Additive Manufacturing Consortium
Operated by EWI

Reflections on Fatigue for AM Components

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Resume: William Mohr

- EWI engineer in Structural Integrity for over 24 years.
- Supporting a wide variety of industries:
  - From pipelines to auto transmissions to heart valves.
- Design chair for AWS D1.9 Structural Welding Code—Titanium.
- Second vice chair for AWS D20 Specification for Fabrication of Metal Components using Additive Manufacturing.
- Bachelors from MIT and graduate degrees from Stanford.

Outline

- Fatigue Data for Laser Powder Bed Fusion
- Categorizing the Data
- Correlation with Imperfections and Inspection
- AWS D20

Fatigue Data Compilation

- **Collect published literature data on fatigue of additively manufactured metal pieces.**
- **Materials:**
  - Largest group – Ti6Al4V
  - Next largest – stainless steel
- **S-N data rather than fatigue crack growth rate.**

Publications in Data List

	Laser – Powder Bed	EB – Powder Bed	Laser – DED Powder	Laser – DED Wire	EB – DED Wire	GTAW – DED Wire
Ti6Al4V	20	5	3	1	1	1
SS – PH Grades	6					
SS – 316	3					
Other Ti	1		1			
718	2		1			
625	2					

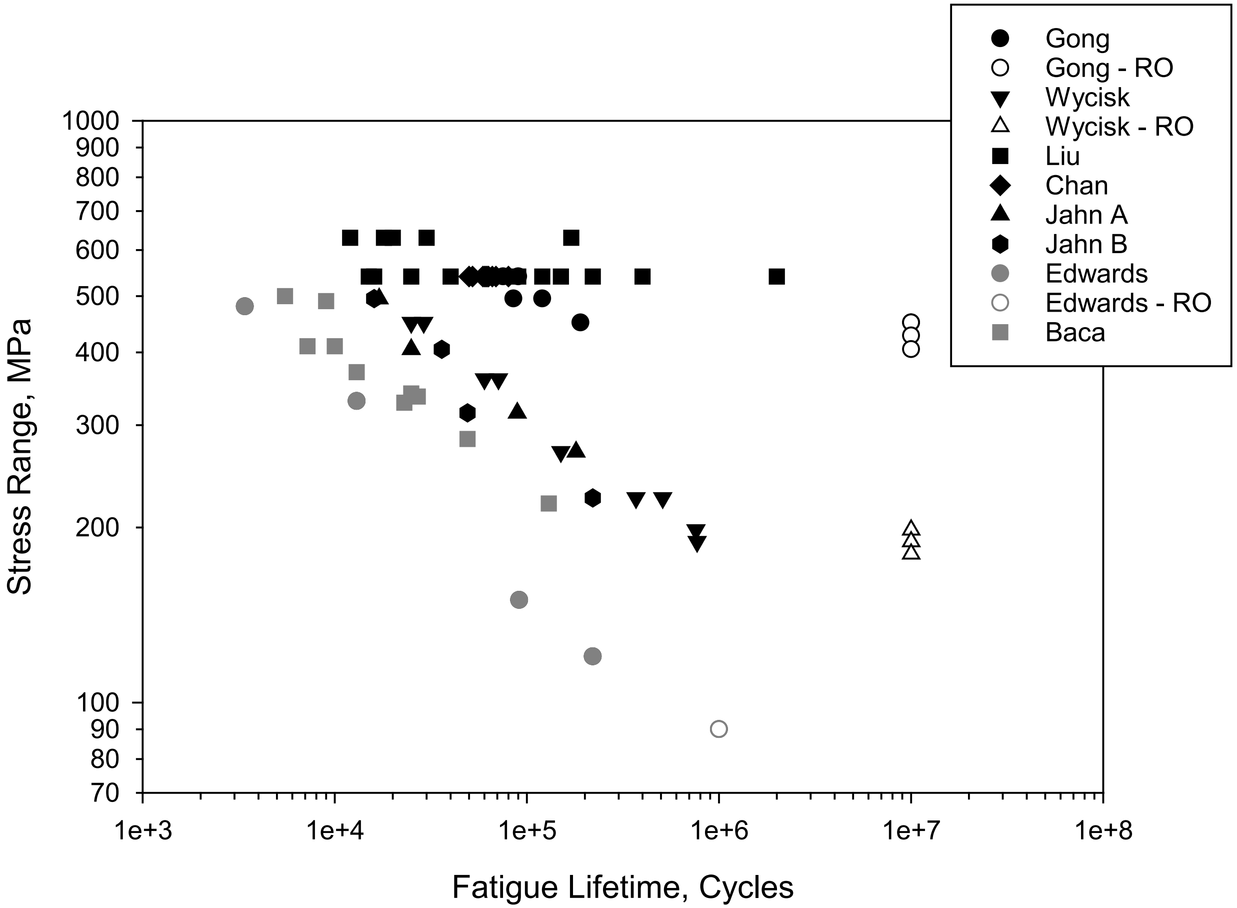
Wide Variety, Little Duplication

- **Variety of orientations (x, y, z, etc.).**
- **Variety of deposition conditions.**
- **Variety of post-deposition heat treatments.**
- **Variety of specimen shapes and sizes.**
- **Two primary test methods and others:**
  - Tension R=0.1 K_t = 1 specimen
  - Rotating Bending R = –1
  - Others include strip specimens.

Plotting Fatigue Data

- **My preferences are based on structural weld fatigue rather than base metal fatigue.**
- **Log-log plot (stress parameter on vertical axis).**
- **Stress range (maximum to minimum) is the stress variable:**
  - Some plot maximum stress alone
  - Others plot stress amplitude (half of range).
- **Cycles of lifetime is the lifetime variable:**
  - Runout (RO) means no failure at end of cycles.

Ti6Al4V – Z Direction: Untreated



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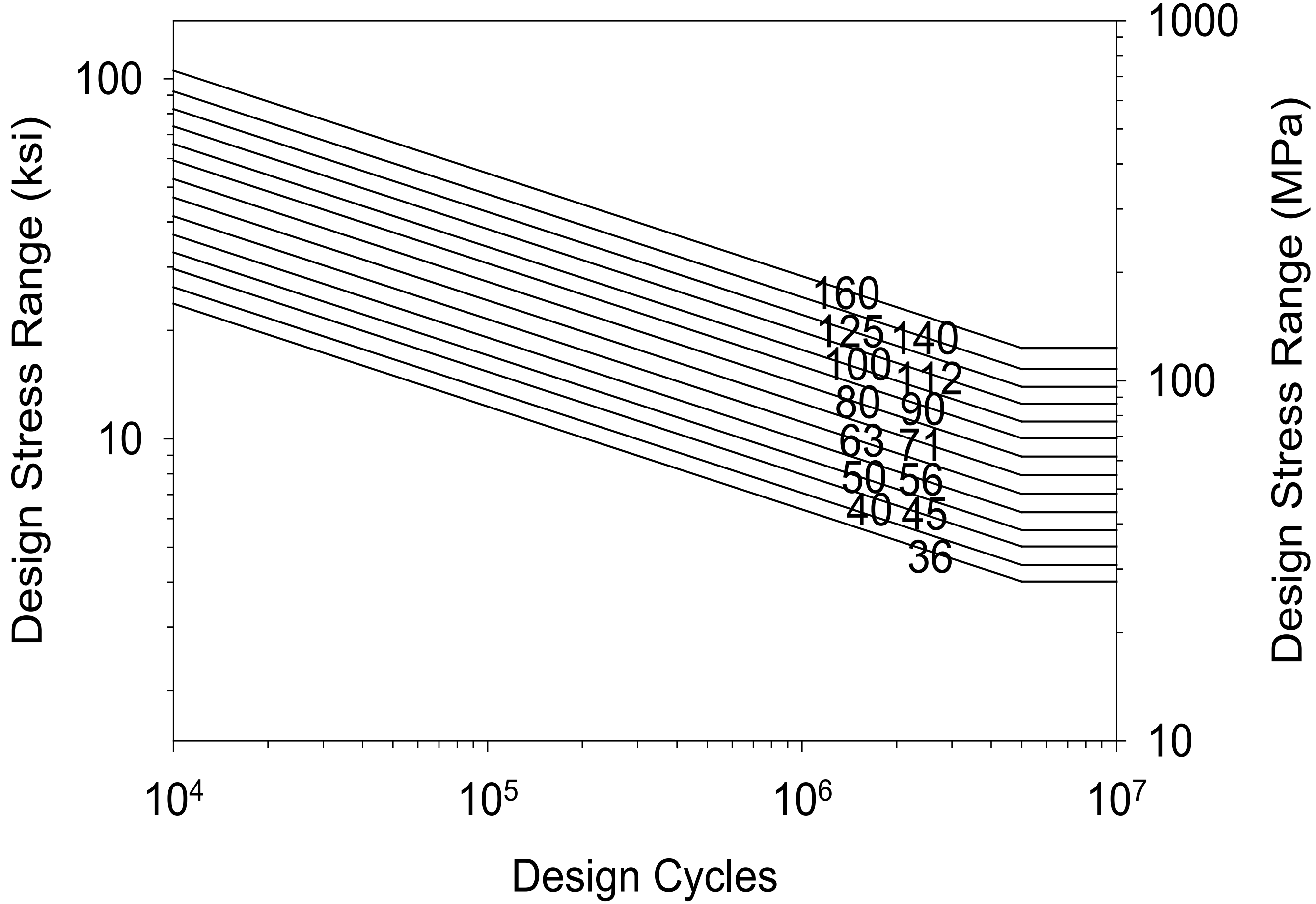
AWS D1.9 Design Curves



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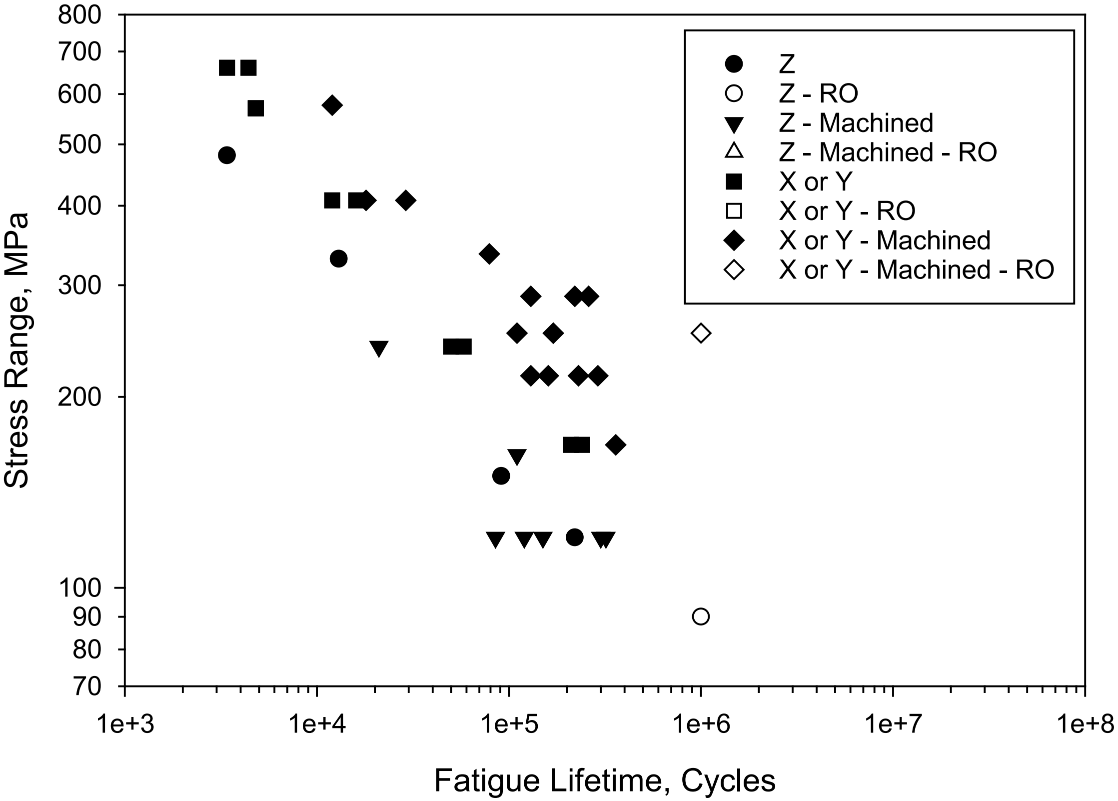
Approach to Grouping

- **Four groups:**
  - Fails from defects throughout part:
    - Removing as-deposited surface not much improvement.
  - Fails from defects on the surface
  - Fails from sub-surface defects:
    - Sensitive to material between defect and surface.
  - Fails from no defect at all.

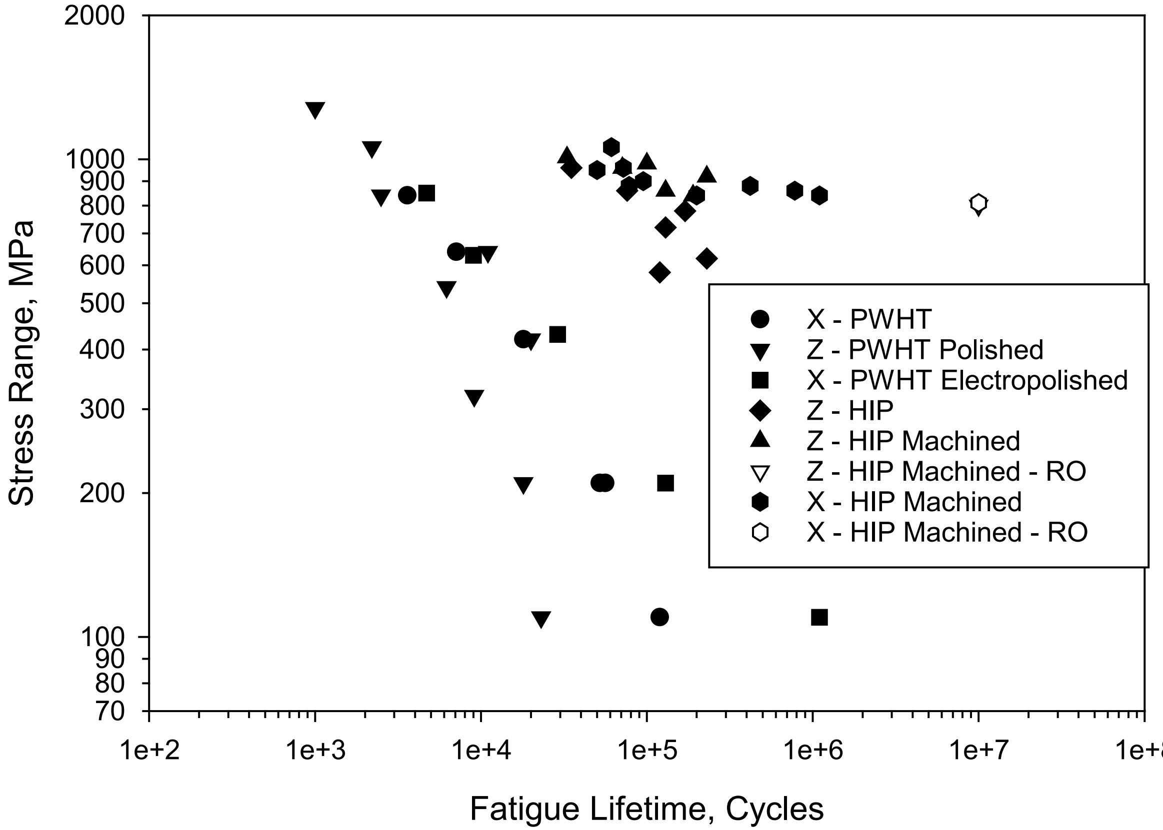
Defects Throughout

- Ti-6Al-4V powder bed.
- Not much difference by orientation or surface finish.



Improvements to Defects Throughout

- **Limited improvement from:**
  - PWHT
  - Surface finish
  - Direction.
- **HIP has more improvement.**



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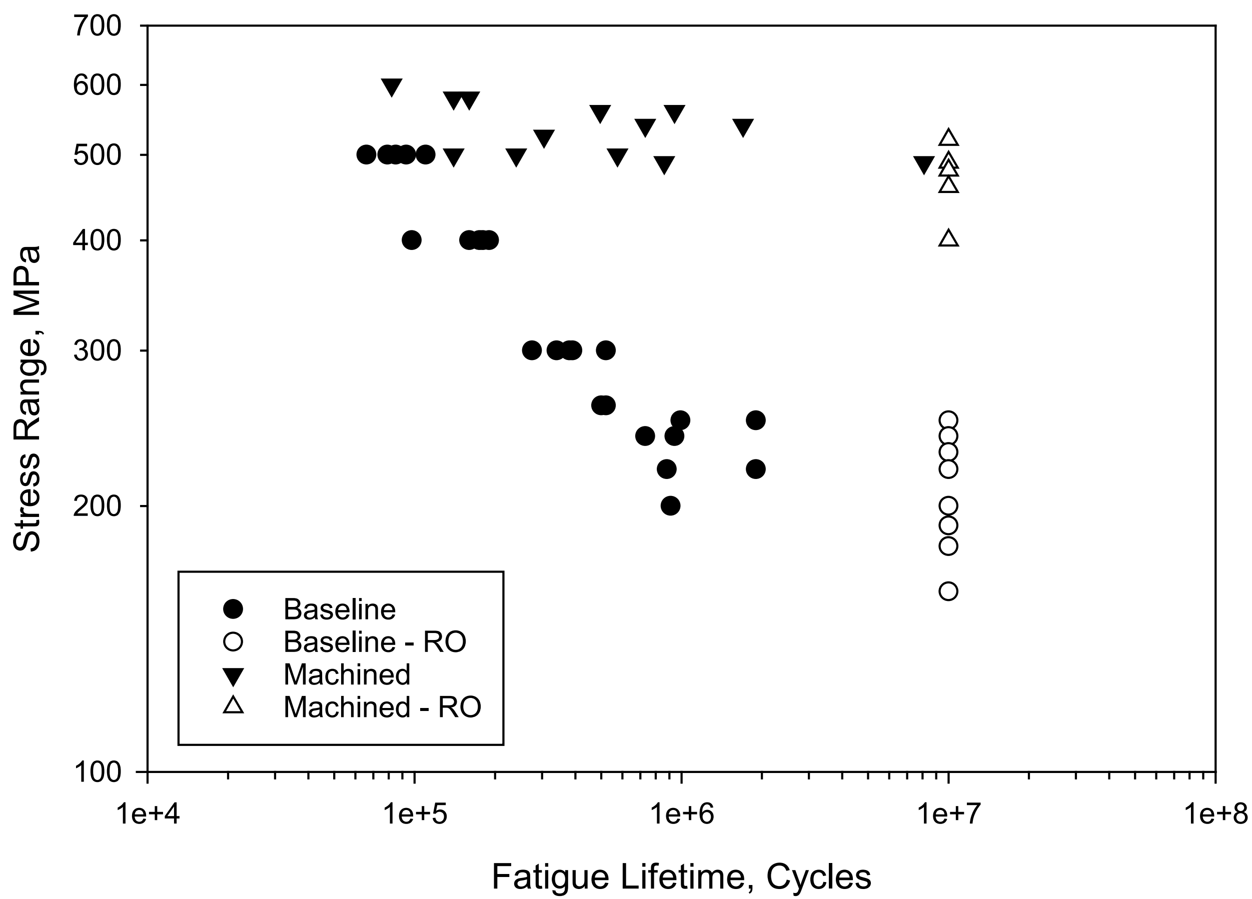
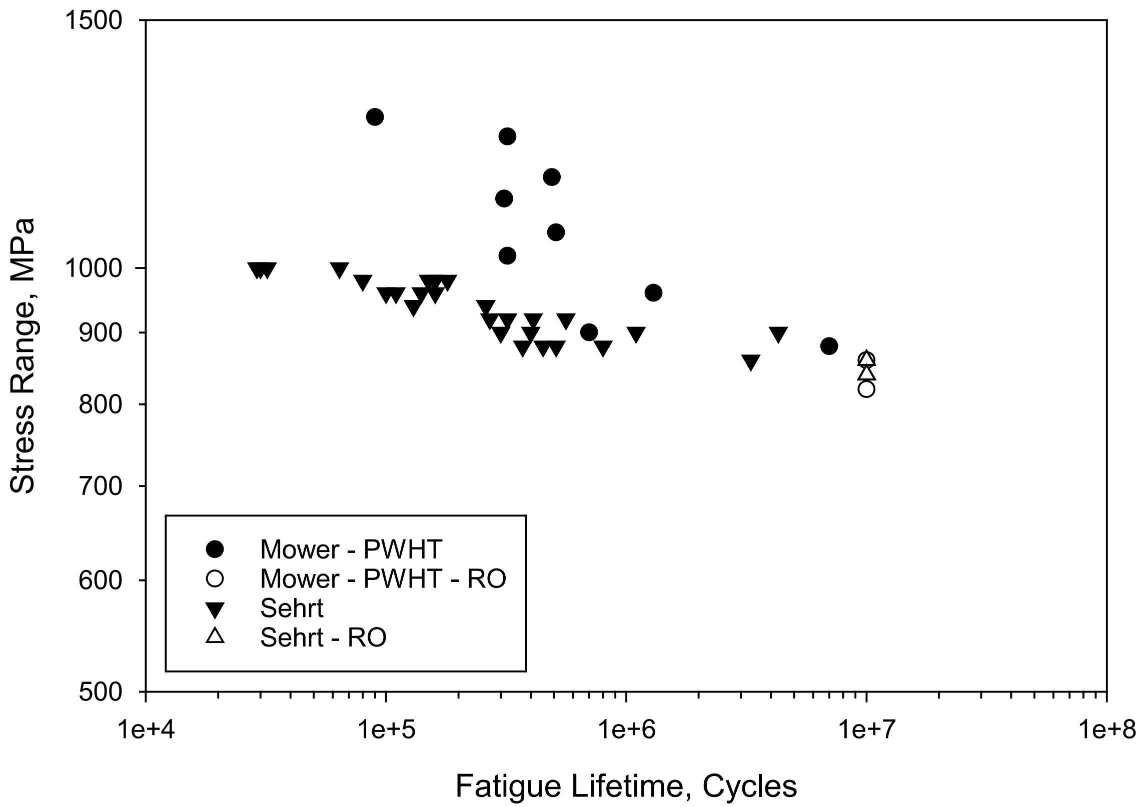
Surface Flaws Removed

- Big effect of machined surface.
- Stoffregen et al. on 17-4PH.

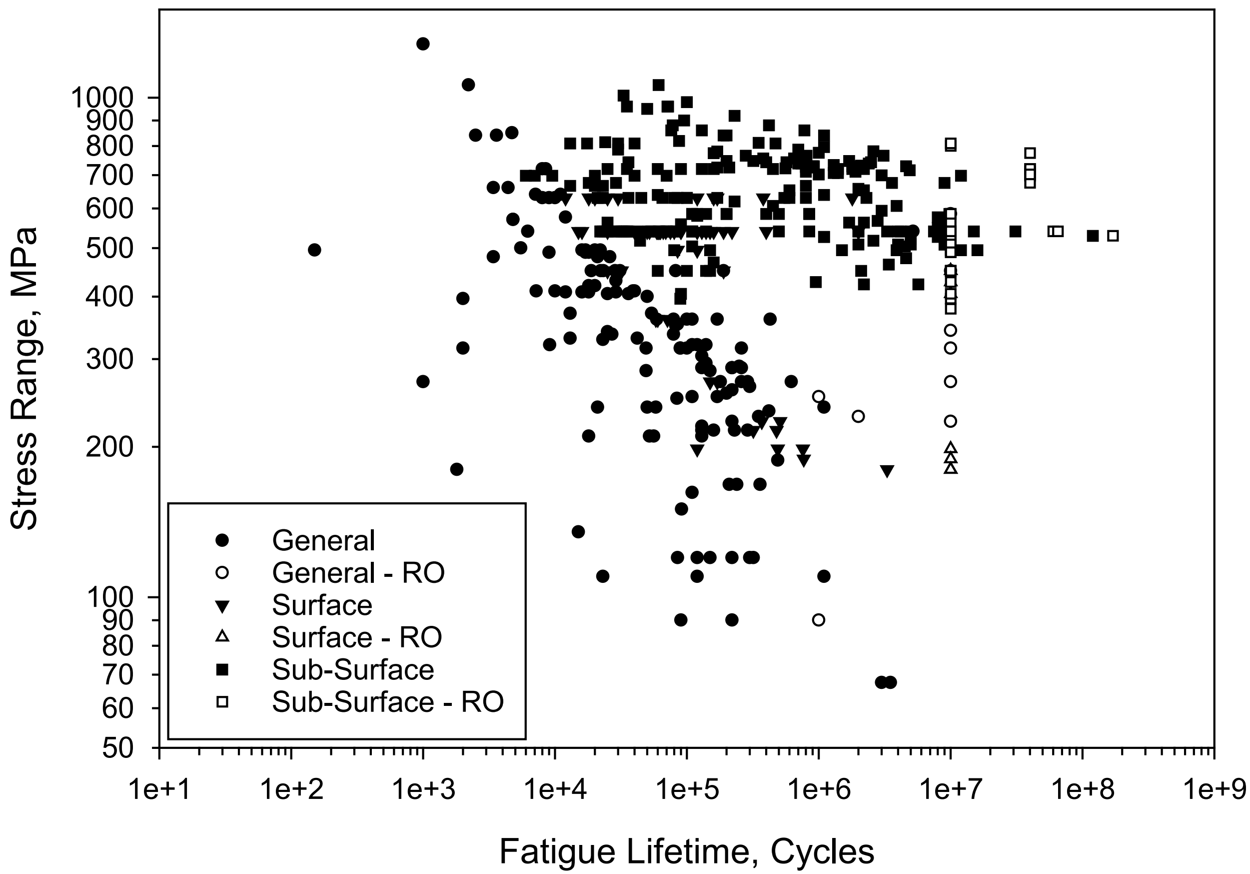


Subsurface Flaws – 17-4PH

- **PWHT by Mower and Long improved performance at high stress range.**
- **R = –1 bending.**



Ti-6Al-4V – Data Characterized



Still a Lot of Variability

- **General:**
  - Severity of flaws
  - Types of flaws (porosity vs. lack of fusion).
- **Surface:**
  - Size of flaws
  - Size of specimen.
- **Subsurface:**
  - Strength from heat treatment
  - Orientation.
- **Microstructure:**
  - Heat treatment and microstructure.
- **Different effects based on behavior mode.**

How to Improve Performance

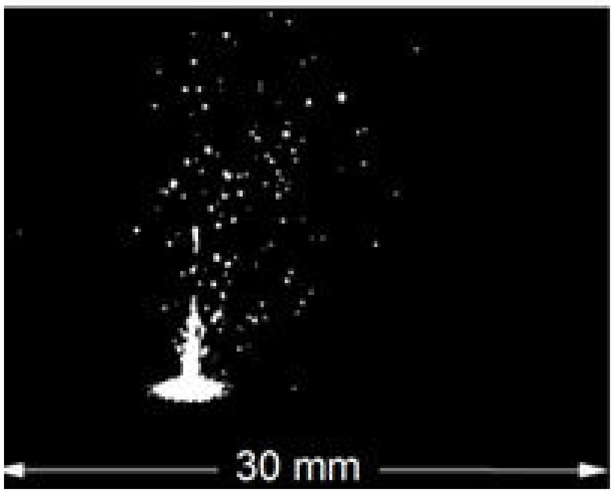
- **General flaws:**
  - Procedure development to eliminate deposited flaws
  - HIP to close up deposited flaws.
- **Surface flaws:**
  - Optimize travel at surface to avoid flaws
  - Machine or surface treat.
- **Subsurface flaws:**
  - Heat treat to increase strength at surface
  - Minimize flaws and maximize their distance from the surface.
- **Microstructure:**
  - Generally choose higher strength structure.

Effect of Material

- **Variability among results for Ti-6Al-4V is greater than for stainless steel.**
- **The lower density of the powder particles may make them easier to move during laser passage.**

Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing

S. Ly, A. M. Rubenchik, S A. Khairallah, G. Guss and M. J. Matthews, Nature 2017



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Inspection of Fatigue Failures

- **Common imperfection sizes associated with failures in fatigue tests:**
  - Less than 1 mm but greater than 0.1 mm.
- **Common shapes:**
  - Irregular outlines
  - Unfused powder particle surfaces.

AWS D20

- **Currently in committee drafting.**
- **Includes clauses on:**
  - Design
  - Procedure qualification
  - Personnel qualification
  - Fabrication
  - Inspection.
- **Includes both PBF and DED.**
- **Full range of metals allowed.**
- **Three levels of service: A, B, and C (non-critical).**

D20 Inspection

- **Procedure qualification includes tensile tests (A, B) and microstructure examination:**
  - Acceptance criteria will be set by the engineer.
- **Procedure qualification includes inspection (A, B).**
  - PT, MT, RT, or CT depending on situation
  - Acceptance criteria are adapted from AWS D17.1.
- **Inspection for built parts (A, selection of B).**

D20 Inspection and Fatigue

- **Flaw size acceptance criteria from D20 are much larger than the flaw sizes found on fatigue test fracture surfaces.**
- **Acceptance criteria are based on comparing to welds rather than trying to meet wrought metal properties.**