

# **Reflections on Fatigue for AM Components**

Rockville, MD November 28, 2017

William Mohr Principal Engineer, EWI 614.688.5182 bmohr@ewi.org

### **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.



## **Ti6AI4V – Z Direction: Untreated**





## **AWS D1.9 Design Curves**





## **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-6AI-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.



Fatigue Lifetime, Cycles



### **Surface Flaws Removed**

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



Additive Manufacturing Consortium

## Subsurface Flaws – 17-4PH

PWHT by • Mower and Long improved performance at high stress range.

• R = -1 bending.



Fatigue Lifetime, Cycles



### **Ti-6AI-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-6AI-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





## **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.

22

