Excellence in Science

Application News

Ultrasonic Testing Machine USF-2000A
Microfocus X-Ray CT System inspeXio™ SMX™-225CT FPD HR Plus
Electron Probe Microanalyzer EPMA™-8050G

Influence of Voids on Fatigue Life of 3D Printed Titanium Alloy Specimens

Bressan Stefano, Takuo Ono, Kazunori Odani

User Benefits

- Internal voids due to 3D printing manufacturing processes can be visualized with the CT scan
- Fatigue fracture due to internal voids can be tested rapidly thanks to the ultra-sonic test frequency
- Analysis of the influence of voids on fatigue life made possible by determining void location with surface fracture analysis and correlating with cycles to failure

■ Introduction

The titanium alloy Ti6Al4V is characterized by high specific strength, good corrosion resistance and biocompatibility, and it is mainly used in prosthesis and aircraft industry related parts. As an alternative technology to fabricate such components, 3D printing (or additive manufacturing, AM) is increasingly drawing more interest. Compared to traditional manufacturing techniques such as machining or forging, 3D printing offers several advantages such as higher degree of freedom of the component shape, a shorter fabrication time, etc[1]. Among the available 3D printing techniques, the most used for metallic materials is the PBF (Powder Bed Fusion). An image of the fabrication process with electron beam PBF (E-PBF) is represented in Fig. 1.

In contrast to its advantages, 3D printed materials tend to exhibit more internal voids (trapped gas or lack of fusion). For this reason, to enhance the reliability of 3D printed components the correlation between the characteristics of internal defects (distribution, size, position, etc.) with the fatigue strength must be analyzed.

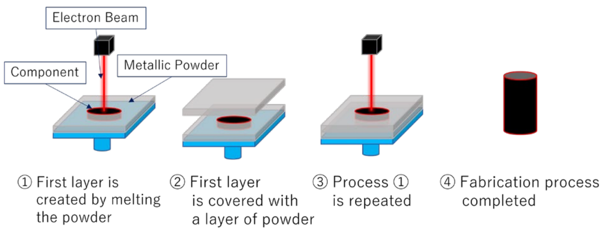

Fig. 1 Representation of E-PBF 3D Printing process

In this article, the results of an analysis conducted with 3 different instruments using samples fabricated via electron beam PBF are presented. Firstly, a CT scan was conducted on the samples to visualize and measure the size of internal voids. Afterwards, the fatigue strength of the specimens was analyzed by using an ultrasonic testing machine. Finally, the fracture surface has been observed with an electron probe microanalyzer (EPMA) to detect the crack initiation site. A correlation between the void position and the fatigue strength could be obtained.

■ Test Specimens

The size and shape of the specimens is shown in Fig.2. Firstly, a cylindrical sample with a radius of 10mm was created with the electron beam PBF technique, and then machined to obtained the final shape. The shape of the sample has been determined according to the specifics of the ultra-sonic testing machine. A total of 6 specimens have been used in this analysis.

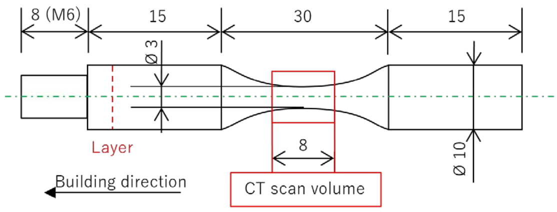

Fig. 2 Specimen shape and dimensions (in mm)

■ CT scan results

The CT scan was conducted on a volume including the central section of the specimen, taken at ±4 mm from the center of the specimen (Fig.2 red frame). The CT scan was conducted on the central section as it is the volume with the highest probability of developing a fatigue crack.

The CT scan of the specimen was conducted with the X-ray CT System inspeXio SMX-225CT FPD HR Plus (Fig.3) which allows for non-destructive analyses. The image processing software VGSTUDIO MAX was used for the analysis of the inner void size and distribution.

An example of CT analysis results is reported in Fig. 4. The size of the void could be measured with the image processing software, and it is represented with a different color based on the size, as shown by the color bar on the left side of the picture. The maximum volume of the inner voids was approximately 1 x 10^{-3} mm^3, and the void distribution was similar for each specimen. The similar void distribution indicated a good reproducibility of the 3D printing fabrication process. Fig.5 shows a magnification of a specimen cross section including and internal void. Most of the voids were spherically shaped, although some elongated voids (crack like defects) were also present. Voids were observed both inside of the specimen and on the surface.

Fig. 3 inspeXio™ SMX™ -225CT FPD HR Plus

Fig. 4 Void distribution on specimen 1

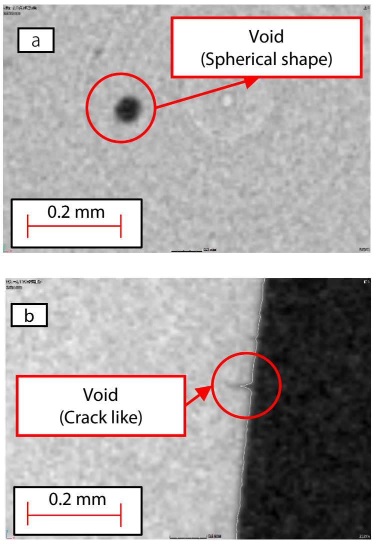

Fig. 5 Cross section image of specimen including voids
(a) Spherical void(b) Crack like void

■ Fatigue test and test results

Fatigue tests were performed with the ultra sonic fatigue testing machine USF-2000A*1 (Fig. 6). For tests up to 10^9 cycles, a test conducted at 10Hz would take up to 3 years. However, the USF-2000A is capable of applying loads with up to 20kHz of frequency, consequently reducing the test time (in case 10^9 cycles) from 3 years to 14 hours. A picture of the test setup is shown in Fig.7. The specimen is connected to a horn which vibrates and applies the load. When dealing with loads at very high frequency, there is the risk that the temperature of the specimen will drastically increase, which might influence the test results as well as leading to a premature rupture of the specimen. To prevent this, the specimen is cooled with air and specimen surface temperature is monitored with a temperature sensor. The official regulation regarding ultra sonic fatigue tests issued by the Japan Welding Engineering Society (JWES, Regulation number WES 1112:2022 Method for ultrasonic fatigue testing in metallic material) recommends the temperature to be maintained under 30ºC for metallic materials.

As shown in Table 1, two different loads were applied to the specimens. The number of cycles that lead to failure for each sample is shown in Table 1 and Fig. 8. The results clearly show that the number of cycles to failure can be divided in two macro areas: 10^5~10^6 cycles (high cycle fatigue) for specimens 1,3 and 6 and 10^8~10^9 cycles (very high cycle fatigue) for specimens 2, 4 and 5. The results show that there is not a correlation between the applied load and the number of cycles to failure. A picture of the fracture surface taken with an optical microscope is shown in Fig.9.

Fig. 6 Ultrasonic fatigue testing machine USF-2000

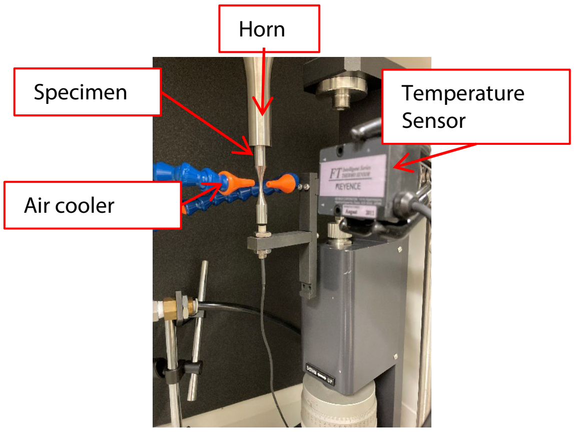

Fig.7 Picture of the test setup

Table 1 Test Results

Specimen	Stress	Cycles to Failure
-	MPa	N
1	350	6.42×10^5
2	350	4.50×10^8
3	350	6.65×10^5
4	300	1.19×10^8
5	300	3.56×10^9
6	300	3.50×10^5

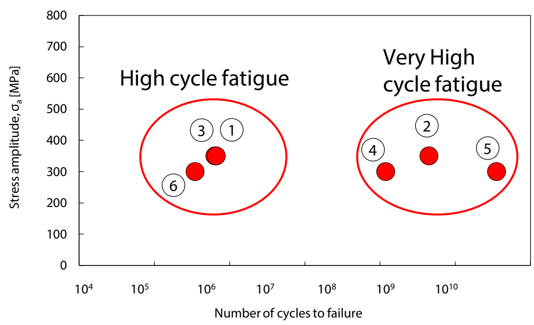

Fig.8 Relationship between stress and number of cycles to failure

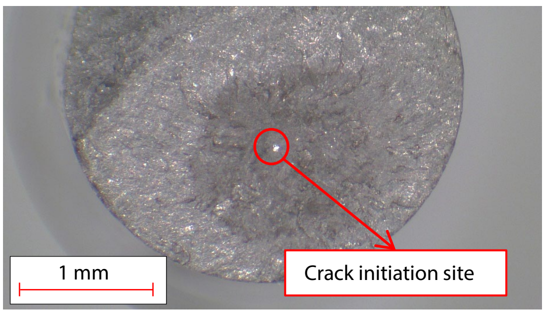

Fig.9 Picture of the fracture surface（Specimen 2）

■ Crack initiation site observation

To accurately detect the crack initiation site, the fracture surface and the cross sections taken with CT scanning have been compared. The fracture surface has been observed using an electron probe micro analyzer EPMA-8050G (Fig. 10).

Fracture surface analysis results of the specimens which failed in the high cycle fatigue region (specimens 1 and 6) are reported in Fig. 11. Starting from the left, the position of the voids from which the crack initiated is represented with a red dot on the specimen (part a). The central part (b) shows a magnified picture of the crack initiation site for each specimen. Finally, the rightmost part (c) shows the CT image of the cross section containing the crack initiation void. In each specimen which failed in the high cycle region, the crack initiation site (void) was located on the specimen surface. The results of the specimen (specimens 4 and 2) which failure occurred in the very high cycle region are shown in Fig. 12, similarly to Fig. 11. In this case, the crack initiation site was an internal void.

From the results above, it is clear that the location of the void has influence on the fatigue life of the specimens. The results are confirmed in the literature[2].

Fig. 10 Electron Probe Microanalyzer EPMA^{TM}-8050G

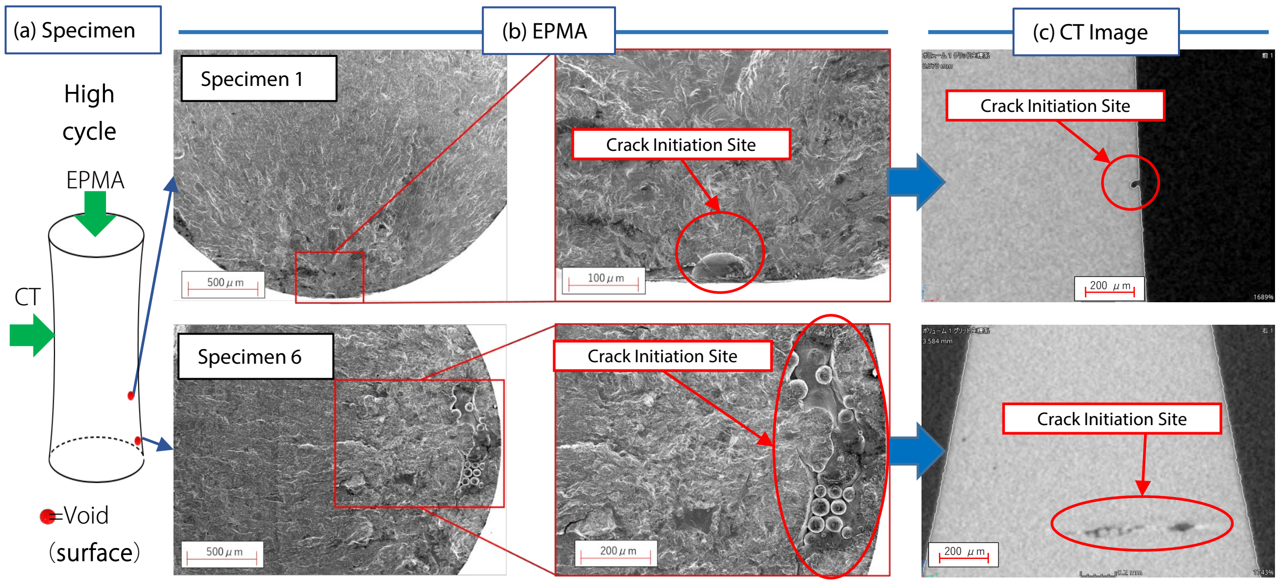

Fig. 11 EPMA and CT scan observation results of specimens which failure occurred in the high cycle region (1 and 6)
(a) EPMA and CT scan observation direction and crack initiation site position (b) EPMA fracture surface image (c) crack initiation site cross section

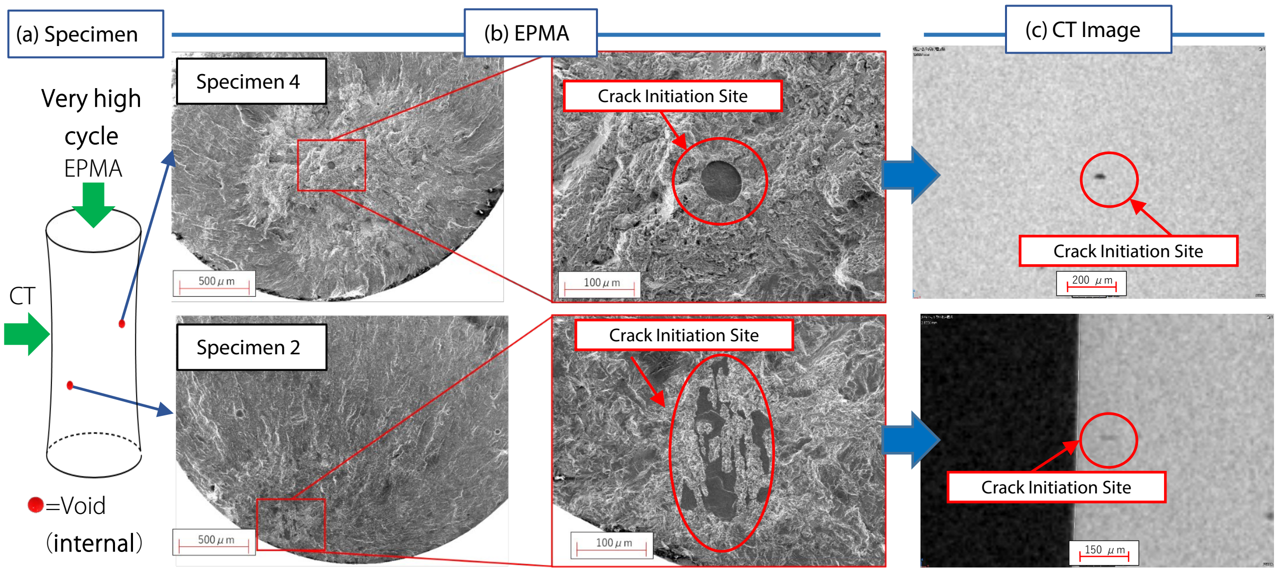

Fig. 12 EPMA and CT scan observation results of specimens which failure occurred in the very high cycle region (4 and 2)
(a) EPMA and CT scan observation direction and crack initiation site position (b) EPMA fracture surface image (c) crack initiation site cross section

■ Conclusion

Based on the results of CT scan, fatigue testing, and fracture surface analysis, it can be concluded that the position of internal voids have a remarkable influence on the fatigue life of 3D printed Titanium specimens. However, in order to estimate the influence of other parameters connected to the voids such as size and distribution, other tests are necessary. With this analysis system, it is possible to conduct research for enhancing the reliability of 3D printed products.

<References>

1) P.Li, D.H Warner, A.Fatemi, N.Phan, "Critical assessment of the fatigue performance of additively manufactured Ti6Al4V and perspective for future research" [International Journal of Fatigue] Volume 85, 2016, Pages 130-143Brookhaven National Laboratory, Upton, NY, USA, Tech. Rep. BNL-23103. Jan. 1977.

2) J. Günther, D. Krewerth, T. Lippmann, S. Leuders, T. Tröster, A. Weidner, H. Biermann, T. Niendorf "Fatigue life of additively manufactured Ti–6Al–4V in the very high cycle fatigue regime" [International Journal of Fatigue] Volume 94, Part 2, 2017, Pages 236-245

<Related Applications>

1. Application News No. i258

01-00515-EN First Edition: Dec. 2023

SHIMADZU

Shimadzu Corporation

www.shimadzu.com/an/