National Center for Additive Manufacturing Excellence

Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts

Project sponsored by: Federal Aviation Administration (FAA)

Introduction

- **Project Title**: Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts
- **Principal Investigator**: Nima Shamsaei

(See next slide for complete list of participants.)

- **FAA Technical Monitor**: Kevin Stonaker
- **Source of matching contribution**: Faculty time and graduate research assistant tuition

JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Project Team

Kevin Stonaker
Project Manager
FAA TPOC

Aziz Ahmed
Cindy Ashforth
John Bakuckas
Michael Gorelik
Jeffrey D Stillinger
Walter Sippel

Advisory Group

Jim Dobbs
Boeing

Jeffrey Gaddes
US Army

Richard Grylls
Beehive3D

Frederic Marrion
GE Additive

Mahdi Habibnejad
GE Additive

Mohsen Seifi
ASTM Int.

Brandon Phillips
US Army

Katherine Olson
US Army

Ankit Saharan
EOS – N.A.

Douglas Wells
MSFC, NASA

NCAME Project Team
Auburn University

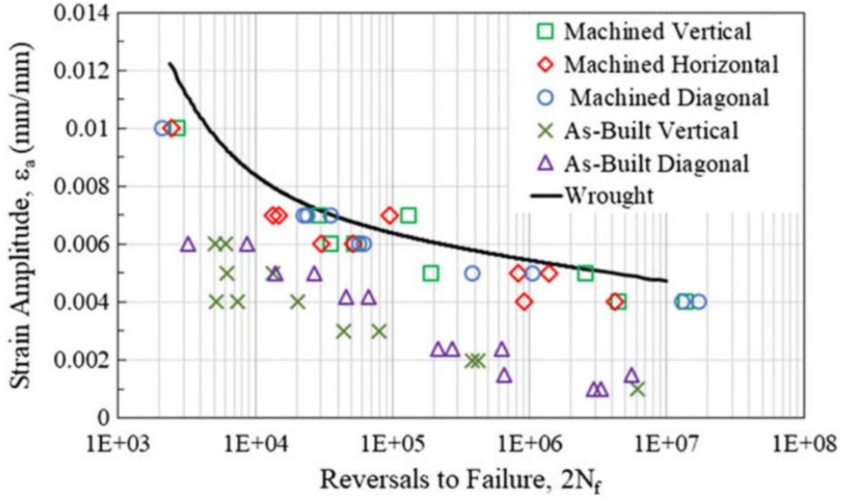
7 Senior Investigators
8 Graduate Research Assistants

PI: Nima Shamsaei (Mechanical Engr.)

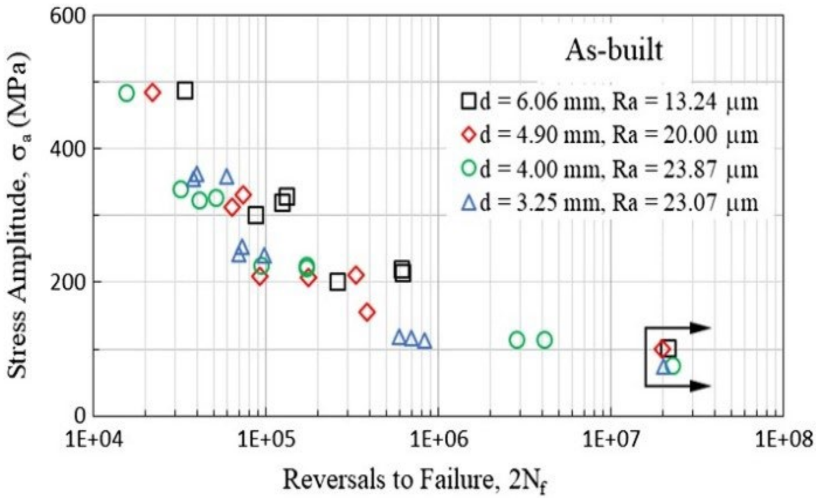
Co-PIs:
Shuai Shao (Mechanical Engr.)
Robert Jackson (Mechanical Engr.))
Kyle Schulze (Mechanical Engr.)
Daniel Silva Izquierdo (Indus. Sys. Engr.)
Aleksandr Vinel (Indus. Sys. Engr.)
Jia Liu (Indus. Sys. Engr.)

Background

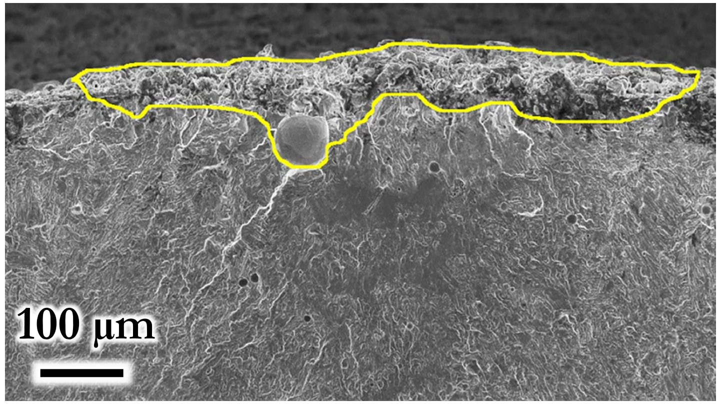
L-PBF Ti-6Al-4V



L-PBF Ti-6Al-4V



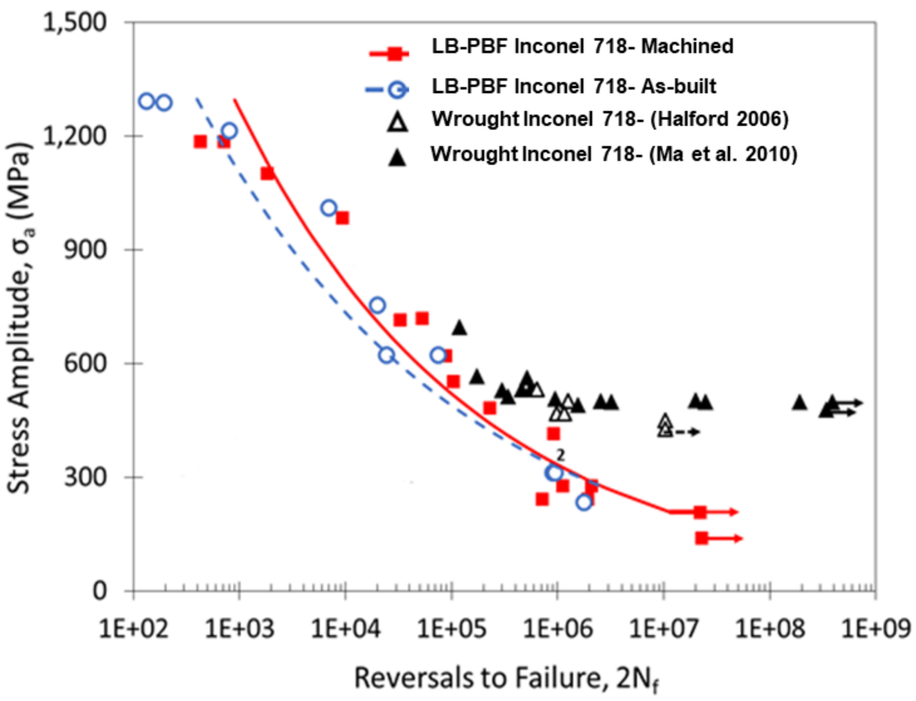
L-PBF 17-4 PH SS

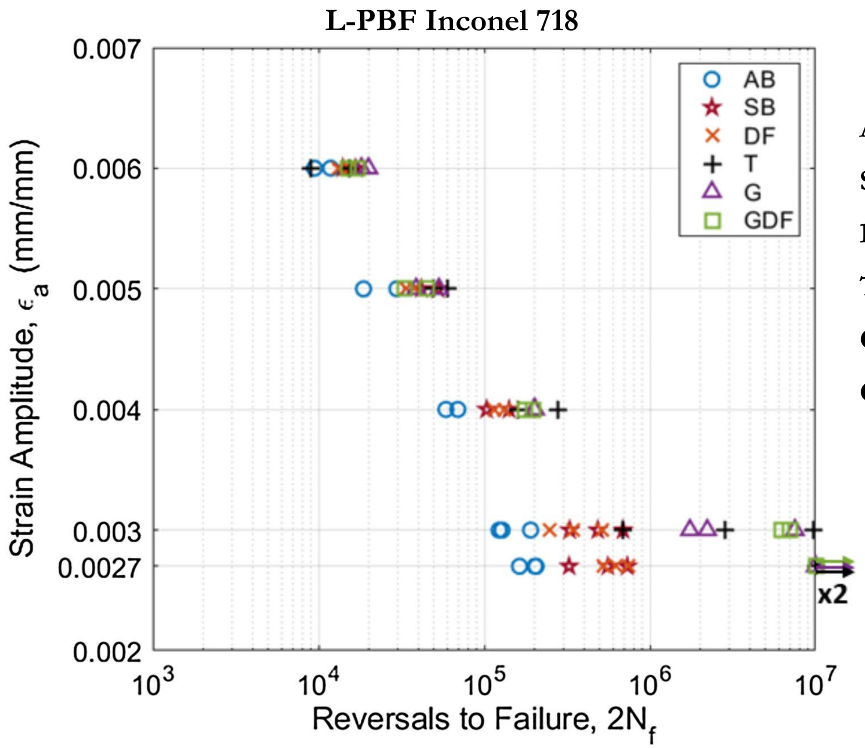


- The fatigue lives of L-PBF Ti-6Al-4V specimens in as-built surface are consistently shorter compared to the specimens with machined surface condition
- Fatigue cracks in specimens with as-built surface typically initiate from micro-notches on the rough surface
- In some cases, one or two volumetric defects, often gas entrapped pores, are also found near the crack initiation site
- The fatigue strength appears to decrease with the increase in surface roughness

Fatemi, Molaei, Simsiriwong, Sanaei, Pegues, Torries, Phan, Shamsaei, Fatigue Fract Eng Mater Struct. 42 (2019) 13000
Romano, Nezhadfar, Shamsaei, Seifi, Beretta, Theoretical and Applied Fracture Mechanics 106 (2020) 102477

Background





AB: As-built

SB: Sand-blasting

DF: Drag Finishing

T: Turned

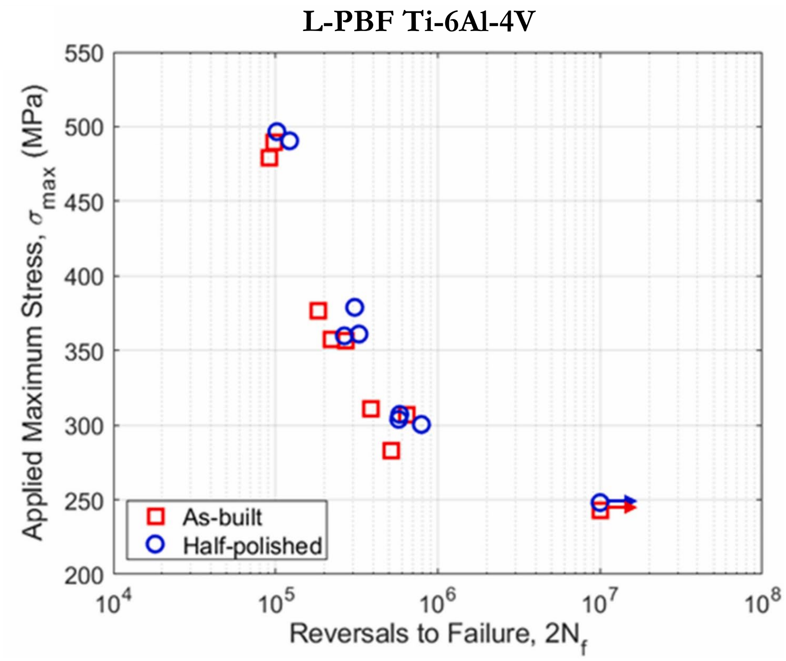
G: Grinding

GDF: Grinding+Drag Finishing

- Different surface treatments can improve fatigue life to different extents
- Efficacy of surface treatments depends on the material and selected parameters
- Insufficient machining depth may expose near-surface pores to the surface

Yadollahi, N. Shamsaei, Int. J. Fatigue 98 (2017) 14–31
Lee, Shao, Wells, Zetek, Kepka, Shamsaei, Journal of Materials Processing Tech. 302 (2022) 117475

Challenge

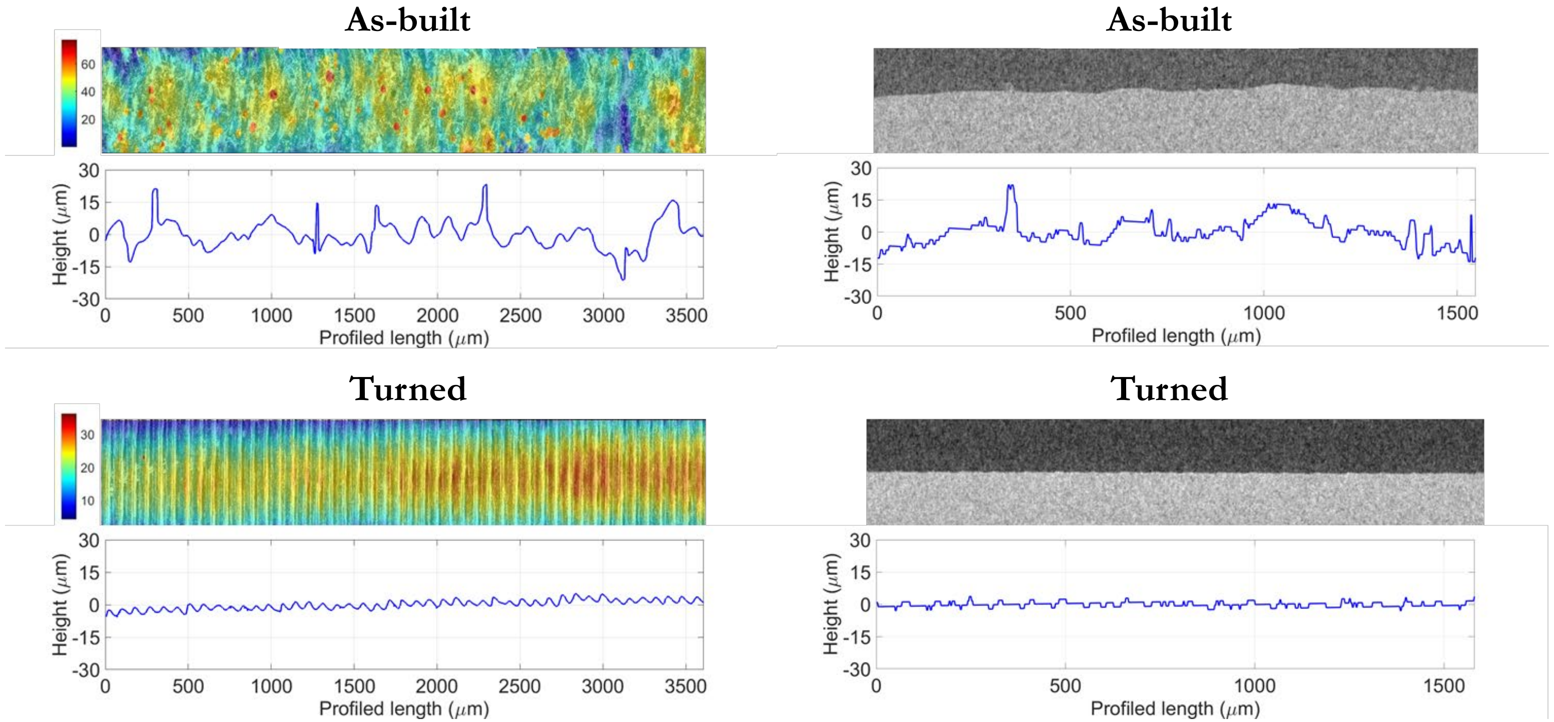


Surface texture parameters	As-built		Half-polished	
	Line	Area	Line	Area
Arithmetical mean height (Ra or Sa)	18.8 μm	19.8 μm	9.0 μm	11.6 μm
Root mean square deviation (Rq or Sq)	23.2 μm	24.5 μm	11.0 μm	14.0 μm
Maximum profile peak height (Rp or Sp)	62.8 μm	111.8 μm	15.5 μm	31.0 μm
Maximum profile valley depth (Rv or Sv)	58.7 μm	87.7 μm	35.2 μm	56.7 μm

- Although standard surface parameters for as-built and half-polished specimens differ by almost a factor of two, fatigue lives of half-polished specimens did not improve
- Standard surface parameter could not capture the effect of surface texture on the fatigue behavior of AM parts

S. Lee, B. Rasoolian, D. Silva, J. Pegues, N. Shamsaei, Additive Manufacturing 46 (2021) 102094

Challenge



- The applicability of different non-destructive inspection (NDI) techniques to measure the surface texture of AM parts has not been thoroughly studied
- While x-ray computed tomography (XCT) can capture surface texture and subsurface volumetric defects, it is costly to use and the resolution may not be adequate
- Depending on the measurement technique employed, the calculated values of standard surface parameters may vary

Objective & Approach

- **Objective**: Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts
- **Approach**: Four steps are taken,
  I. Explore the effect of key process variables and/or post-processing on surface and near-surface conditions
  II. Evaluate the effectiveness of NDI techniques to assess their capability of detecting material and manufacturing critical anomalies on the surfaces and near-surface
  III. Determine the combined effect of surface and near-surface defects on tensile behavior and fatigue life
  IV. Identify the key influencing defect features on tensile and fatigue properties and establish appropriate metrics for characterizing surface conditions

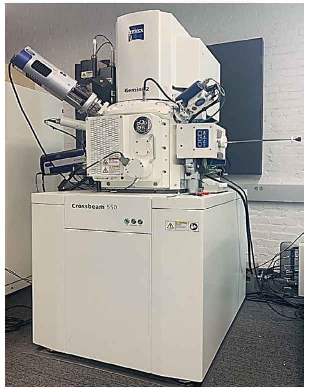
Task List

- **TASK 1: Literature Review & Design of Experiment (DoE)**
  - 1.1. Literature review
  - 1.2. DoE
- **TASK 2: Fabrication & Surface Treatments of Specimens**
  - 2.1. Fabrication of specimens with recommended infill parameters
  - 2.2. Fabrication of specimens with recommended contour parameters
  - 2.3. Surface treatments of specimens
- **TASK 3: NDI**
  - 3.1. Digital/optical microscope
  - 3.2. XCT
  - 3.3. Florescent penetrant inspection
- **TASK 4: Mechanical Testing & Fractography**
  - 4.1. Tensile & fatigue tests
  - 4.2. Fractography
- **TASK 5: Data Analysis & Modelling**
  - 5.1. Effectiveness of NDI techniques to detect surface/near-surface critical anomalies
  - 5.2. Surface/near-surface defect features – tensile behavior correlation
  - 5.3. Surface/near-surface defect features – fatigue life correlation
  - 5.4. Representative surface metrics for the tensile and fatigue behavior of AM parts
- **TASK 6: Final Report**

Fabrication and Testing Equipment

EOS M290 L-PBF

MTS Fatigue Testing



Scanning Electron Microscope

XCT

Keyence

Dektak

SWLI

- AP&C Ti-6Al-4V Grade 5 powder (15-53 μm) was used as feedstock
- XCT, Keyence, Dektak, and SWLI were used to measure surface texture

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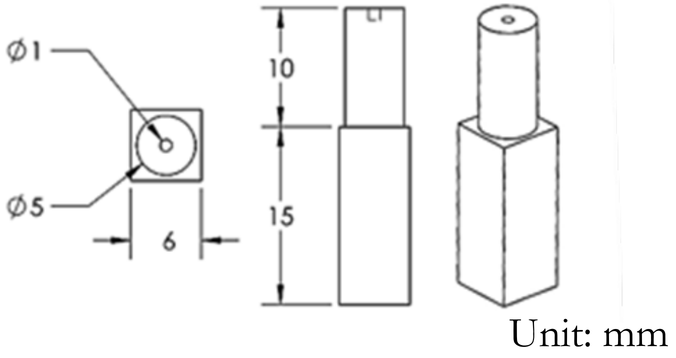
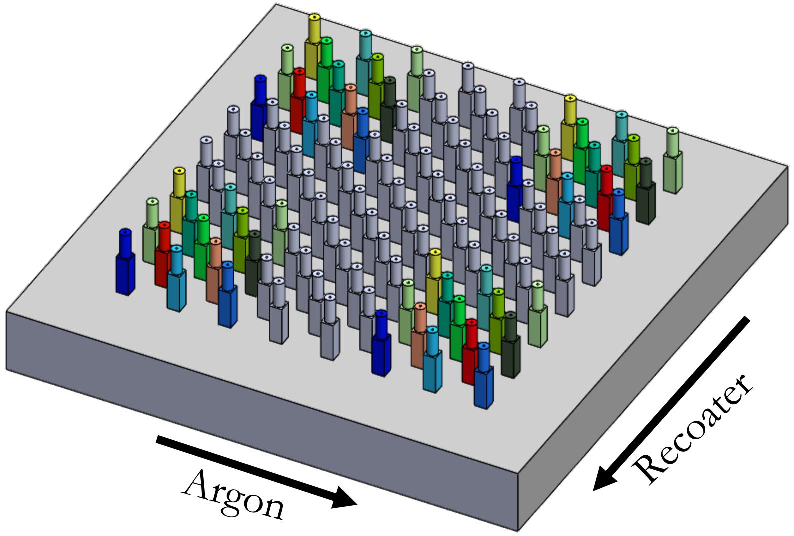
DoE: XCT Coupons

Condition	Laser order 1	Laser order 2	Laser order 3	P	V	h
Recommended	Infill	20 µm	0 µm	280	1200	0.14
LoF				252	1200	0.14
LoF				224	1200	0.14
LoF				280	1200	0.17
KH				364	960	0.14
KH				336	840	0.14
No contour	N/A	N/A	N/A			
Contour order	Offset, 20 µm	Offset, 0 µm	Infill			
Contour order	Offset, 20 µm	Infill	Offset, 0 µm			
Contour order	0um	Infill	Offset, 20 µm			
Single contour	Infill	Offset, 20 µm	N/A			
Single contour	Infill	Offset, 0 µm	N/A			
Different offset	Infill	Offset, 40 µm	Offset, 20 µm			
Different offset	Infill	Offset, 40µm	Offset, 0 µm			

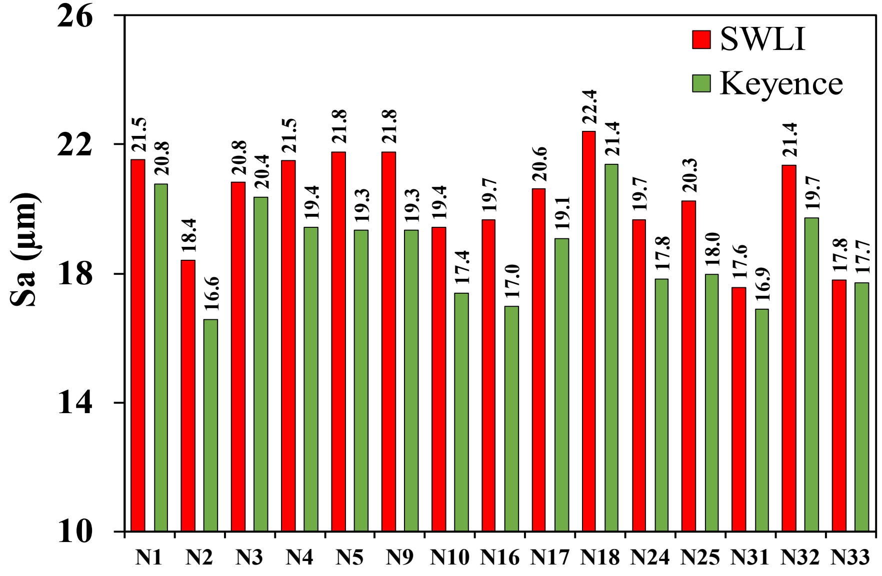
- 14 different key process variables were considered

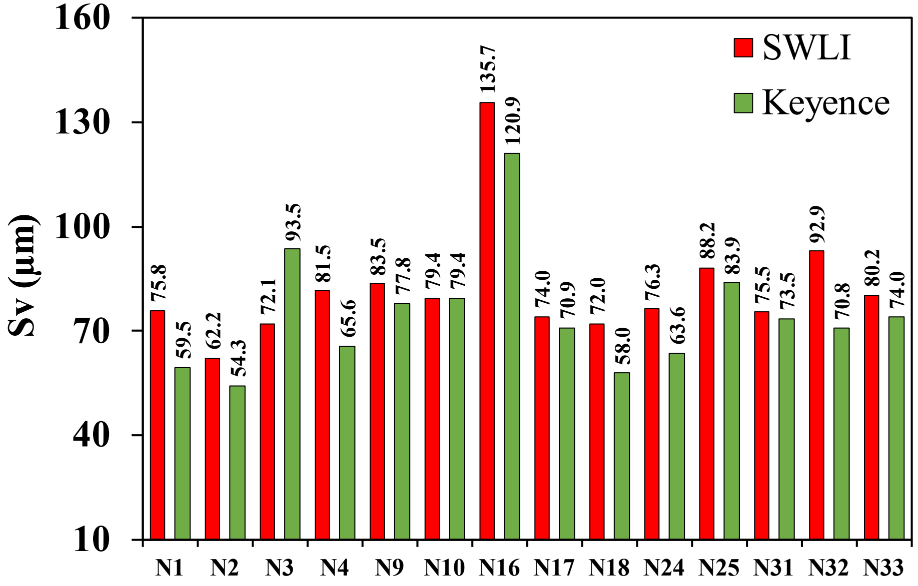




Coupon colors correspond to different process parameters, which are shown using corresponding color in the table

Results: Surface Texture of XCT Coupons





Coupons	N1	N2	N3	N4	N5	N9	N10	N16	N17	N18	N24	N25	N31	N32	N33
Condition	LoF	LoF	LoF	Default	Default	KH	KH	No contour	Contour order	Contour order	Contour order	1 contour	1 contour	Different Offsets	Different offsets

- Coupon without contour resulted in deepest surface valleys
- Infill process parameters (i.e., KH and LoF) did not significantly affect Sa and Sv values

Results: Selection of Process Parameters

Geometry	Orientation	Contour	Infill	Sa (µm)	Sv (µm)	Surface Treatment
Solid	Vertical	No contour	Default	19	135	No
Solid	Vertical	Order of contours	Default	20	74	No
Solid	Vertical	Order of contours	Default	20	70	No
Solid	Vertical	Order of contours	Default	19	76	No
Solid	Vertical	1 contour	Default	20	88	No
Solid	Vertical	1 contour	Default	17	75	No
Solid	Vertical	Different offsets	Default	21	92	No
Solid	Vertical	Different offsets	Default	17	70	No
Solid	Vertical	Default	KH	19	79	No
Solid	Vertical	Default	KH	21	83	No
Solid	Vertical	Default	LoF	21	75	No
Solid	Vertical	Default	LoF	18	62	No
Solid	Vertical	Default	LoF	20	93	No
Solid	Vertical	Default	Default	21	81	No

Note: Green shading indicates selected process parameters for fabrication of tensile and fatigue specimens

- Reported Sa and Sv values were obtained using SWLI

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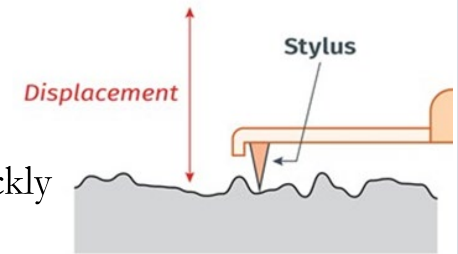
Overview of NDI Techniques

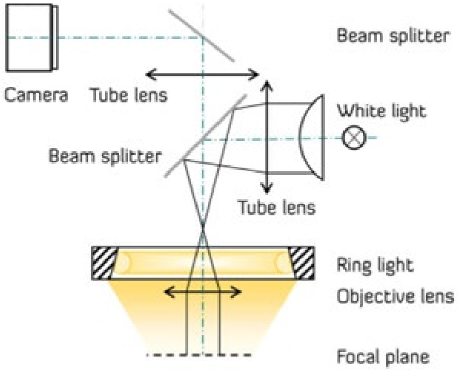
Dektak



Advantages:
-Measurements can be obtained quickly
Disadvantages:
-Requires continuous contact with the surface
-Performs line scans not area
Cost:

Cost	~$10,000
Scan Time	2 Minutes

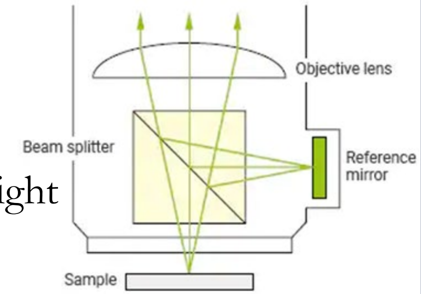
Keyence



Advantages:
-Measurements can be obtained quickly
Disadvantages:
-Glare can cause outliers in the data
-Resolution is not as fine as other methods

Cost	~$60,000
Scan Time	6 Minutes

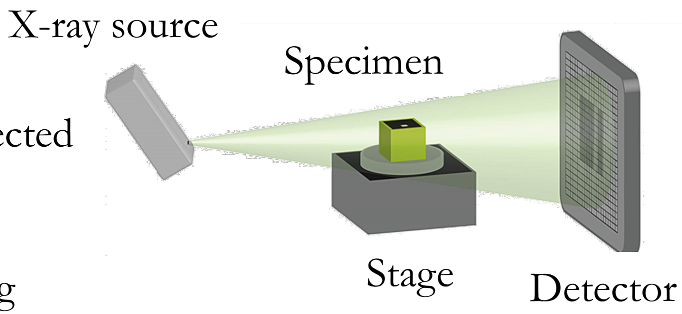
SWLI



Advantages:
-Measurement can
achieve sub-nanometer precision in height
Disadvantages:
-Cannot read spiky or nonreflective
asperities

Cost	~$200,000
Scan Time	40 Minutes

XCT

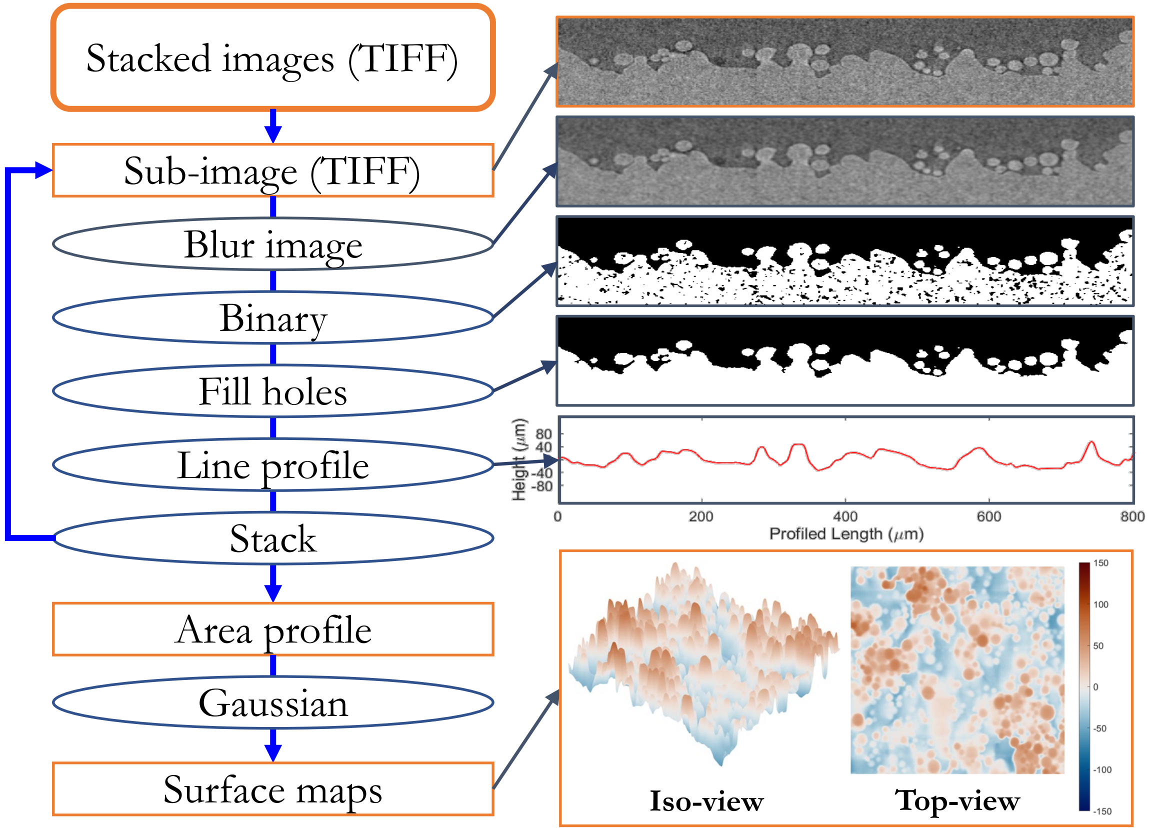


Advantages:
-Subsurface defects can be detected
Disadvantages:
-Scan time can be long
-Requires heavy post processing

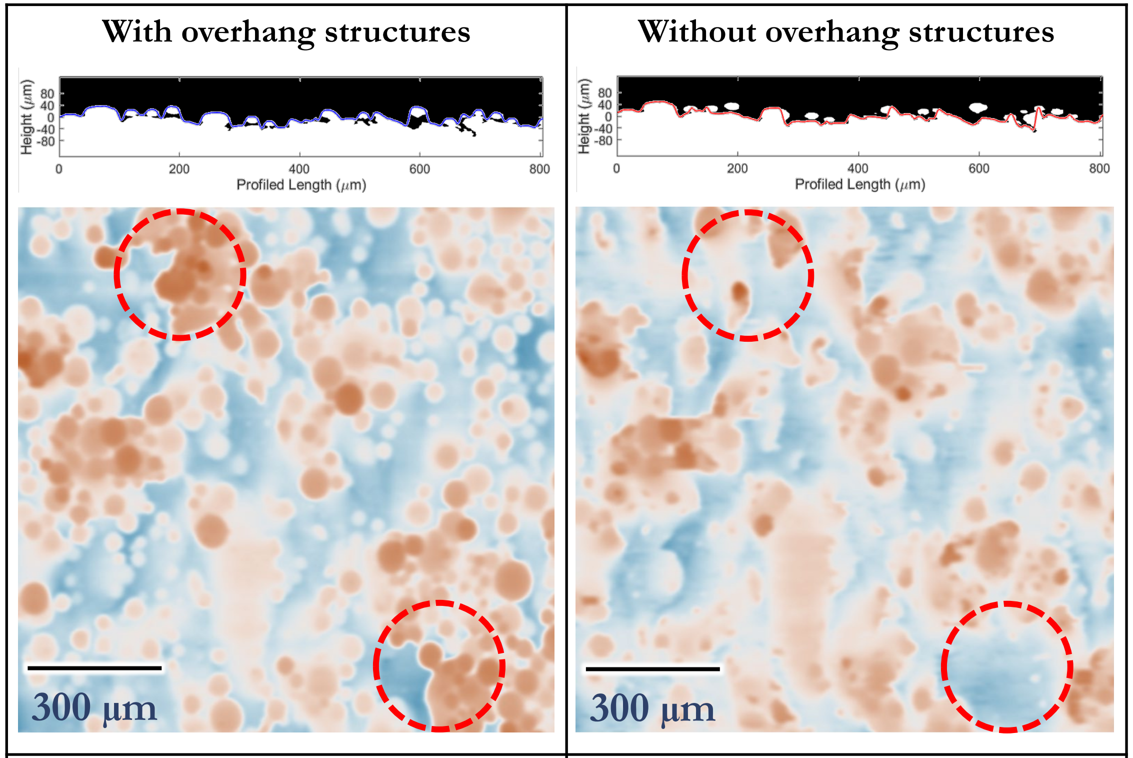
Cost	~$1,000,000
Scan Time	>2.5 hours

Post-processing: XCT

Flow chart for XCT image processing



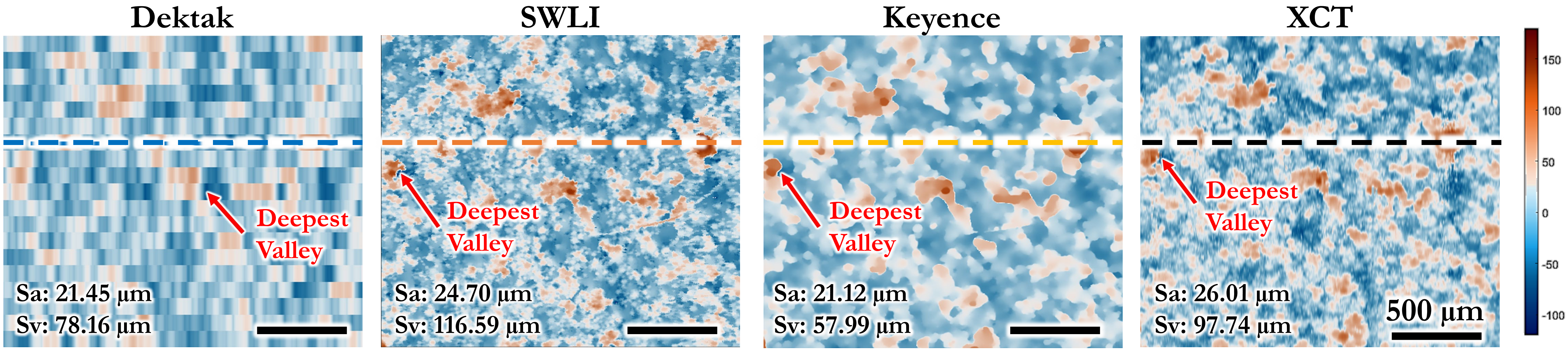
Implications from overhang structures



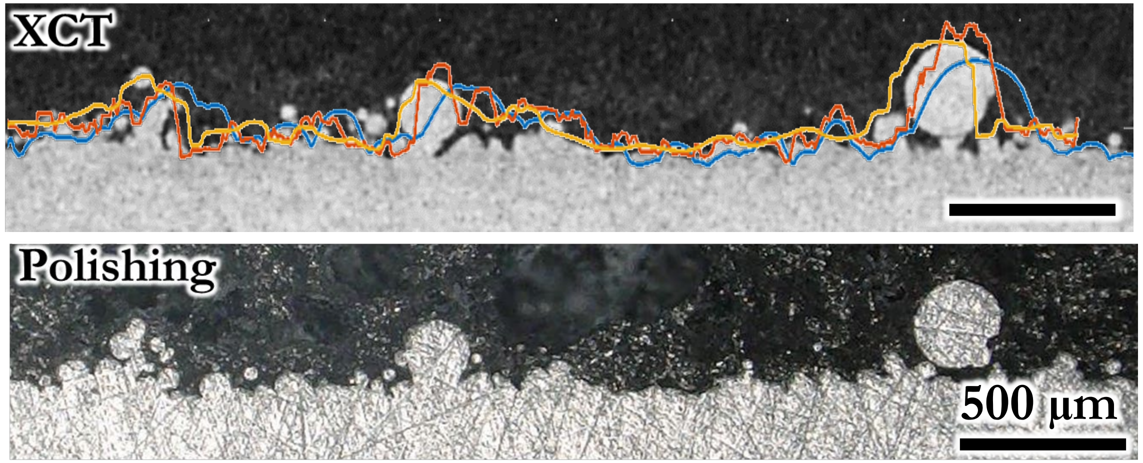
With overhang structures	Without overhang structures
Sa = 19 μm, Sv = 58μm, Sz = 142 μm	Sa = 16 μm, Sv = 53μm, Sz = 140 μm

- Surface topography was obtained by stacking line profiles

Results: Surface Texture from the Matching Areas



- XCT surface topography with overhang structures showed similar results to other techniques
- Dektak and Keyence showed lower roughness values compared to SWLI and XCT
- Surface profile obtained from polished cross-section was similar to XCT profile, indicating XCT results are more representative of the true profile



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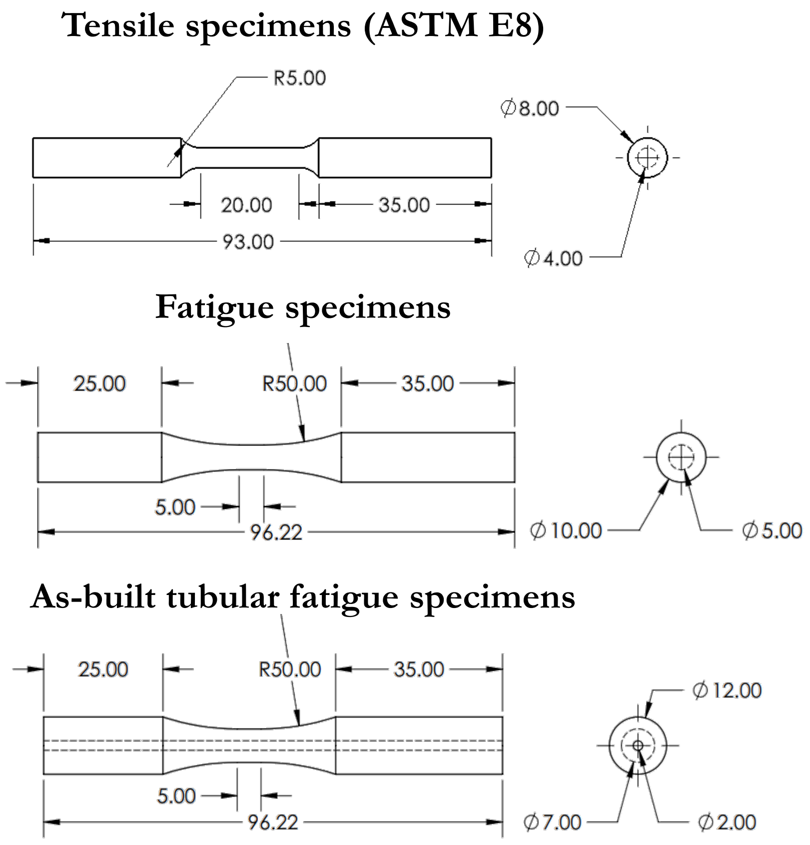
DoE: Tensile and Fatigue Specimens

#Fatigue Specimens per Set	#Tensile Specimens per Set	Geometry	Orientation	Contour	Infill	Surface Treatment
15	6	Solid	Vertical	No contour	Default	No
15	6	Solid	Vertical	No contour	KH	No
15	6	Solid	Vertical	No contour	LoF	No
15	6	Solid	Vertical	Default	Default	No
15	6	Solid	Vertical	Default	KH	No
15	6	Solid	Vertical	Default	LoF	No
15	6	Solid	Vertical	1 contour	Default	No
15	6	Solid	Vertical	Different offset	Default	No
15	6	Solid	Vertical	Default	Default	S/M
15	6	Solid	Vertical	Default	Default	D/M
15	6	Solid	Vertical	Default	Default	M/P
15	6	Solid	Vertical	Default	Default	Only P
15	-	Tubular	Horizontal	Default	Default	No
15	-	Tubular	Horizontal	Default	Default	Yes
15	-	Tubular	Vertical	Default	Default	No
15	-	Tubular	Vertical	Default	Default	Yes



S/M: Shallow machining
D/M: Deep machining
M/P: Machining and polishing
P: Polishing

- 3 stress levels with 4 tests per level were chosen for each condition
- Geometries for D/M and S/M were oversized from outer diameter by 2 mm and 0.2 mm, respectively

Summary

- Variation in infill process parameters did not affect surface texture values
- Coupons without contour exhibited deepest surface valleys
- In general, Dektak and Keyence showed lower surface texture values compared to the SWLI and XCT
- The surface texture values obtained from the XCT were dependent on the specific method used for processing the raw data
- Surface profile obtained from the XCT was more representative of the true profile obtained from the polished cross-section

Thank you for your attention !

- National Center for Additive Manufacturing Excellence (NCAME)