Research on Post-processing Microstructure and Property of Titanium Components with Selective Laser Melting (SLM)

Ming Qiang Chu¹,*, Shu Yan Zhang¹,², Guan Qiao Su¹, Ren Gen Ding¹, Lei Wang¹ and Sanjooram Padde¹

¹ Centre of Excellence for Advanced Materials, Songshan Lake, Dongguan 523808, China
² Materials laboratory of Song Shan Lake, Dongguan 523808, China
³ Shanghai Aircraft Manufacturing Co., Ltd., China

Email address: a mingqiang.chu@ceamat.com; b shuyan.zhang@ceamat.com

Abstract. Additive manufacturing of titanium component holds promise to deliver benefit such as reduced cost, weight and carbon emissions during both manufacture and use. To capitalize on the benefits, it must be shown that the mechanical performance of parts produced by additive manufacturing can meet design requirement that are typically based on wrought material performance properties. Of particular concern for safety critical structures is the fatigue property of parts produced by additive manufacturing. Microstructure evolution, and its influence on mechanical properties of the alloy in the as-fabricated condition, has been documented by various researchers. However, fatigue crack propagation and the effects of the directional structure have not been sufficiently studied, imposing a barrier for this technology’s potential extension to high-integrity applications. In this study, fatigue life (S-N) and fatigue crack growth (FCG) both parallel and perpendicular to the build directions was studied. The interaction between the directional as-fabricated SLM microstructure and FCG was investigated and compared to that of the hot isostatic pressing (HIP) specimens with and without the stress relief after fabricating with SLM.

1. Introduction
Additive Manufacturing (AM) is a process in which parts are built up by progressive consolidation of raw materials, such as powder or wire, in a layer-by-layer fashion. This is a different approach to traditional fabrication methods, such as machining from block or plate, where the final part geometry is produced by subtracting, or removing material. With this additive approach, parts of greater complexity can be economically produced. Furthermore, by optimizing the design of the part for a given boundary conditions, such as attachment interfaces with other parts and applied loads, using numerical techniques, while leveraging the complex geometric build capabilities of the AM process, parts with minimum weight can be achieved. An additional potential advantage of the AM process is reduction of carbon emissions during part manufacture compared to traditional processes like casting and machining. During the last decade, several additive manufacturing (AM) techniques for processing of complex metallic parts were developed and extensively investigated [1-6]. In recent years, the tensile strength values of additive manufactured laser powder bed (SLM) and electron beam melted (EBM) TiAl6V4 [3,4] have been well characterized for different heat treatments and surface conditions. In particular, Ti-6Al-4V has a great potential, since it shows a high specific strength, low density and high corrosion resistance at temperatures of up to 350 °C. To capitalize on the benefits, it
must be shown that the mechanical performance of parts produced by additive manufacturing can meet design requirements that are typically based on wrought material performance properties. Of particular concern for safety critical structures is the fatigue property of parts produced by additive manufacturing.

The SLM technologies applied to Ti–6Al–4V due to the typical process conditions, i.e. layer by layer generative principle, short energy pulses resulting in highly localized melting and solidification and strong temperature gradients of this manufacturing process, which promotes the formation often acicular/lamellar alpha hcp phase (martensitic), a fine microstructure; the microstructure also exhibits strong directionality, i.e. columnar grain structure, consequently anisotropic structure. The strongly textured microstructure results in anisotropy of the mechanical properties [7-9]. Residual stresses are also expected due to this process and can be managed by appropriate post-fabrication heat treatment [10]. This further thermomechanical treatment adjusts the microstructure and reduces internal stresses, in comparison to ‘as-cast’ and wrought standards. Thus, the completely satisfied ductility and strength values can be optimal by the applied post-treatment. The post heat treatment for the SLM part can also be applied hot isostatic pressing, which is used in traditional powder metallurgy and foundry technology. HIP’ing seems to be very promising to restore Ti-6Al-4V properties due to the combined effect of high temperature and high pressure, and allows not only to adjust the microstructure, but also to fuse unmolten particles. This reduction of residual porosity is very important, since the pores within the sample can act as strong stress raisers and lead to failure, especially under fatigue loading. While many references, for example [8,9], discuss the link between process parameters and static mechanical properties of SLM Ti–6Al–4V, the fatigue strength characterization appears more recently in the literature [9-11]. In fact, fatigue crack propagation and the effects of the directional structure have not been sufficiently studied, imposing a barrier for this technology’s potential extension to high-integrity applications. Fatigue testing is known to be expensive and time consuming as it is susceptible to a number of intrinsic and extrinsic factors that complicates the data generalization and exploitation. On the other hand, the fatigue behaviour of SLM Ti–6Al–4V is critical for sectors, in which high structural integrity is a paramount requirement for aerospace.

This study is aimed at Ti–6Al–4V materials presented and directed to the evaluation of the anisotropic fatigue behavior including the effect of post heat treatment on the fatigue life of Ti-6Al-4V obtained using the SLM process. While the directionality of static mechanical properties of SLM Ti–6Al–4V has been documented [11,12], little information is available of such influence on the high cycle fatigue behavior. Therefore, Fatigue life (S-N) and fatigue crack growth (FCG) both parallel and perpendicular to the build directions was studied. The interaction between the directional as-fabricated SLM microstructure and FCG was investigated and compared to that of the hipped specimens with and without the stress relief heat treatment (HT) after fabricating with SLM to understand whether the stress relief HT has effect on the fatigue property.

2. Experimental Procedure

Ti-6Al-4V alloy powder was produced by the gas atomization process and was spherical with a maximum particle size 53μm. Ti-6Al-4V alloy samples were fabricated on an EOS M280 machine including a laser unit delivering a continuous single mode laser power of 400W, which produces a laser beam with a wavelength of 1070 nm and an intensity distribution of Gaussian. The laser spot diameter was 100–500μm and the maximum scanning speed was 7m/s. In addition, the layer thickness can be selected between 20–100μm and the deposition was carried out on a 30mm thick Ti-6Al-4V alloy plate. During the SLM process, the processing chamber will be filled with argon in order to maintain the oxygen level during the process. A double optimization procedure is necessary in order to obtain a high quality SLM part. Firstly, the optimization of the SLM parameters for the minimization of inherent defects, and secondly, the application of further thermo mechanical treatment to minimize internal stresses and adjust the microstructure. These two stages of optimization are presented in this paper, which aims to comprehensively examine the factors influencing defects in Ti-6Al-4V processed by SLM. For this reason, more than 87 small Ti-6Al-4V cuboids were previously produced with the
various scan parameters. The porosity of each test sample was quantitatively two- and three-dimensionally analyzed using optical microscope and X-ray computed tomography. The optimized process parameters were afterwards used in the second part of the program to produce cylindrical specimen for the mechanical testing.

After the deposition with SLM, the specimens underwent a stress relief heat treatment (HT) with exposure to 800 °C for 2 h in a vacuum furnace as specified in the optimization temperature of the stress relief heat treatment. The build configuration and SLM reference axis system on the build platform of the EOS machine is shown in Figure 1. The cylindrical specimens (Ø10 mm×70 mm) are orientated with their longitudinal axis perpendicular to the build platform (parallel to the build direction/ Z axis). The rectangular specimens have their longitudinal axis perpendicular to the build direction/Z axis, 10×10×70 mm³ for horizontal samples. In this study, the terms vertical orientation and horizontal orientation are used to identify samples that are oriented parallel and perpendicular to the build direction/Z axis respectively. The diagonal samples to the build direction/Z axis also were tested as a comparison. The room temperature tensile property was tested according to ASTM E8/E8M. The tensile test was employed for the verification of mechanical property with SLM. Some of the samples were then hot isostatic pressed (HIP) to eliminate the porosities produced during the fabricating. Then an investigation using fatigue specimens fabricated using SLM were studied, fatigue crack propagation testing with force controlled constant amplitude axial, the loading condition was cyclic tension with R = 0.1 for the specimen as HT and HIP. In addition, each specimen was tested at different constant maximum stress levels, from 100 to 600 MPa, to failure in order to generate an approximate S–N curve for that given condition/orientation. Testing of the samples was carried out per ASTM E466 at a frequency of 20 Hz, a load ratio of R = 0.1 on an MTS load frame at room temperature in atmosphere. The fracture surfaces of the fatigue specimens were characterized with both optical and scanning electron microscopy (SEM) to provide further insight into the resulting fatigue test data. Then, the tensile properties and FCG fatigue resistance and S-N curve of all HIP treated and non-treated samples were tested, and compared with the wrought Ti-6Al-4V alloy. The microstructure, porosity and the received mechanical properties were analyzed and was comprehensively examined and discussed.

Figure 1. The specimen fabricated with SLM (a) Specimen building horizontal direction (b) Specimen building vertical direction (c) Specimen building diagonal direction

3. Results and Discussion

3.1. Characteristic of the Microstructures

Microstructures have been studied in Ti-6Al-4V alloy produced with SLM. Figure 2 shows the microstructure features of Ti-6Al-4V alloy fabricated by SLM in the X-Z and X-Y sectional directions. In general, the as-built condition exhibits fine martensitic acicular alpha morphology with elongated beta columnar grains that span across multiple build layers. It seems to mean that this unidirectional grain growth may also influence the anisotropy of properties of the SLM as-built alloy. Heat treatment, either stress relief or HIP, after SLM allows the fine acicular α to precipitate into a more lamellar α + β
structure. These SLM microstructures are more similar to a weldment or casting than the equiaxed primary alpha grain structure in wrought Ti-6Al-4V mill products such as plate, sheet. As expected, this microstructure yields higher strengths and lower ductility than wrought material [3–10]. Figure 3 provides an overview of the microstructure for Ti-6Al-4V as built and as the post built-up heat treatments. It is assumed that the martensite was expected to be present (Fig. 3a). A significant coarsening of the lamellar microstructure can be observed for the hipped specimen. (Fig. 3c).

**Figure 2.** Microstructure of Ti-6Al-4V alloy fabricated by SLM: (a) is longitudinal section through columnar grains of the prior-β phase in the X-Z plane. (b) Cross-section through columnar grains of the prior-β phase in the X-Y plane

**Figure 3.** Microstructure of Ti-6Al-4V alloy (a) as fabricated (b) post heat treatment at 800 °C/2 h (c) Hipped after heat treatment at 800 °C/2 h
3.2. X-ray Computed Tomography Analysis

Ti–6Al–4V fabricated with SLM technology due to the strong temperature gradients of this manufacturing process, which promotes the formation of very fine pores. This residual porosity is very important, since the pores within the sample can act as strong stress raisers and lead to failure, especially under fatigue loading. Methods for detecting defects in AM parts can be divided into two categories: destructive testing and non-destructive testing. Destructive testing includes metallographic and scanning electron microscopy; non-destructive testing methods include ultrasonic testing, infrared detection, eddy current testing, and X-ray inspection. Among these methods, X-ray micro computed tomography (X-ray micro CT) has been widely employed to study defect and dimensions accuracy in additive manufacture parts because of its high precision spatial information of parts form almost any material [13]. Lopez E et al.[14] has compared micro CT with optical 3D scanner about different demonstrators and features by measuring parts made by electron beam melting (EBM) and SLM. Maskery I et al.[15] investigated the size and shape distribution of the pores inside the SLM alloy Al-Si10-Mg through micro CT, which prove than the X-ray CT has the ability of monitoring and detection for SLM process. The research of many scholars shows that X-ray scanning technology is a reasonable and feasible method to study the internal defects of metal additive products. Therefore, X-ray computed tomography was applied to measure the porosity distribution for various processing parameters in this study. A relatively large amount of porosity was observed as shown in Figure 4(a).

Pore sizes of the annealed Ti–6Al–4V SLM specimen were typically found to be less than 60μm in diameter and randomly distributed. The hipped specimen after SLM was also measured with micro CT as a comparison shown in Figure 4(b). Obviously, the porosities were not detectable after hipping. Various types of defects inherent to the SLM have been well described by Kim et al[16], and are very important for the mechanical properties of the material. Presently, the pores and other defects cannot be avoided completely, but they should be kept to a minimum at the stage of the powder-layer consolidation, as was clearly confirmed among other by Kruth et al.[17]. Detailed investigation of the influence of manufacturing process parameters on the defect as well as analysis of the surface roughness will be published elsewhere.

Figure 4. X-ray Computed Tomography image showing the pores in (a) Annealed sample (b) Hipped sample

3.3. Mechanical Testing

Microstructures have been studied in Ti-6Al-4V alloy produced with SLM. Figure 2 shows the microstructure features of Ti-6Al-4V alloy fabricated by SLM in the X-Z and X-Y sectional directions. In general, the as-built condition exhibits fine martensitic acicular alpha morphology with elongated
beta columnar grains that span across multiple build layers. It seems to mean that this unidirectional grain growth may also influence the anisotropy of properties of the SLM as-built alloy. Heat treatment, either stress relief or HIP, after SLM allows the fine acicular α to precipitate into a more lamellar α + β structure. These SLM microstructures are more similar to a weldment or casting than the equiaxed primary alpha grain structure in wrought Ti-6Al-4V mill products such as plate, sheet. As expected, this microstructure yields higher strengths and lower ductility than wrought material [3–10]. Figure 3 provides an overview of the microstructure for Ti-6Al-4V as built and as the post built-up heat treatments. It is assumed that the martensite was expected to be present (Fig. 3a). A significant coarsening of the lamellar microstructure can be observed for the hipped specimen. (Fig. 3c).

3.3.1. Tensile. Figure 5 provides a summary of the mechanical properties obtained from this research on Ti-6Al-4V manufactured by SLM. These value are compared with accepted values for wrought Ti-6Al-4V tested in the annealed and solution treated and aged condition, dash line is AMS standard strength of annealed die forgings of Ti–6Al–4V at O~1400 ppm, Yield stress = 827 MPa, UTS = 896 MPa (El = 10%). The yield and tensile strengths in laser-based AM specimens are generally higher than those in annealed material and in the same range as age-hardened Ti–6Al–4V, which is likely due to the presence of a fine grained microstructure in laser-based AM specimens. An influence of specimen orientation with respect to the build direction on tensile properties was also observed as shown in Fig. 5. This was primarily attributed to the elongated, directionally oriented (vertically), grain structure across build layers. Heat treatment for the stress relief improves ductility but decreases strength. After hot isostatic pressing, the strength of specimen is decreased, however, plastic stability of the specimens is in a relatively good level, shown in table1, the reason for the good comprehensive performance with the hot isostatic pressing is that in the process of heat treatment, the test specimen under three directions to compressive stress, pore closure or disappear gradually, sample density increase. In addition, after the hot isostatic pressure, the microstructure is relatively coarser, resulting in a decrease in the strength level. However, the strength of specimen seems no much difference with and without the stress relief HT before hipping. Therefore, the best combination of strength and ductility for Ti-6Al-4V SLM specimens was obtained after hipping.

| Heating method | Sample Direction | YS/MPa | UTS/MPa | TE/% |
|----------------|------------------|--------|---------|------|
| SLM            | Horizontal       | 1039.9 | 1201.2  | 9.5  |
|                | Veridical        | 1049.9 | 1194.8  | 10.2 |
|                | Diagonal         | 1070.4 | 1222.4  | 9.9  |
|                | Horizontal       | 944.6  | 1036.3  | 14.9 |
| 800°C/2h/FC    | Veridical        | 964.9  | 1035.7  | 14.6 |
|                | Diagonal         | 967.3  | 1052.5  | 14.3 |
|                | Horizontal       | 866.8  | 961.1   | 16.1 |
| SLM+SR*+HIP*   | Veridical        | 851.4  | 950.4   | 15.3 |
|                | Diagonal         | 869.2  | 976     | 15.7 |
|                | Horizontal       | 859.8  | 968.7   | 16.7 |
| SLM+HIP        | Veridical        | 864.3  | 968.3   | 17.4 |
|                | Diagonal         | 870.4  | 979.7   | 15.8 |

SR: stress relief; HIP: hot isostatic pressing; UTS: Ultimate tensile strength; YS: yield strength; TE: total elongation.
3.3.2. Fatigue. In addition to metallurgical and static performance evaluations, the primary goal of this study was to evaluate the fatigue performance of Ti–6Al–4V materials produced by the SLM additive manufacturing process as a function of build orientation. Furthermore, to minimize manufacturing costs and carbon emissions during manufacture, no post-fabrication heat treatment was desired, so it was also necessary to determine if residual stresses left in the part not removed by a subsequent heat treatment would be acceptable in terms of the resulting fatigue performance. Figure 6 is shown that fatigue crack propagation curves according to the crack plane oriented parallel (Z sample) and perpendicular to the build layers (X-Y sample). The trend in a linear-log plot is well behaved with fatigue crack growth of the Z specimens that are considerably different and slower than the other two specimen orientations. That is because that the microstructure exhibits strong directionality, i.e. columnar grain structure vertically, and crack plane oriented perpendicular to the columnar grain structure. Therefore, the fatigue crack growth path is slightly tortuous along the build layers. Experimental results also show that the impact of different heat treatment process on the fatigue performance as shown in Fig. 7, samples as fabricated and annealed heat treatment states fatigue life is much scattered, but the fatigue test performance of the samples after hot isostatic pressing treatment, the data divergence become smaller, and the repeatability of the sample in each direction is obvious, these results highlight a dependence of fatigue performance specimen porosities, while the analysis indicate that the hot isostatic pressing may eliminate the sample internal defects such as porosity, incomplete fusion, make samples of fatigue life and stability are greatly increased, the fracture surface as shown in Fig.8&9. Leuders et al.[18] investigated an effect on the high cycle fatigue (HCF) behaviour of SLM-processed Ti-6Al-4V and revealed that minimization of porosity is much more important than the microstructure to avoid premature crack initiation under cyclic loading. The fatigue experiment in the HCF regime conducted by the aforesaid authors showed a multiple increase in durability of samples after HIP’ing. This was also confirmed in the work by Leuders et al.[19], they found that heat treatment and HIP’ing both increased fatigue life. HIP’ing improved the life by an order of magnitude over the as-deposited condition. Porosity was the primary cause for premature failure in the un-HIP’ed conditions, while microstructure and tensile residual stresses present in the as-built condition played a secondary role. It was also interesting to note that the fatigue life seems slightly better when specimen is directly HIP’ed after fabricated with SLM, which enables avoidance of any post-process stress relief heat treatment as well as the associated cost and the carbon emissions. It can conclude that fatigue life is improved by HIP’ing. In addition, Chan et al.[19,20] were able to show that when SLM specimens were machined, in the absence of porosity, the fatigue life became comparable with cast and wrought Ti-6Al-4V. Obviously, further research of HIP treatment on the SLM specimen with preliminary minimization of the porosity during the fabrication is certainly needed. To better understand these fatigue results, effect of the metallography, surface roughness
characterization, residual stress measurements, tensile testing and fracture surface evaluations were also need to be considered to ensure the reliability of a SLM parts. Fatigue tests should be therefore with surfaces in the ‘as built’ and ‘machined’ conditions should be performed. A careful double optimization procedure is necessary to obtain a high quality material. Then the ductility and durability of SLM specimens produced with optimized process parameters and subsequently hot-isostatically pressed were equal to the values of the reference wrought material. As a result, the high quality production of a real, geometrically complex Ti-6Al4V part was enabled. While some data on the fatigue performance of AM titanium components is currently available, much more data is still needed due to the number of processing variables involved and inherent scatter associated with titanium fatigue testing in order to gain a more in-depth understanding and level of confidence in the process.

4. Conclusions
The following conclusions about Ti-6Al-4V specimens fabricated with SLM can be drawn from the results of this study:

1) The tensile strength, regardless of crack orientation with respect to the build direction, is higher than wrought and cast product forms. This increase is most likely attributed to the fine martensitic structure obtained from rapid solidification of the material in the as-deposited condition. Cracks orientated transversally to the build layers have higher ductility than those oriented parallel to the build layers due to the columnar grain structure vertically.

2) The fatigue crack growth of the Z specimens that are considerably different and slower than the Y-X specimen orientations. The fatigue life was found to be highly variable, or erratic, which was consistent with previous research in materials produced by this process.

3) The fatigue behavior of SLM Ti-6Al-4V is influenced by: (i) microstructure, because it introduces a directional effect; (ii) defects, such as porosity that being typically located between adjacent layers, affect most the direction Z, a HIP treatment often considered reduces that influence of defects but would lower the material strength.

4) Post-process heat treatment or HIP’ing should be tested to validate the assumption that fracture and crack growth properties would be increased by microstructural modification and removal of residual stresses.

5) In-situ neutron/synchrotron radiation combination needs to be done to understand the mechanism of the defects and deformation are caused by rapid solidification of molten pool under high temperature gradient.

5. Future Study
The relationships between microstructure, defects, post-processing and performance would be expected in AM parts such as those built in this study. The fatigue of SLM part can be comparable to wrought materials if defects, such as porosity, can be avoided and proper post-processing, like machining and stress relieving, are performed. The porosity present in the samples fabricated for this study. Figure 7 was likely a key contributor to the poor fatigue life observed relative to wrought material. These pores serve as stress concentrations and sites for fatigue crack initiation. The porosity was only identified qualitatively, and not quantitatively measured, in one small metallurgical sample that was built with equal dimensions in the x, y and z-directions. It is entirely possible, and highly likely, that the porosity levels could vary throughout with the volume of a sample and also be dependent on the sample aspect ratio, or build orientation. Such potential variations may have also contributed to the orientational dependence on fatigue performance observed. In the future, additional analysis should be done to further characterize the variation of porosity with respect to build orientation, location within a specimen and location of the specimen within the build chamber to better understand the resulting mechanical and fatigue performance dependence on these same variables.

Furthermore, during SLM, defects and residual stress are caused by rapid solidification of molten pool under high temperature gradient, to further investigate the influence of the processing parameters on the defect in SLM products, X-ray micro computed tomography (X-ray micro CT) has been widely
employed to study defect and dimensions accuracy. However, the X-ray micro CT methods mainly analyze the mechanism based on the detection results after forming. So far, due to the lack of effective and intuitive means, the causes of the porosity, crack, deformation and so on are not clear, resulting in poor consistency and great contingency of the formed parts. Therefore, it is very necessary to do the research on manufacturing defects and deformation mechanism of laser additive based on in-situ neutron/synchrotron radiation combination, so as to obtain abundant information of melting behavior intuitively in situ. There are precedents for in-situ neutron/synchrotron radiation observation of welding fusion, phase change, stress change, heat treatment, mechanical stretching and other behaviors [21,22]. In situ neutron/synchrotron radiation based measurements of SLM process produce unique data for model validation and improved process understanding.

**Figure 6.** Fatigue crack propagation curves

**Figure 7.** Fatigue life for different heat treatments

**Figure 8.** Typical fatigue fracture surfaces showing fatigue cracks initiated site

**Figure 9.** Typical fatigue fracture surfaces showing the fatigue striations

**Acknowledgements**

This project is supported by the Program for Guangdong Introducing Innovative and Entrepreneurial Teams (No: 2016ZT06G025) and Guangdong Natural Science Foundation (No: 2017B030306014)

**References**

[1] Murr L E, Martinez E, Gaytan S M, Ramirez D A, Machado B I, Shindo P W, Martinez J L, Medina F, Wooten J, Ciscel D, Ackelid U and Wicker R B 2011 *Metall. Mater. Trans. A* **42** 3491

[2] Li S J, Murr L E, Cheng X Y, Zhang Z B, Hao Y L, Yang R, Medina F and Wicker R B 2012 *Acta Mater.* **60** 793

[3] Singh S, Ramakrishna S and Singh R 2017 *J. Manuf. Process* **25** 185

[4] Alafaghani A, Qattawi A and Castañón M A G 2018 *Int. J. Adv. Manuf. Tech.* **99** 2491

[5] Heeling T, Cloots M and Wegener K 2017 *Addit. Manuf.* **14** 116
[6] Shah P, Racasan R and Bills P 2016 Case Stud. Nondestruc. Test. Evaluat. 6 69
[7] Khorasani A M, Gibson I, Ghaderi A and Mohammed M I 2019 Int. J. Adv. Manuf. Tech. 101 3183
[8] Thijs L, Verhaeghe F, Craeghs T, Humbeeck J V and Kruth J 2010 Acta Mater. 58 3303
[9] Qiu C, Panwisawas C, Ward M, Baoaalto H C, Brooks J W and Attallah M M 2015 Acta Mater. 96 72
[10] Spierings A B, Starr T L and Wegener K 2013 Rap. Prototyp. J. 19 88
[11] Edwards P and Ramulu M 2014 Mater. Sci. Eng., A 598 327
[12] Chu M, Zhou X W, Sun X F and Wang L 2018 Evaluation of Mechanical Properties of Ti-6Al-4V Fabricated by Selective Laser Melting, 31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018.
[13] Kim F H and Moylan S P 2018 Adv. Manuf. Ser. (NIST AMS) 100-16
[14] Lopez E, Felgueiras T, Grunert C, Brückner F, Riede M, Seidel A, Marquardt A, Leyens C and Beyer E 2018 J. Laser Appl. 30 032307
[15] Maskery I, Aboulkhaiir N, Corfield M, Tuck C, Clare A T, Leach R, Wildman R, Ashcroft I and Hague R 2016 Mater. Charact. 111 193
[16] Zhang B, Li Y and Bai Q 2017 Chin. J. Mech. Eng. 30 515
[17] Kruth J, Levy G, Klocke F and Childs T H C 2007 CIRP Ann. Manuf. Technol. 56 730
[18] Leuders S, Thöne M, Riemer A, Niendorf T, Tröster T, Richard H A and Maier H J 2013 Int. J. Fatigue 48 300
[19] Agius D, Kourousis K I and Wallbrink C 2018 Metals 8 75
[20] Chan K S, Koike M, Mason R L and Okabe T 2013 Metall. Mater. Trans. A 44 1010
[21] Leung C L A, Marussi S, Atwood R C, Towrie M, Withers P J and Lee P D 2018 Nat. Commun 9 1355
[22] Calta N P, Wang J, Kiss A M, Martin A A, Depond P J, Guss G M, Thampy V, Fong A Y, Weker J N, Stone K H, Tassone C J, Kramer M J, Toney M F, Buuren A Van and Matthews M J 2018 Rev. Sci. Instrum. 89 055101