun & workpiece	Average 155 mm
Angle between gun and workpiece	45 deg

Glass Bead Blaster

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i|$$

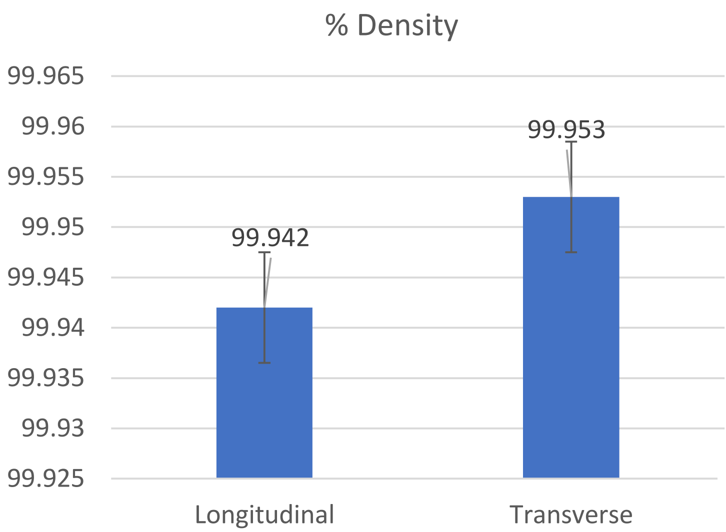
Left: As-Printed

Right: Glass Bead Blasted



Roughness decreases by almost 70% upon glass bead blasting in both Transverse and Longitudinal directions

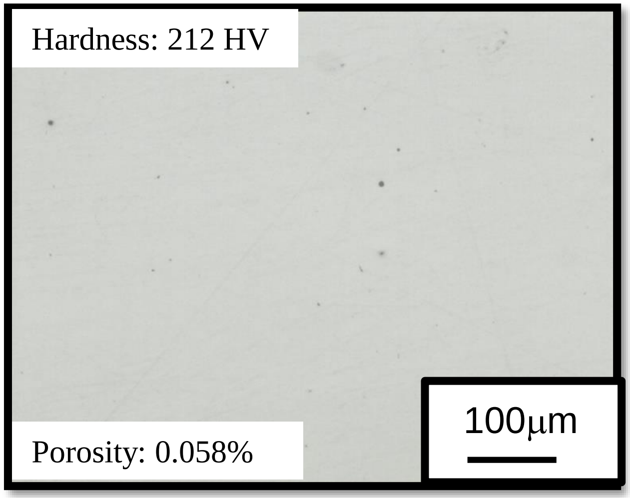
Porosity: Optical Images



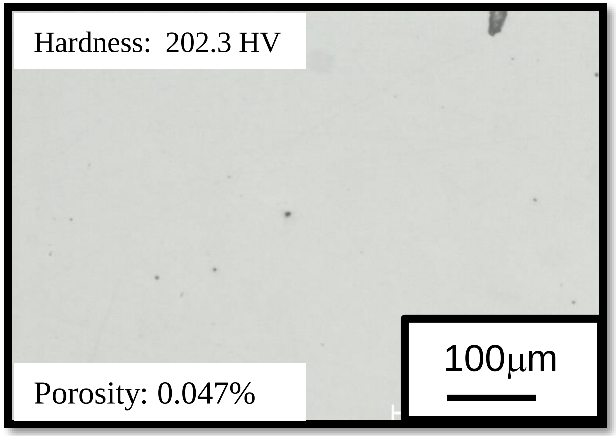
% Porosity:
Longitudinal: 0.058%
Transverse: 0.047%
Overall: 0.053%

Porosity is slightly higher when viewed from longitudinal surface compared to transverse surface.

Longitudinal

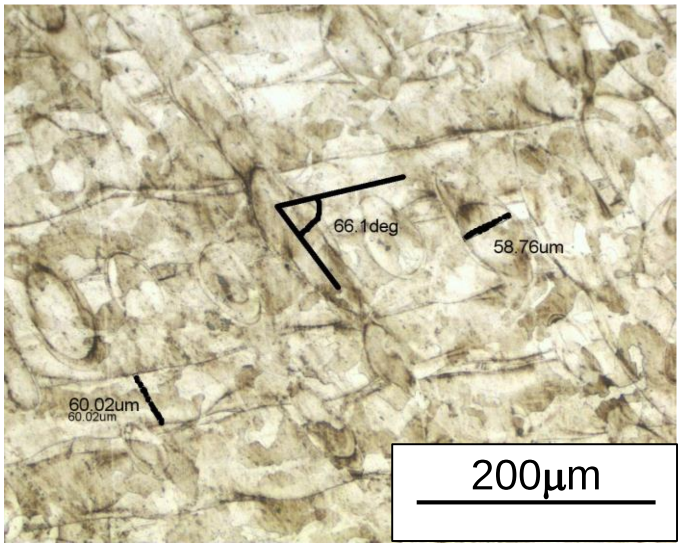


Transverse



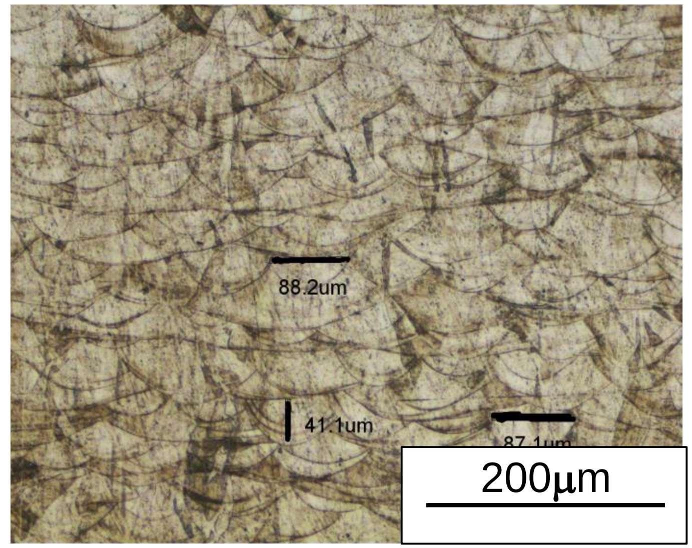
Optical Microstructure

Transverse



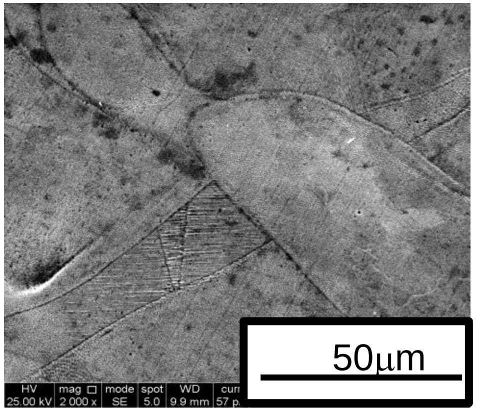
Average width : 59.4 microns
Angle between layers of 3D printed sample as measured was: 66.1 degrees

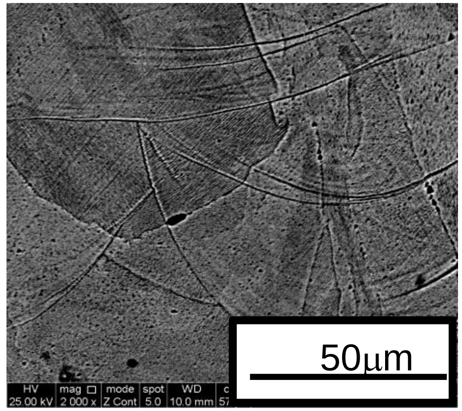
Longitudinal

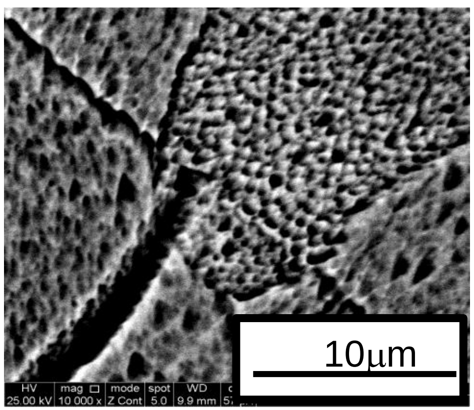


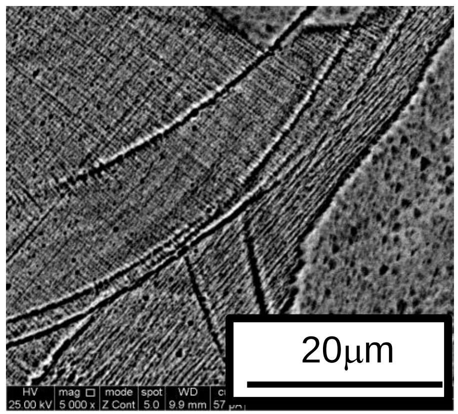
Average Diameter: 87.65 microns
Average Depth: 41 microns

Scanning Electron Microscope Images (Microstructure)

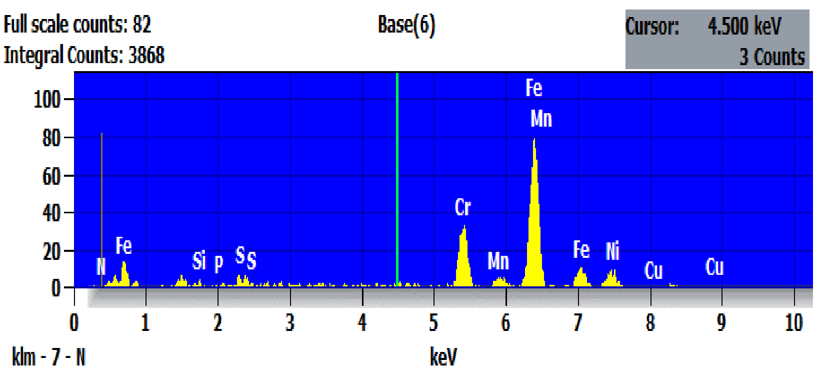








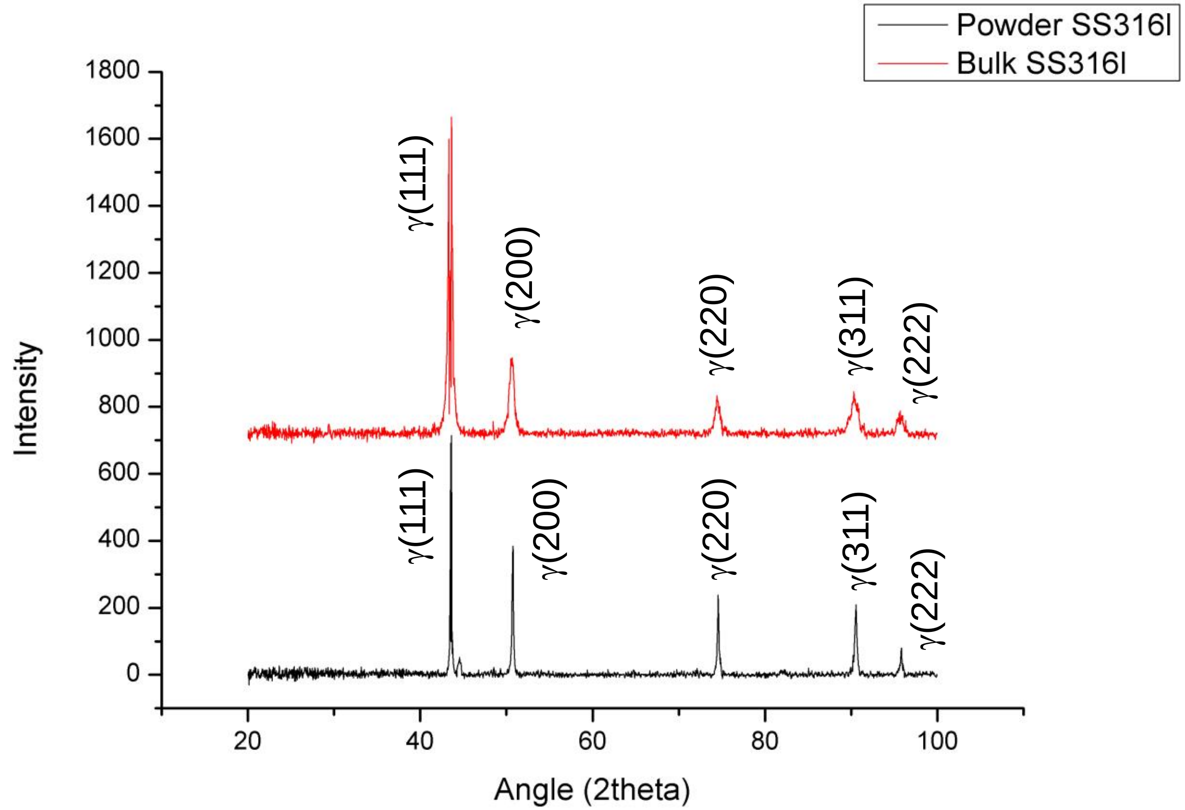
Elements	Weight(%)
Iron (Fe)	64.72
Chromium	18.09
Nickel	11.76
Molybdenum	2.21
Manganese	1.24
Copper	0.98
Phosphorus	0.21
Silicon	0.79
Sulphur	0
Nitrogen	0



SEM images and EDS (Chemical Composition) were done and results were compiled

X-Ray Diffraction (XRD)

Parameter	Values
Starting angle (deg)	20
Finishing angle (deg)	100
Wavelength (Å)	1.54
Voltage(KV)	40
Current (mA)	30
Step size(deg)	0.003

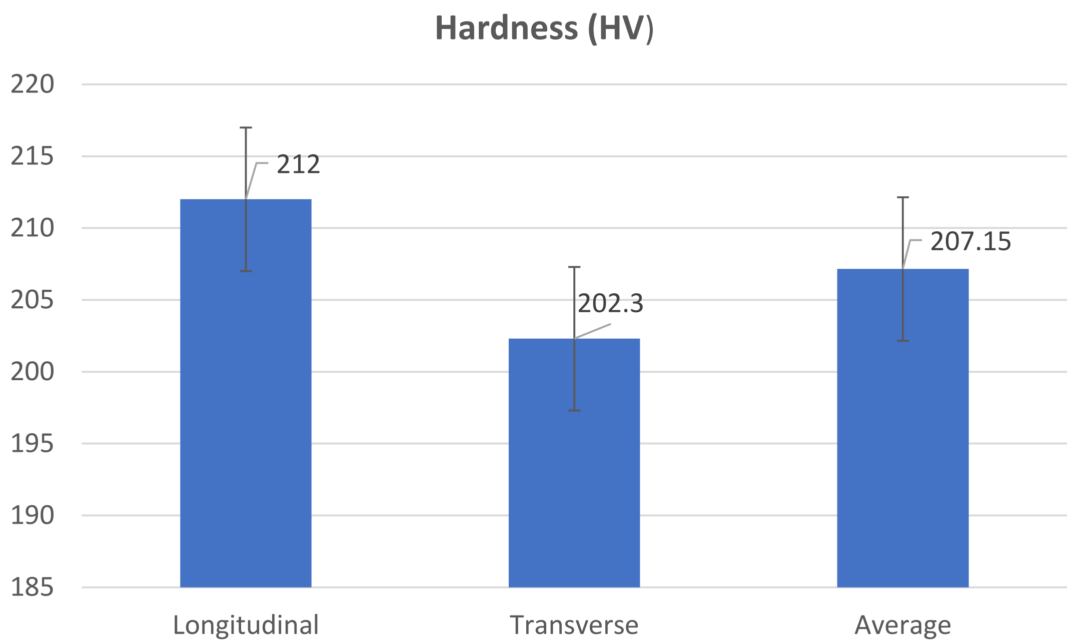


Referring to close matches in (Austenite peaks)

1) ***ICDD 00-033-0945 for powder***
2) ***ICDD 00-033-0945 for ASP***

The peaks are matched for γ FCC phases of iron in SS316L.

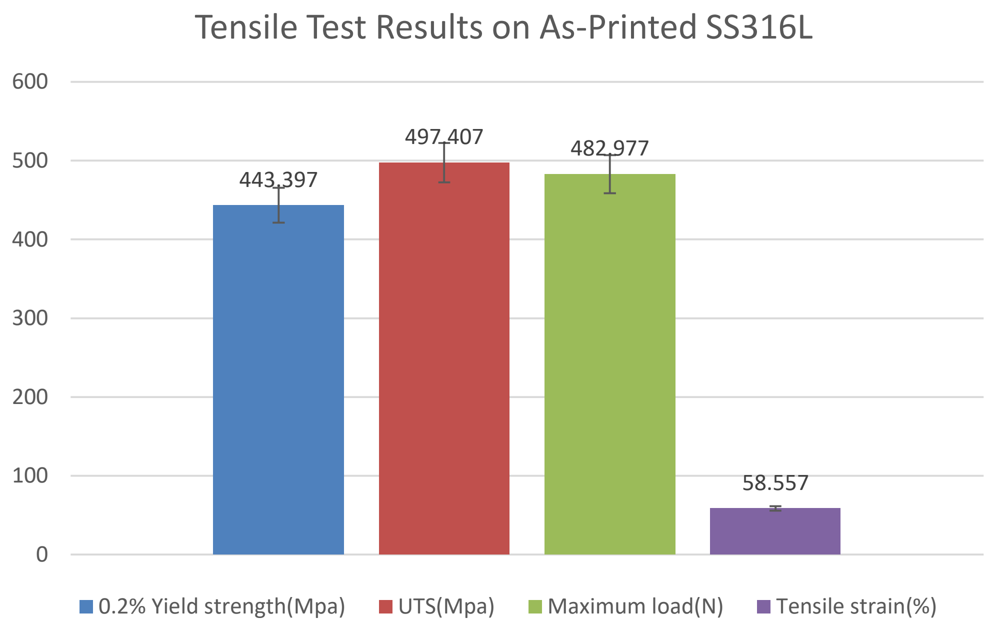
Vickers Microhardness



Future Tech FM 800
Tester Load=300gf;
Vickers Method

Comparing with data in literature, the Hardness values are perfectly in range of 90-95 HRB ~~ 200-210 HV

Tensile Testing- Room Temperature- Small scale test



Load v/s Displacement

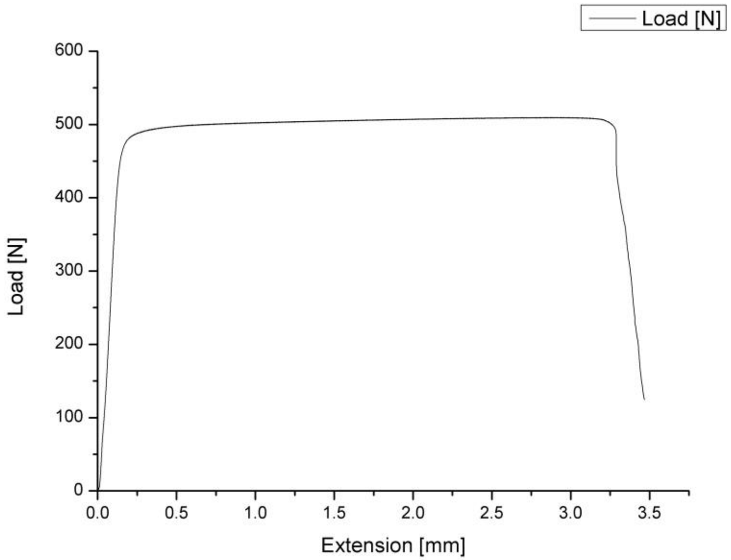
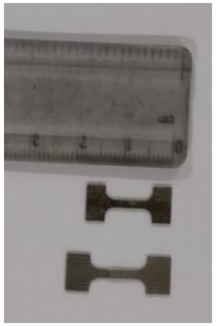


Image of specimen (before and after fracture)
Extension: 3.2mm

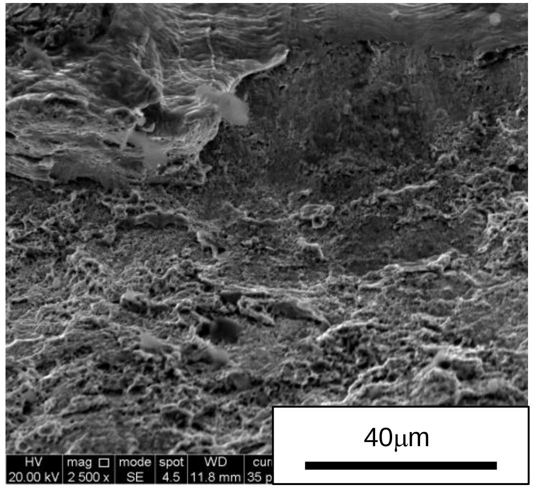


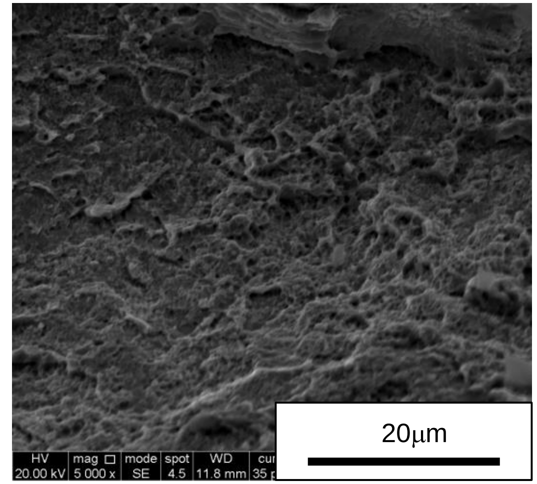
The As-Printed sample has a 0.2% yield strength of about 443 MPa.
The small scale tensile test results match with EOS regular size sample standards.

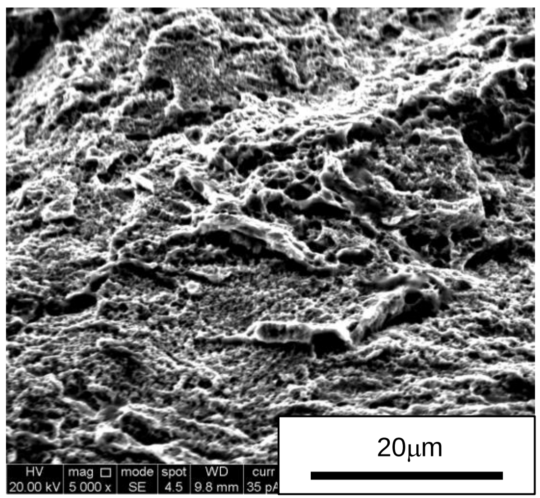
%Elongation: 58%

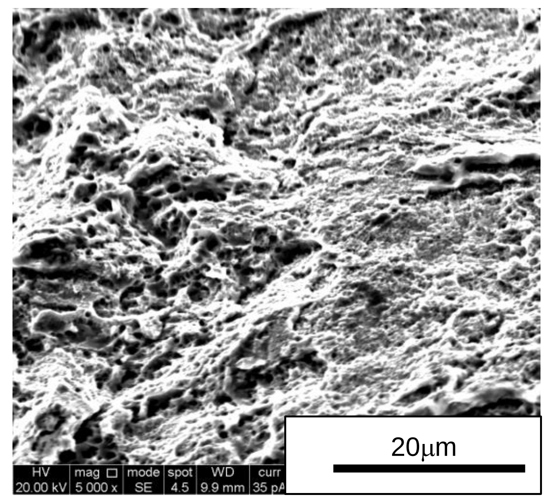
Fractographs

As-Printed (all 4)









In the austenitic SS316L, the fractographs resembles a ductile failure with fine feature dimples.

Executive Summary

Attribute	Overall	As-Printed (mm)	Glass Bead Blasted (mm)
Powder Particle size	34mm		
Surface Roughness		6.85	1.98
Porosity	0.05%		
Weld Pool: Avg. width	59mm		
Angle bw layers	66.1 deg		
Weld Bead: Avg. Diameter	87.6mm		
Weld Bead: Avg. Depth	41mm		
XRD		γ FCC phase	
Hardness	207 HV		
% Elongation	58%		
Fractograph	Ductile Fracture		

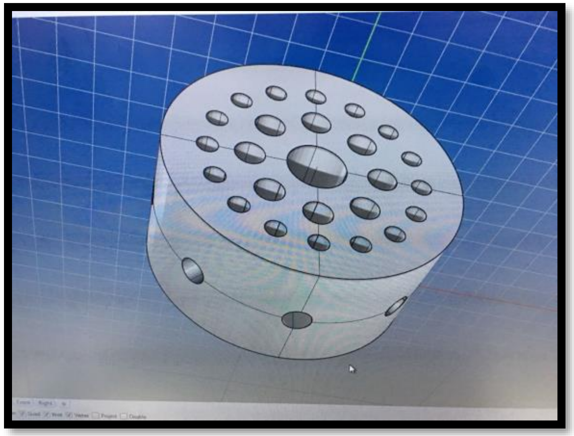
References:

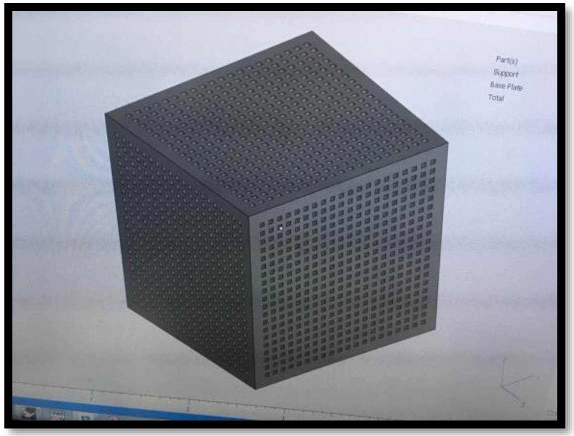
1) http://www.georgevandervoort.com/metallography/
2) https://www.finishing.com/
3) www.metallographic.com/Etchants/Etchants.htm
4) https://www.cartech.com/
5) *'Microstructural Evolution and Mechanical Properties of Direct Metal Laser-Sintered (DMLS) CoCrMo After Heat Treatment '* Bawane et.al **Metallurgical and Materials Transactions A, 2018**
DOI 10.1007/s11661-018-4771-4
6) '*Study of Process Parameter and Powder Variability on the Properties and Recrystallization Behavior of Direct Metal Laser Sintered CoCrMo'* **Santhosh Kumar Rao Chandrasekara, Anigani Sudarshan Reddy, Dheepa Srinivasan, Durga Ananthanarayanan; Proceedings of the ASME 2017 Gas Turbine India Conference**

SS316L: Biocompatibility Studies

3D- Model
Images

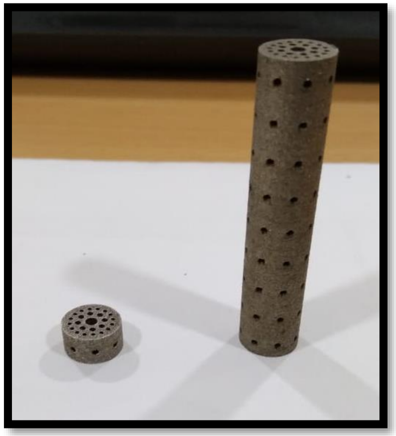
(Software used:
Rhinoceros)



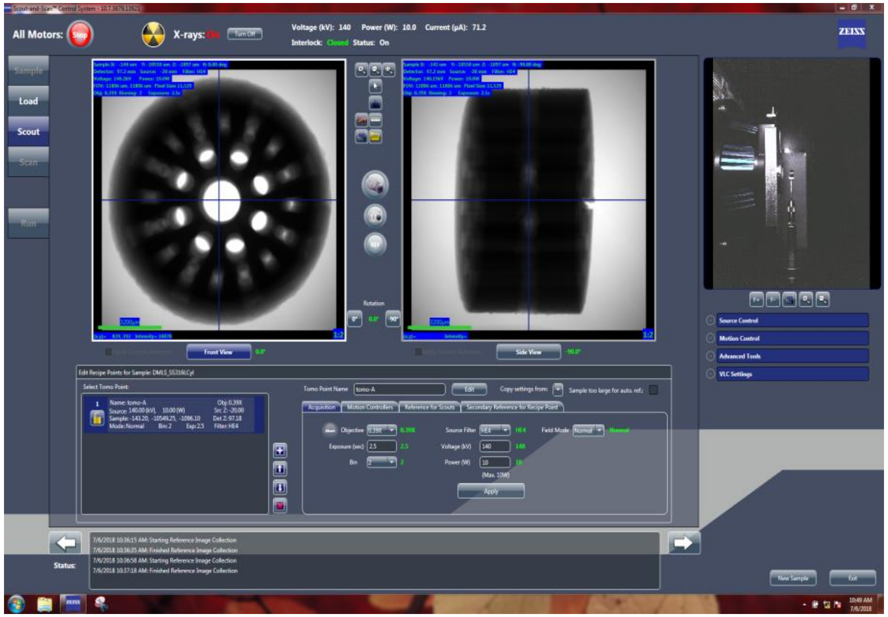


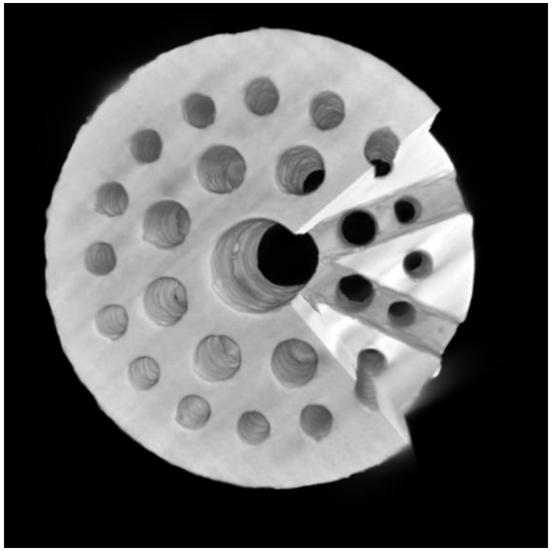
Actual 3D printed
Sample

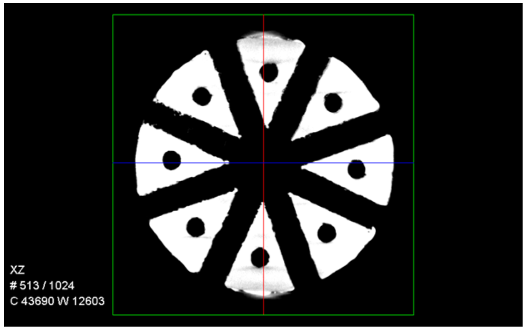
Dimensions of Cube :
1inch^3
Cylinder: 2inch height;
Radius 1.5 cm

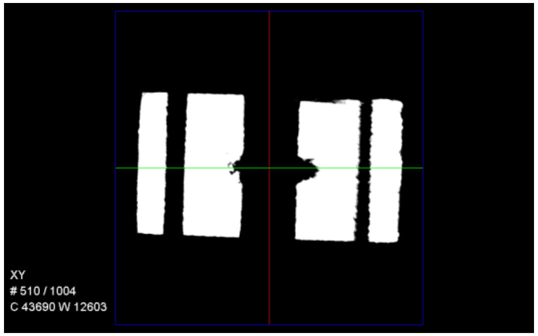


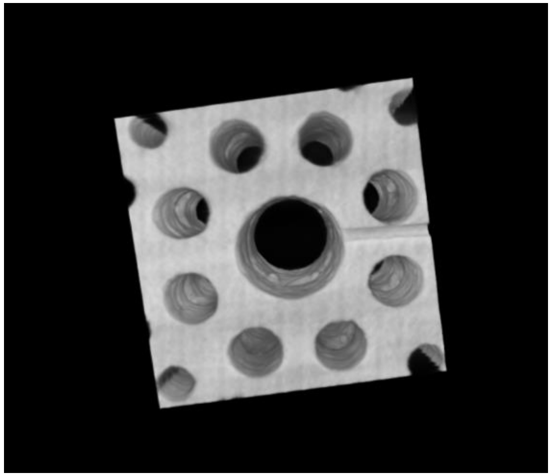
Cylinder shape



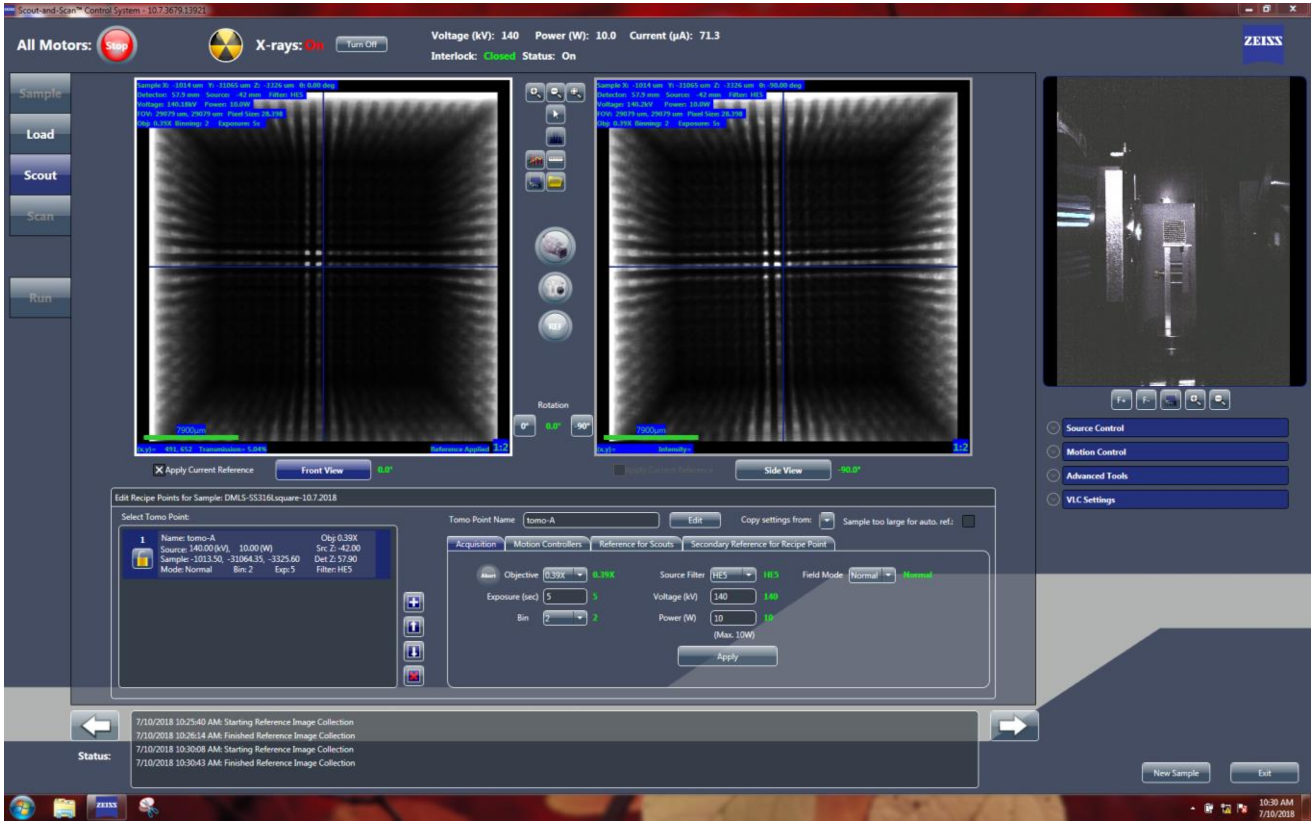


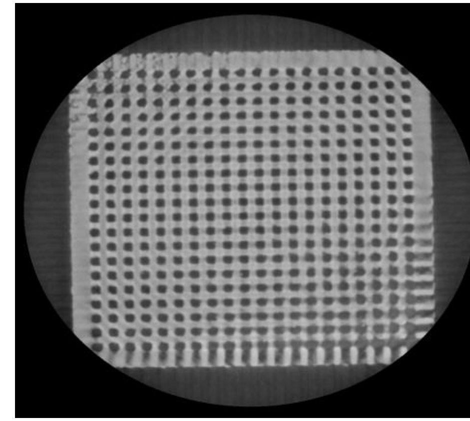


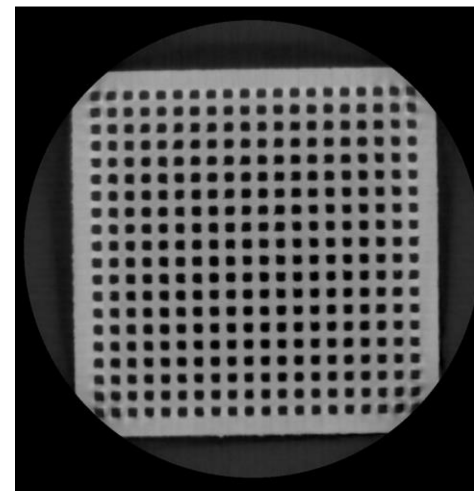




Cubic shape


All Motors:
Stop
X-rays: On
Turn Off
Voltage (kV): 140 Power (W): 10.0 Current (µA): 71.3
Interlock: Closed Status: On
ZEISS
Sample
Load
Scout
Scan
Run
Rotation
Apply Current Reference
Front View
Side View
Edit Recipe Points for Sample: DMLS-SS316Lsquare-10.7.2018
Select Tomo Point
Tomo Point Name
tomo-A
Edit
Copy settings from:
Acquisition
Motion Controllers
Reference for Scouts
Secondary Reference for Recipe Point
Objective
Exposure (sec)
Bin
Source Filter
Voltage (kV)
Power (W)
Field Mode
Apply
Source Control
Motion Control
Advanced Tools
VLC Settings
Status:
7/10/2018 10:25:40 AM: Starting Reference Image Collection
7/10/2018 10:26:14 AM: Finished Reference Image Collection
7/10/2018 10:30:08 AM: Starting Reference Image Collection
7/10/2018 10:30:43 AM: Finished Reference Image Collection
New Sample
Exit





Watch: Tomography video (360 deg view)