VHCF response of AM materials: a literature review

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Abstract

The present paper is an overview of the recent experimental results on the Very High Cycle Fatigue (VHCF) response of materials produced through Additive Manufacturing (AM) processes. At present, VHCF tests have been carried out on AlSi12, AlSi10Mg and Ti6Al4V specimens produced through AM processes (SLM and EBM). The VHCF strength and the main findings provided in the literature are analysed in the paper, focusing on the main factors that affect the fatigue response.

Keywords: Additive Manufacturing; Very-High-Cycle-Fatigue (VHCF); AlSi12; AlSi10Mg; Ti6Al4V.

1. INTRODUCTION

In the last few years, the rapid and continuous improvements of the Additive Manufacturing processes and technologies have permitted to significantly enhance the quality of AM parts, which are currently being employed in an increasing number of applications (e.g., turbine palette, heat exchanger, biomedical applications). However, there are still some issues regarding the structural integrity of components produced with different AM processes[1, 2]. In particular, there are many concerns on the fatigue response of AM parts, due to the formation of large defects during the AM process, which represent a critical site for crack initiation. The assessment of the structural integrity of AM parts subjected to fatigue loads is therefore one of the main challenges for researcher from universities and industries working in the AM field.

Many experimental tests have been carried in the literature up to 10^6 cycles to investigate the fatigue response of AM parts and to understand the mechanism of crack initiation. The High-Cycle Fatigue (HCF) response[1, 2] has been widely investigated and specific design methodologies have also been proposed to prevent the HCF failures and to take into account the presence of large defects originating during the manufacturing process[2]. On the other hand, less than 15 papers have been published on the Very-High-Cycle Fatigue (VHCF) response of specimens produced through AM processes. However, as highlighted in Ref.[3] ("*Regarding the fatigue limit of Ni-based superalloy 718, a supplementary description may be necessary in terms of VHCF*.") and in Ref.[4] ("*Due to the lack of VHCF studies for AM materials, there is a critical need to obtain the fatigue behavior at gigacycles and the influences of design parameters, size/geometry, surface roughness, etc.*") the fatigue response at number of cycles above 10^8 and in the VHCF region should be also carefully investigated to completely characterize the fatigue response of AM parts.

In the present paper, a review on the VHCF response of AM parts is provided. The experimental results obtained in the literature by testing AlSi12, AlSi10Mg and Ti6Al4V specimens are reported and analyzed in order to provide an overview of the main findings on the VHCF response of AM materials.

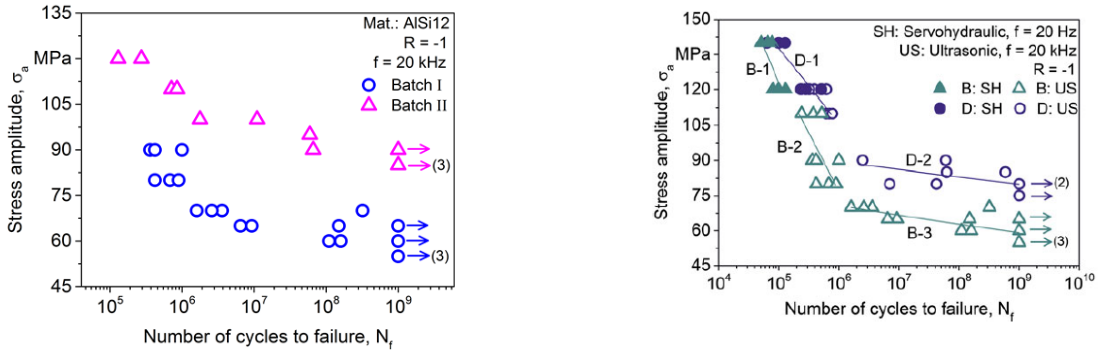
2. AlSi12: VHCF TESTS RESULTS

In Ref.[5-7], fully reversed tension compression VHCF tests were carried out up to 10^9 cycles on hourglass specimens (3 mm gage diameter) with an ultrasonic testing machine (Shimadzu USF-2000). AlSi12 specimens were produced by using an SLM machine SLM 250 HL (laser power of 50 W) with a layer thickness of 50 µm and from powders with an average diameter of 33 µm. Cylindrical samples were manufactured in vertical direction (with the axis perpendicular to the building platform) and then machined to the final sample geometry.

In Ref.[5] the effect of the base platform heating was investigated: the first batch (Batch 1) was produced without base plate heating (BPH), whereas the second batch (Batch 2) was manufactured by heating the base plate to 200 °C. Both batches were subjected to a stress relief heat treatment (SR, heating at 240 °C followed by oven cooling). The VHCF strength t 10^9 cycles, estimated through the stair-case method, was 61 MPa for the first batch and 89 MPa for the second batch, showing thus a significant influence of the base platform heating. The S-N plot of the experimental dataset is shown in Fig. 1a). Defects (surface and internal) were found to be the main cause of crack initiation. For Batch 1, crack initiation started from surface defects and subsurface pores. In Batch 2, cracks mainly originated from surface defects. In both batches, multiple crack initiations occurred.

In Ref.[6], the origin of the VHCF failures obtained in Ref.[5] were analyzed in detail, focusing on the defect originating failures and on the crack propagation behavior. In particular, it was shown that specimens manufactured with base plate heating were characterized by a lower fraction of pores compared to that of specimens manufactured without base plate heating. Moreover, it was found that the difference between the fatigue strength of the two batches increases with the number of cycles (i.e., it is largest at 10^9 cycles than at $2 \cdot 10^6$ cycles). The reason is related to the defect size: at high stress levels (HCF), fatigue cracks originated by smaller pores and the effect of the difference in pore fraction is therefore reduced.

In Ref.[7], the VHCF tests were carried out on “pure” AlSi12 specimens and on “hybrid” AlZn4.5Mg1+AlSi12 specimens. For hybrid specimens, the AlZn4.5Mg1 alloy was used as the base material and the AlSi12 powder was melted on the top of the base material through the SLM process. The tested specimens were subjected to a stress relief heat treatment (heating at 240 °C followed by oven cooling). The experimental dataset is shown in the S-N plot in Fig. 1 b).



(a) (b)

Fig. 1: S-N plot of tests on AlSi12 specimens: a) Ref.[5]; b) Ref.[7].

According to Ref.[7], the VHCF response of hybrid specimens is larger, even if fatigue cracks mainly started from the SLM AlSi12 alloy. In the VHCF region, the slope of the S-N curve was found to be almost the same for pure and hybrid specimens, but the VHCF strength was significantly larger for hybrid specimens (81 MPa with respect to 61 MPa).

Table 1 summarizes the experimental results for the AlSi12 alloy: SR refers to “Stress Relief”, PH refers to “Platform Heating” and “mac” refers to machining. In the Table, the VHCF response at the largest tested number of cycles is reported, if provided in the paper; otherwise, the runout stress amplitude is reported.

Pure AlSi12					
Specimen type	*Building orientation*	*Production process*	*Heat treatment*	*Runout*	*Fatigue strength [MPa]*
Hourglass[5]	Vertical	SLM + mac.	SR	10^9	60.5 ± 4.7
Hourglass[5]	Vertical	SLM (PH 200°C) + mac.	SR (240° C)	10^9	88.7 ± 3.3
Hybrid AlZn4.5Mg1+ AlSi12					
Hourglass[7]	Vertical	SLM + mac.	SR (240° C)	10^9	80.7 MPa

Table 1: summary of the results of tests on AlSi12Mg alloy.

According to Table 1, the largest VHCF response is found for specimens manufactured with PH and subjected to an SR treatment.

3. AlSi10Mg: VHCF TEST RESULTS

In Ref.[8], ultrasonic VHCF tests were carried out on hourglass specimens (5 mm gage diameter) made of AlSi10Mg, with a Shimadzu USF-2000 testing machine. A modified SLM 250 HL system equipped with an external laser source capable of providing a maximum power of 1000 W was used. Cylindrical samples (layer thickness of 50 µm) were manufactured in vertical direction and then machined to the final sample geometry. The first batch (Batch A) was produced without base platform heating, whereas the second batch (Batch B) was produced by heating the building platform to 200° C. Experimental results showed that the VHCF strength is generally larger for batch B, even if the runout stress amplitude was the same (90 MPa). The VHCF failures in batch A originated from a single critical defect. For batch B, multiple fracture initiation sites were found, highlighting that a more homogeneous microstructure is obtained by heating the building platform.

In Ref.[9-12], fully reversed tension-compression VHCF tests on Gaussian specimens (gage diameter of 11 mm) made of AlSi10Mg were carried out by using the ultrasonic testing machines developed at Politecnico di Torino. Spherical gas atomized AlSi10Mg powders (average size of approximately 45 µm) and an SLM Solutions (model 500 HL quad 4 × 400 W) Selective Laser Melting system were used for the specimen production. All the SLM manufactured specimens[9-12] were not subjected to a machining process; only manual polishing was applied to smooth the surface.

In Ref.[9-11], specimens produced in horizontal direction were tested in three condition: as built (AB), subjected to a conventional heat treatment (2 hours heating to 320 °C and air cooling to room temperature, HT-320) and subjected to a heat treatment proposed by the Authors (2 hours heating to 244 °C and air cooling to room temperature, HT-244). Experimental results showed that HT-244 specimens were characterized by the largest median VHCF strength (76 MPa), whereas the HT-320 specimens were characterized by the smallest VHCF strength (61 MPa), with the as-built data between the HT-320 and HT-244 data (Fig. 2b). The fatigue failures originated from different types of defects located close to the specimen surface, highlighting the detrimental effect of surface and sub-surface defects on the VHCF response. On the other hand, also the microstructure was found to play an important role: indeed, an annealing temperature of 320°C induced spheroidization of the Si networks, which instead remained intact in AB and HT-244 specimens characterized by a larger VHCF response.

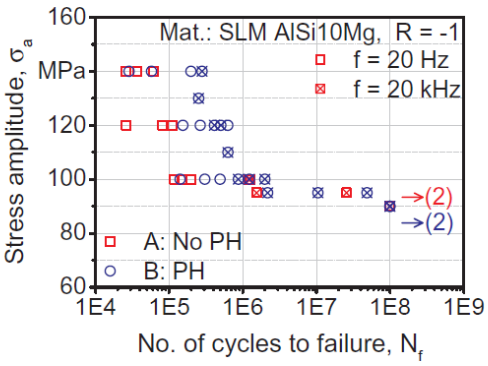
In Ref.[12], VHCF tests up to 10^9 cycles were carried out on Gaussian specimens manufactured in vertical direction. The S-N plot of the experimental dataset is shown in Fig. 2 c). All the fatigue failures originated from defects concentrated in a region of material close to the surface (maximum distance from the specimen surface equal to 1.1 mm). The median VHCF at 10^9 cycles was found to be equal to 63 MPa, but the experimental failures showed a large scatter: for instance, if the 0.1% P-S-N curve is considered, the VHCF strength at 10^9 cycles reduced to 30 MPa, due to the presence of premature failures originating from large defects.

Table 2 summarizes the results of the VHCF tests carried out in the literature.

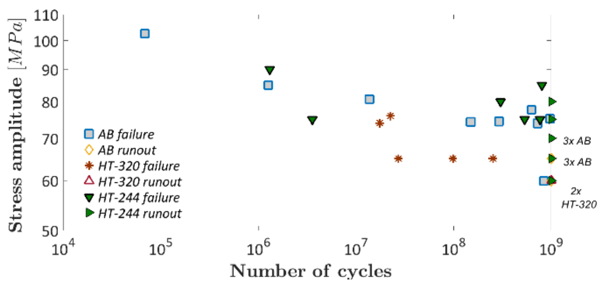
Specimen type	*Building orientation*	*Production process*	*Heat treatment*	*Runout*	*Fatigue strength [MPa]*
Hourglass[8]	Vertical	SLM + mac	-	10^8	90
Hourglass[8]	Vertical	SLM (PH 200°C) + mac	-	10^8	90
Gaussian[11]	Horizontal	SLM (PH 150°C)	-	10^9	68
Gaussian[11]	Horizontal	SLM (PH 150°C)	SR (320°C)	10^9	61
Gaussian[11]	Horizontal	SLM (PH 150°C)	SR (244°C)	10^9	76
Gaussian[12]	Vertical	SLM (PH 150°C)	-	10^9	63

Table 2: summary of the results of tests on AlSi10Mg alloy (SLM=Selective Laser Melting, mac=machining, PH=Platform Heating, SR=Stress Relief).

According to Table 2, the VHCF strength of hourglass specimens tested in Ref.[8] is larger than the VHCF strength of large Gaussian specimens built in horizontal and vertical direction. The difference could be due to the different tested risk-volumes (and, accordingly, to a possible size-effect) and to the different testing condition (hourglass specimens were machined after the AM process).



(a)



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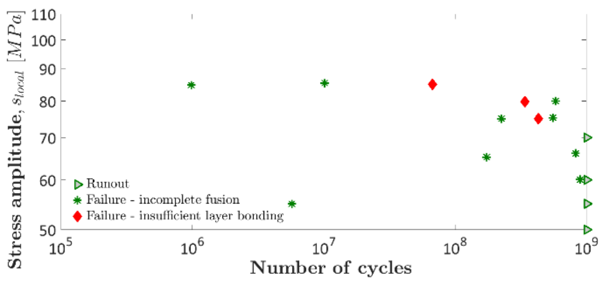

(c)

Fig. 2: S-N plot of tests on AlSi10Mg specimens: a) Ref.[8]; b) Ref.[11]; c) Ref.[12]

4. Ti6Al4V: VHCF TEST RESULTS

In Ref.[13], fully reversed tension compression VHCF tests were carried out on Ti6Al4V specimens produced in vertical direction with a Shimadzu SF-2000 testing machine. Specimens were manufactured with an EOS M270 SLM machine (power of 200 W, powder with grain size distribution of 20–63 µm and layer thickness of 30 µm). Two batches were tested: specimens subjected to a stress relief treatment (650°C for 3 h in vacuum, SR) and specimens subjected to a hot-isostatic-pressing process (HIP, at 920°C and 1000 bar pressure for 2 h). After the heat treatment, the specimens were machined to the final geometry. Fig. 3a (SR) and Fig. 3b (HIPped specimens) show the S-N plot of the experimental dataset. Tests above 10^7 cycles showed a monotonic decreasing fatigue strength in the VHCF region and, both in SR and in HIPed specimens, cracks started from internal defects. The HIP treatment strongly influenced the VHCF response: HIPed specimens showed a significantly larger VHCF strength at 10^9 cycles (483 MPa for HIPped specimens with respect to about 200 MPa for SR).

In Ref.[14], the VHCF response of Ti6Al4V hourglass specimens was assessed with ultrasonic tests at 19 kHz[15]. Three batches were tested: specimens of batches "SLM-1b" and "SLM-2" were manufactured through SLM by using a SLM 250HL system with a single 400W fiber laser (powder size ranging from 20 to 63 µm, layer thickness of 30 µm and build platform heated to 200° C). Specimens of batch SLM-1b were heat treated at 800 °C for 2 h in Argon atmosphere, whereas specimens of batch SLM-2 were subjected to a HIP process at 920 °C for 2 h at 1000 bar in an Argon atmosphere.

Specimens of batch "EBM" were produced with an Electron Beam Melting (EBM) machine (Arcam A2X system) in vacuum atmosphere (Ti6Al4V powder with an average size ranging from 45 to 100 µm and layer thickness of 50 µm). The EBM specimens were tested without any post treatment. The SLM and EBM specimens were obtained through machining from cylindrical bars manufactured in vertical direction. The S-N plot of the experimental dataset is shown in Fig. 3 b). All the fatigue failures in the VHCF region originated from "internal defects". The fatigue lives of the SLM batch SLM-1b and of the EBM specimens were similar. Failure initiation was governed by process-induced porosity and lack of fusion. Similar defect types (pores and incomplete fusions), failure mechanisms and microstructures were observed in the batches SLM-1b and EBM. On the other hand, the HIP process (SLM-2) significantly improved the VHCF response, which became comparable with the conventionally processed material. In batch SLM-2, fatigue crack originated at α-phase clusters and facets.

Finally, in Ref.[16], fully reversed tension-compression VHCF tests were carried out on Gaussian specimens with the ultrasonic testing machines developed at Politecnico di Torino. Ti6Al4V powders (average size of approximately 45 µm) were used for the specimen production. SLM specimens were manufactured with a Renishaw AM400 system (layer thickness of 60 µm). After the manufacturing process, specimens were subjected to a traditional heat treatment (850 °C for 1 hour, followed by cooling in flowing Ar atmosphere). Specimens were tested in the as-built condition and only a manual fine polishing was carried out to smooth the surface. Fig. 3d) shows the experimental dataset obtained in Ref.[16].

A clear monotonic decreasing trend between the stress amplitude and the number of cycles to failure was not found in the S-N plot, with failures concentrated in the range 180 MPa ±20 MPa. The large scatter of the VHCF life was mainly correlated to the defect location. Failures originating from surface defects were characterized by a significantly smaller fatigue life, below $5 \cdot 10^6$ cycles; whereas, the fatigue life was above 10^8, if the fatigue crack originated from an internal defect.

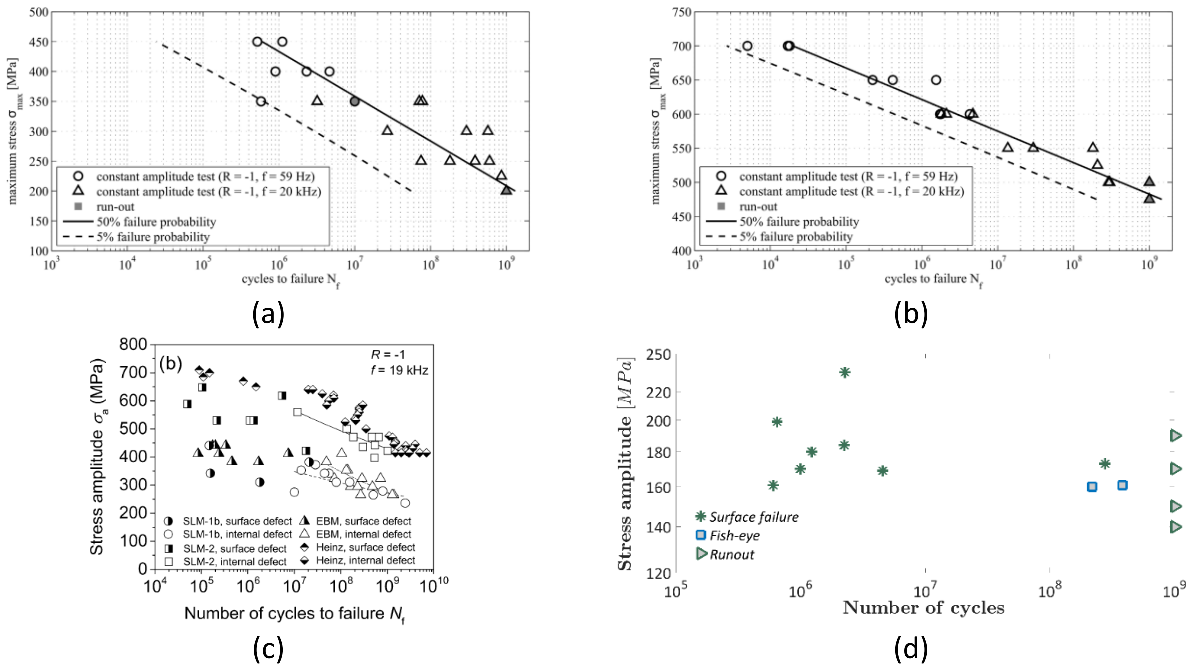

Fig. 3: S-N plot of tests on Ti6Al4V specimens: a) and b) Ref.[13]; c) Ref.[14]; d) Ref.[16].

Table 3 summarizes the results of the VHCF tests on Ti6Al4V reported in the literature.

Specimen type	*Building orientation*	*Production process*	*Heat treatment*	*Runout*	*Fatigue strength [MPa]*
Hourglass SR[13]	Vertical	SLM + mac.	SR (650°C)	10^9	200
Hourglass HIP[13]	Vertical	SLM + mac	HIP	10^9	483
Hourglass SLM_1b[14]	Vertical	SLM + mac.	SR (800°C)	10^9	240
Hourglass SLM-2[14]	Vertical	SLM + mac.	HIP	10^9	400
Hourglass EBM[14]	Vertical	EBM + mac.	-	10^9	260
Gaussian[16]	Vertical	SLM	SR (850°C)	10^9	150

Table 3: summary of the results of tests on Ti6Al4V alloy.

According to Table 3, the VHCF response of as-built specimens is the smallest, due to the presence of large surface defects. On the other hands, for machined specimens, a heat treatment permitted to enhance the VHCF response. Finally, the best VHCF strength is achieved with the machined and HIPped specimens.

CONCLUSIONS

The present paper presented an overview of the experimental results on the Very-High-Cycle-Fatigue (VHCF) response of Additive Manufacturing (AM) parts. At present, VHCF tests on AlSi12, AlSI10Mg and Ti6Al4V alloys have been carried out. The main results can be summarized as follows:

- As for High Cycle Fatigue, defects originating during the AM process control the VHCF response.
- For the Aluminium alloys (AlSi12 and AlSi10Mg), a base plate heated to 200°C permits to enhance the VHCF response. A stress relief heat treatment with a heating temperature of 240°C improves the VHCF response; a heating temperature above 320°C is, on the contrary, detrimental.
- For the Ti6Al4V alloy, a HIP post treatment on AM specimens machined to the final shape permits to obtain a VHCF response similar to that of traditionally processed materials.

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