Assessment of Literature on Fatigue Performance of Additively Manufactured Metals

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Introduction

Additive manufacturing for metal parts holds the promise of being a widely-used manufacturing method allowing much shorter lead times to create pieces than for conventional manufacturing methods.

Useful components must not only be manufactured with short lead times, but also provide attractive mechanical properties on which designers and users can rely for the performance of the finished part.

The resistance to fatigue, the growth of cracks due to cyclic loading, is an important part of the performance of many metal parts, so that they can be used in repetitive service environments. Recently, testing of specimens built by additive manufacturing has been a part of many programs with a wide range of test results obtained. For instance, limiting the deposition method to only laser powder bed, the material to only Ti-6Al-4V, the loading direction to the build direction (Z) and the surface condition to as-deposited, still leaves a wide range of fatigue test results as shown in Figure 1.

This paper assesses constant amplitude cyclic loading test data for metal pieces built by additive manufacturing as reported by many groups. The purpose is to check for general behaviors in fatigue that can be useful in the development of standard procedures and qualification methods. A similar data collection has been reported by Li et al.(1)

Fatigue test results are naturally variable, but the differences observed in testing of additive manufactured metal parts are so huge (similar lives with four times larger stresses, or increases in lifetimes by a factor of more than 100) that categorizing the tested material is an important part of assessing the data.

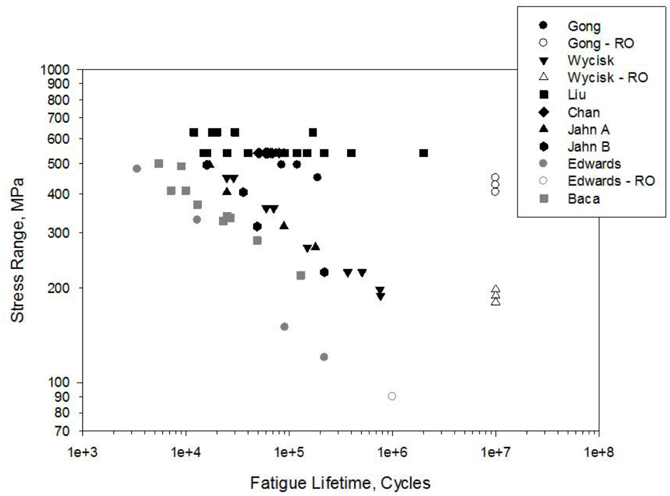

Figure 1: Fatigue data from several programs testing laser powder bed Ti6Al4V with loading in the Z direction and as-deposited surfaces with widely varying results.

Fatigue life results are plotted in many formats by investigators, with the loading parameter given by maximum stress, stress amplitude, and strain amplitude. The plots here show of the stress range (minimum to maximum) versus the cyclic lifetime. Both are shown as a log-log scale because this has been found to be effective for assessing welded structures with retained residual stresses. This format can easily be converted to other formats for comparison with new data. Runouts (RO) that reach the number of cycles shown without failure are marked with open symbols.

Tables 1 and 2 give a summary of the testing programs that have included fatigue life data compared to applied stresses.

Deposition Methods

Many different deposition methods have been used in programs that tested fatigue lifetime. For Ti-6Al-4V, there are tests on material deposited by laser powder bed, laser powder directed energy deposition, laser wire directed energy deposition, electron beam (EB) powder bed, EB wire directed energy deposition, and gas tungsten arc welding (GTAW) wire directed energy deposition. A variety of stainless steels have also been tested, but the range of processes recorded is smaller, with all reports collected here based on tests of laser powder bed deposition.

Testing Methods

Most fatigue lifetime testing has been on round cross-section specimens, with more programs testing specimens to the ASTM E466 standard than using other shapes and conditions. Somewhat larger specimens have been used by groups testing rotating bending (RB). Other types of specimens, such as cantilevers, 3-point bend bars, rectangular cross-section tension specimens and tubular tension specimens have been tested by individual groups, see Tables 1 and 2. Testing is generally performed on a single specimen type by any given program, so comparisons between specimen types can be difficult. For instance, the performance of Wycisk et al.'s (2) round cross-section specimens compared to Edwards and Ramulu's (3) larger rectangular specimens may be a stronger function of the differences in deposition conditions than of the specimens.

Some groups have created specimens for testing of fatigue crack growth rate rather than fatigue lifetime. These tests are less sensitive to imperfections in the piece and more sensitive to the microstructural effects. These will not be further discussed in this paper.

Categorization Proposal

Given the very wide range of results even for seemingly similar situations, it was decided that the data needed to be characterized into groups based on the conditions in the original deposit and the material.

Four categories of conditions of built pieces can be considered:

- Pieces with general flaws controlling fatigue performance,
- Pieces with surface flaws controlling fatigue performance,
- Pieces with subsurface flaws controlling fatigue performance,
- Pieces with microstructure controlling fatigue performance.

The expectation of fatigue performance is better for a given material as it goes further down the list. The improvement techniques, for instance heat treatment after fabrication, here listed as post-weld heat treatment (PWHT) that can be used effectively will depend upon the category of the built piece. Quite large differences in performance can be observed, as shown by data from Gong(4) in Figure 2, where changes in beam parameters and spacing lead in one case, but not in the other, to much lower fatigue performance even for machined test specimens.

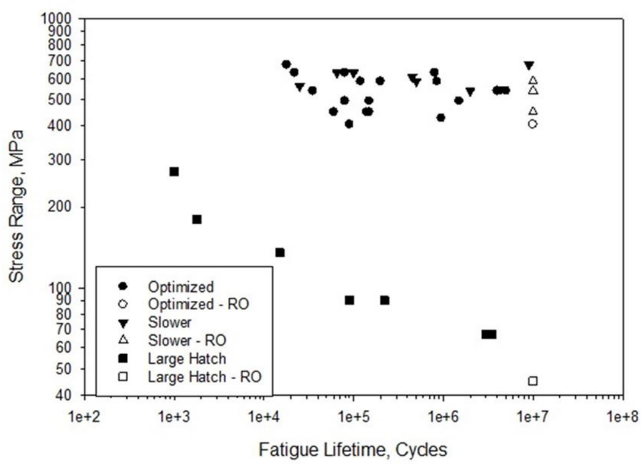

Figure 2: Gong(4) fatigue data on machined electron beam powder bed Ti-6Al-4V ELI as a function of deposition procedure with major change in performance due to one of two variations from optimized conditions.

In the case of general flaws, the overall procedure is not optimized for either the surface or the bulk of the deposit. This leads to flaws that degrade the fatigue performance of as-built specimens and machined specimens, since machining simply opens new flaws to the surface. The behavior of the large hatch samples of Gong(4) give an example for how much general flaws can reduce performance. Heat treatment will also not greatly improve performance, but the hot isostatic process (HIP) can provide some significant improvement. The differences between directions of loading compared to the direction perpendicular to the layers may be minor, since the flaws have a volumetric component.

Examples of performance tests with general flaws can be found in Edwards and Ramulu(3) (Figure 3) for Ti-6Al-4V material deposited with a pulsed laser in a powder bed system. The improvement due to HIP of Ti-6Al-4V can be seen compared to heat treatment in Mower and Long (5) (Figure 4) for laser powder bed and in Kobryn and Semiatin(6) (Figure 5) for laser powder directed energy deposition.

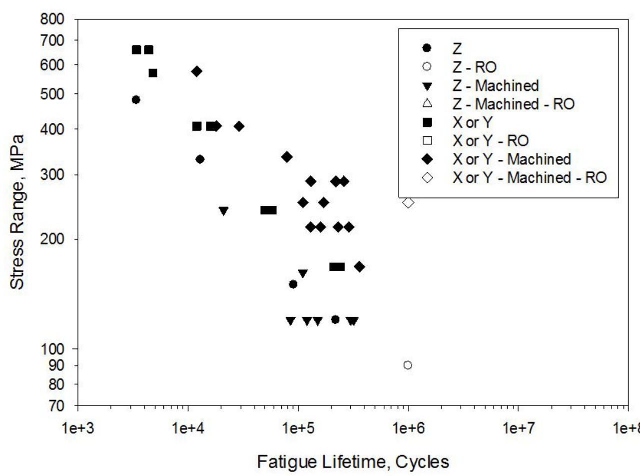

Figure 3: Edwards and Ramulu(3) fatigue data on laser powder bed Ti-6Al-4V, with small variation as a function of procedure and surface condition.

In the case of surface flaws, the overall procedure is not optimized for the surface of the deposit. This leads to strong differences in performance between the cases that are loaded perpendicular to the deposited layers and those loaded parallel to the layers. It also will be strongly affected by surface finishing, with machining and other removal methods giving large improvements in performance. More minor removals, such as light sand blasting, may provide much less improvement, since it will not extend to the bottom of the surface defects. Electropolishing that will round surface defects can also be effective. Both

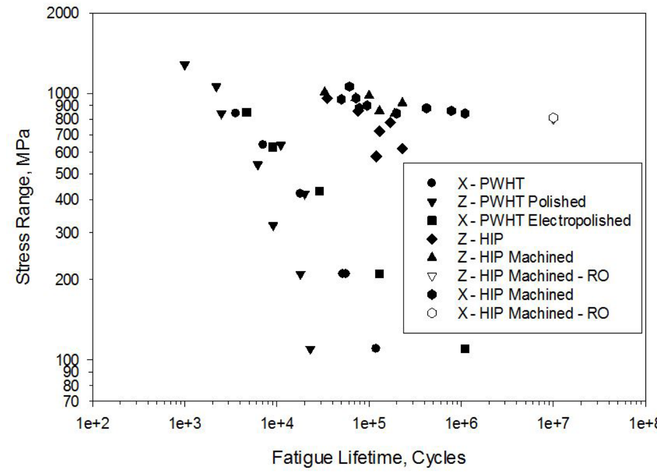

Figure 4: Mower and Long (5) fatigue data on laser powder bed Ti-6Al-4V with small variation based on orientation and surface, and larger effect of HIP.

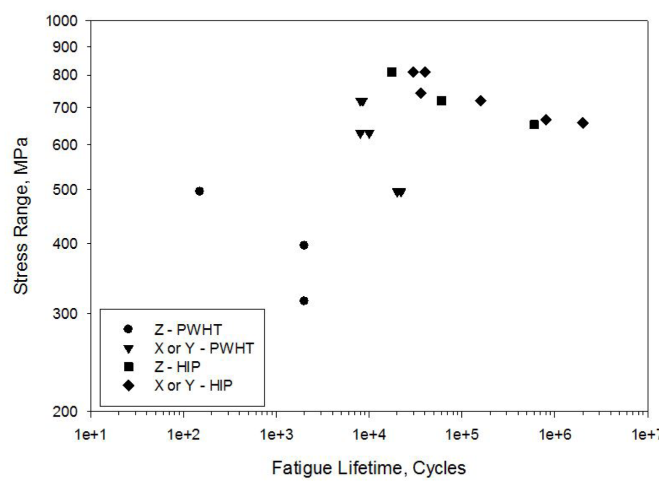

Figure 5: Kobryn and Semiatin(6) fatigue data on laser directed energy deposition Ti-6Al-4V with large effect of HIP.

heat treatment and HIP will have more limited effect in this case.

Examples of performance tests with surface flaws include Stoffregan et al.(7) (Figure 6) on precipitation-hardened stainless steel.

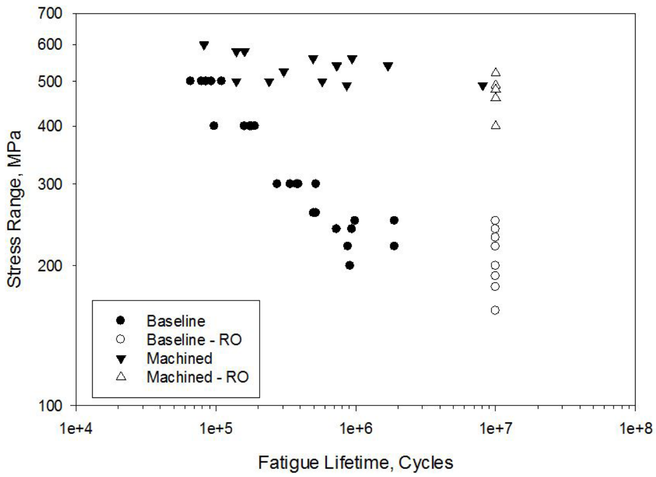

Figure 6: Stoffregen et al.(7) fatigue test results on 17-4PH stainless steel with large effect of surface finish.

In the case of subsurface flaws, the overall procedure has been optimized to avoid general flaws and surface flaws, but the remaining smaller imperfections near the surface can be activated as initiation sites for fatigue by local damage to the ligament between the small imperfection and the surface. This can be affected by both heat treatment and surface finish process. Heat treatments optimized for retaining or increasing strength will provide more resistance. The influence of microstructure on fatigue life is discussed in the next category. HIP can be less effective than these heat treatments because it is optimized for reduction of flaw sizes, but the crack growth in the ligament does not happen until after the piece is cyclically loaded.

Examples of cases dominated by subsurface flaws include the results of Suo et al.(8) on electron beam with wire directed energy deposition in Figure 7. The publication is not clear on the process of surface preparation for the specimens, but the relatively high performance makes machining the most likely.

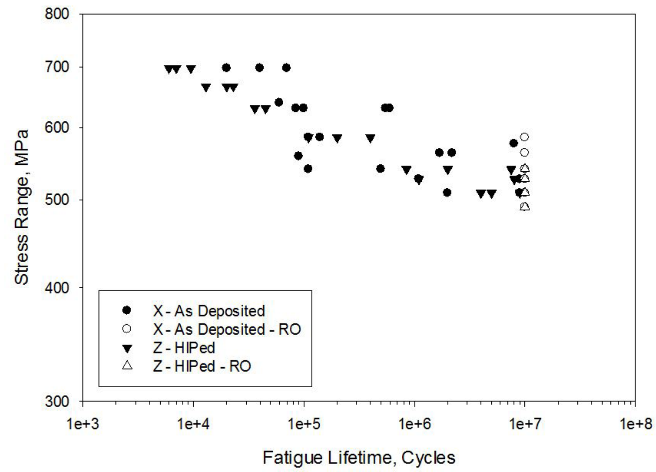

Figure 7: Suo et al.(8) fatigue data for electron beam directed energy deposition Ti-6Al-4V with little effect of HIP.

When the other flaws such as pores and unfused powder have been eliminated, the metallurgical conditions can have much greater effect on the fatigue lifetime. This can be related to both the metallurgical phases present and the grain sizes and orientation. Short crack growth in fatigue can be slowed, for instance, by repeated transitions between different microstructures, as has been observed for wrought Ti-6Al-4V. Under these conditions, heat treatment may be optimized at low temperatures and the additional grain growth during higher temperature HIP processes may degrade performance.

Examples for control by metallurgical conditions are more difficult to find in a single study. Both Sehrt and Witt(9) and Mower and Long(5) tested 17-4PH fabricated in an EOS laser powder bed machine made into horizontal rotating bending (RB) specimens. The additional heat treatment used by Mower and Long(5) provided an increase in the lifetime only at higher stress ranges, a behavior likely to be driven by a combination of microstructural change and residual stress modification (Figure 8).

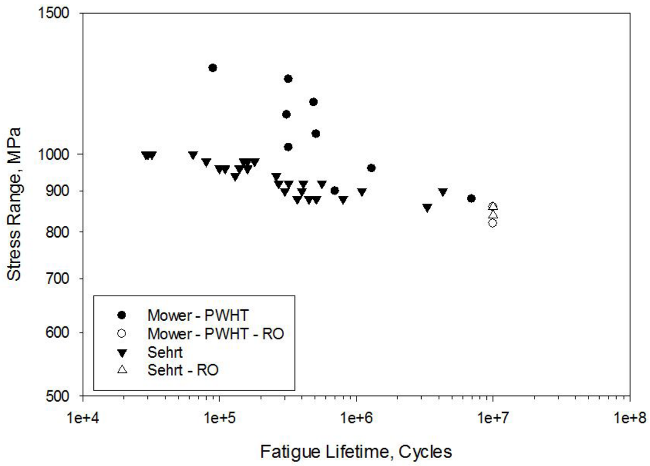

Figure 8: Rotating bending (R=-1) fatigue test data for 17-4PH in the X direction with machined surfaces showing an effect of PWHT.

Categorizing all the data on Ti-6Al-4V and Ti-6Al-4VELI as in Table 3 separates the results as shown in Figure 9. Specimens designed with flaws and those with only limited estimates of lifetime are excluded. One can note for instance that preventing general and surface flaws leads to fatigue performance with no failures below the 350 MPa stress range. The data is characterized uniformly for each test group, even though some investigators report differing locations of crack initiation on the fracture surface for some samples within the test groups.

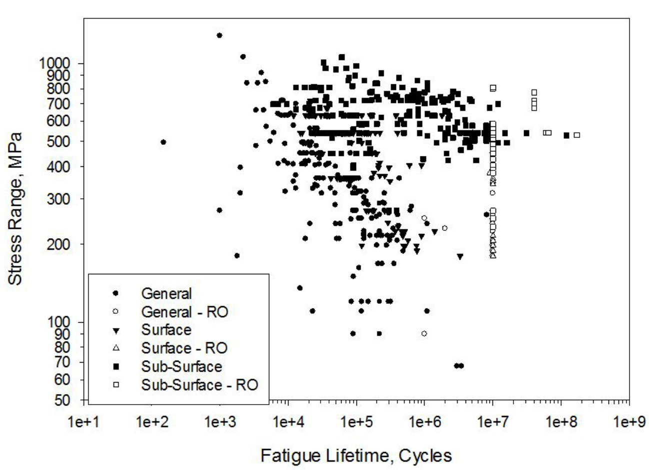

Figure 9: All process categorized fatigue data for Ti-6Al-4V, showing the wide variation based on flaw type.

Discussion

Primary testing methods have been using ASTM E466 with standard specimens in tension at R = 0.1 and using RB testing with round cross-section specimens at R = -1. Other tests have been performed on other shapes of specimens, such as the rectangular cross sections for tension-compression tests of Edwards and Ramulu(3), the hollow cylinders for tension tests of Lipinski et al.(10), the in-plane bending specimens of Bača(11), and the cantilever bending specimens of Scott-Emuakpor et al.(12).

There is some indication that tests of rectangular cross-section specimens, such as those of Edwards and Ramulu(3) for untreated specimens and Rekedal(13), particularly for HIP and machined specimens, gave poorer fatigue performance than other configurations.

Fatigue test specimens have been made as close as possible to the support platen. The effect of material being built on a support structure above the platen has not been widely assessed. The limited data from Edwards and Ramulu(3) suggests that this can be a problem area, since other locations in the build volume may have poorer fatigue performance. The other data available is on specimens built at a 45-degree angle to the vertical as in Wycisk et al.(2) that have been similar to those built in the vertical direction.

Gong(4) provided fatigue data and porosity determination for a range of deposition parameters (laser power and speed) for laser powder bed deposition of Ti-6Al-4V. The results suggest that volumetric porosity assessment checking overall density may miss differences in pore configuration that affect fatigue lifetime. Processes biased toward rounder porosity rather than irregular porosity gave higher performance, similar to tests with parameters minimizing porosity.

Conclusions

Fatigue testing of additively-manufactured metal pieces has shown a wide variety of results for many investigators. Categorizing the results based on the control of the results by general, surface, and sub-surface flaws allows the data to be put in more coherent groups and compared across processes. This method also allows better estimation of the effect of post fabrication treatments, such as machining, HIPing, and heat treatment.

Optimization of the deposition method to limit pores and regions of incomplete fusion is needed to allow further substantial improvements due to surface finishing and PWHT. While HIPing can overcome some of these imperfections, it is not a cure-all. If initial deposition procedures are optimized to avoid general flaws and surface flaws, then HIPing may provide little or no benefit.

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Table 1: Fatigue lifetime data collected (Ti-6Al-4V)

First Author	Heat Source	Consumable	Specimen	As-deposited	Treated
Gong(14)	Laser	Powder Bed	E466	Yes	No
Wycisk(2)	Laser	Powder Bed	E466	Yes	Yes
Liu(15)	Laser	Powder Bed	E466	Yes	No
Scott-Emuakpor(12)	Laser	Powder Bed	Cantilever	Yes	No
Rafi(16)	Laser	Powder Bed	E466	No	Yes
Chan(17)	Laser	Powder Bed	3-point bend	Yes	Yes
Jahn(18)	Laser	Powder Bed	E466	Yes	Yes
Simonelli(19)	Laser	Powder Bed	Rectangular	No	Yes
Edwards(3)	Laser	Powder Bed	Rectangular	Yes	Yes
Mower(5)	Laser	Powder Bed	RB Cylinder	No	Yes
Gong(4)	Laser	Powder Bed	E466	No	Yes
Bača(11)	Laser	Powder Bed	Plane bend	Yes	Yes
Rekedal(13)	Laser	Powder Bed	Rectangular	Yes	Yes
Van Hooreweder(20)	Laser	Powder Bed	Rectangular	No	Yes
Suo(8)	EB	Wire	Rectangular	No	Yes
Chan(17)	EB	Powder Bed	3-point bend	Yes	Yes
Akelid(21)	EB	Powder Bed	Not named	Yes	Yes
Baufeld(22)	Laser	Wire	Cylinder	No	Yes
Baufeld(22)	GTAW	Wire	Cylinder	No	Yes
Kobryn(6)	Laser	Blown Powder	Cylinder	No	Yes
Amsterdam(23)	Laser	Blown Powder	Cylinder	No	Yes
Grylls(24)	Laser	Blown Powder	Cylinder	No	Yes

Table 2: Fatigue lifetime data collected (other materials)

First Author	Material	Power	Consumable	Specimen	As-deposited	Treated
Spierings(25)	316L	Laser	Powder Bed	E466	Yes	Yes
Spierings(25)	15-5PH	Laser	Powder Bed	E466	No	Yes
Rafi(16)	15-5PH	Laser	Powder Bed	E466	No	Yes
Hietikko(26)	316L	Laser	Powder Bed	Cylinder	No	Yes
Stoffregen(7)	17-4PH	Laser	Powder Bed	E466	Yes	Yes
Mower(5)	17-4PH	Laser	Powder Bed	RB Cylinder	No	Yes
Mower(5)	316L	Laser	Powder Bed	RB Cylinder	No	Yes
Sehrt(9)	17-4PH	Laser	Powder Bed	RB Cylinder	No	Yes
Yadollahi(27)	17-4PH	Laser	Powder Bed	Cylinder	No	Yes
Wang(28)	Ti TC18	Laser	Blown Powder	E466		
Lipinski(10)	Ti Grade 2	Laser	Powder Bed	Tube	Yes	Yes
Scott-Emuakpor(29)	718	Laser	Powder Bed	Cantilever	Yes	No
Amsterdam(23)	718	Laser	Blown Powder	Cylinder	No	Yes
Adams(30)	Re	Laser	Blown Powder	Rectangular	No	Yes
Brandl(31)	AlSi10Mg	Laser	Powder Bed	Cylinder	No	Yes

Table 3: Fatigue data characterized for testing on Ti-6Al-4V

First Author	General Flaws	Surface Flaws	Sub-Surface Flaws
Gong(14)		All	
Wycisk(2)		Original Surface	Machined
Liu(15)		All	
Rafi(16)			Machined
Chan(17)		Original Surface	EDM Surface
Jahn(18)	All		
Simonelli(19)	All		
Edwards(3)	All		
Mower(5)	Not HIP		HIP
Gong(4)	MP2 only		OP and MP1
Bača(11)	All		
Rekedal(13)	Not HIP	HIP	HIP Machined
Van Hooreweder(20)	All		
Suo(8)			All
Baufeld(22)			All
Kobryn(6)	Not HIP		HIP
Amsterdam(23)			All
Grylls(24)			All
Akelid(21)		No HIP	HIP

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