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Investigation on laser welding of selective laser melted Ti-6Al-4V parts: Weldability, microstructure and mechanical properties

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ABSTRACT

In this study, laser welding was successfully used to join selective laser melted (SLMed) to SLMed and SLMed to wrought Ti-6Al-4V specimens. The microstructures, microhardnesses, tensile performances, fatigue lives and fatigue crack growth rates (FCGRs) of the welded specimens as well as SLMed specimens were investigated. It is found that the stress-relieved SLMed Ti-6Al-4V has a good laser weldability. The SLMed to SLMed and SLMed to wrought joints have similar microstructures (columnar prior β grain boundaries with inside acicular α′), microhardnesses (410 HV–450 HV), ultimate tensile strengths (UTSs) (~ 1200 MPa), yield strengths (YSs) (~ 1080 MPa) and FCGRs in the welding zones, which are also similar to those of SLMed specimens. But the fatigue lives of SLMed to SLMed and SLMed to wrought joints are lower than those of SLMed Ti-6Al-4V, and much lower than those of traditionally wrought annealed Ti-6Al-4V. Heat treatment on SLMed to SLMed joints decreases the microhardnesses (390 HV–410 HV), UTSs (1106 MPa), YSs (1008 MPa) and FCGRs in the welding zones, but shows no improvements on the fatigue lives. It can be concluded that microstructures significantly influence the microhardnesses, UTSs, YSs and FCGRs of the welded and SLMed specimens, but have very limited influences on the fatigue lives due to the existences of pores. Pores play a more decisive role in the fatigue lives, but have very limited influences on the UTSs, YSs and FCGRs.

1. Introduction

Selective laser melting (SLM) technique has attracted much attention for the potential to economically build complex-shaped metallic parts in short cycles. However, one of the major application limitations is the sizes of SLMed parts, which are limited by the building volume of SLM equipments. Though the building volumes of SLM equipments (EOS 400-4: 400 × 400 × 400 mm^3 [1], CONCEPTLASER X LINE 2000R: 800 × 400 × 500 mm^3 [2], NRD-SLM-500: 500 × 500 × 530 mm^3 [3], etc.) have been greatly improved in recent years, they still cannot meet the urgent demands for larger SLMed parts.

Under the circumstances, traditional welding process is easily to be considered as a possible way to solve this problem, which may join small SLMed parts to form larger final parts. In the work by Casalino et al. [4], laser-arc hybrid welding was successfully used to join wrought to SLMed AISI 316 L stainless steel, showing the flexibility to form large components by welding. Work by Prashanth et al. [5] shows that friction welding can join SLMed Al-12Si parts and improve their ductility. Nahmany et al. [6] used electron beam welding to join Al-Si10Mg workpieces successfully. However, such studies are still too limited and relevant study on welding SLMed Ti-6Al-4V alloy can hardly be found, though Ti-6Al-4V is one of the most popular materials utilized in SLM for its attractive application potential in aerospace industry, biomedical engineering, etc. [7].

Study on welding rolled Ti-6Al-4V sheets shows that weld cracks will occur under inappropriate parameters [8]. As for SLMed Ti-6Al-4V alloy, the microstructure is mainly composed of less ductile α′ martensites due to the rapid cooling in SLM [9,10]. Whether the martensitic microstructure in SLMed Ti-6Al-4V will lead to a higher cracking tendency and whether there are suitable parameters to weld them are still unknown. In addition, if SLMed Ti-6Al-4V can be successfully welded, the mechanical properties, especially the tensile and fatigue performances of the welded parts need to be evaluated. Evidently, the study on welding of SLMed Ti-6Al-4V parts is of great significance.

In this study, laser welding was used to weld SLMed Ti-6Al-4V, due to its nature of high welding speed, narrow welds with low risk of distortion, excellent adaptability, etc. [11]. An optimization on laser welding parameters was carried out and the welding quality under each parameter was evaluated. The relatively optimal parameters were used to join both SLMed to SLMed and SLMed to wrought Ti-6Al-4V. Part of the SLMed to SLMed welded specimens were heat-treated as a comparison. The microstructures, microhardnesses, tensile and fatigue

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Table 1
Laser welding parameters in the parameter optimization.

No.	#a	#b	#c	#d	#e	#f
Laser power, kW	4	4	4	4	4	4
Welding speed, m/min	1	1.5	2	2.5	2	2
Beam defocused distance, mm	0	0	0	0	+2	−2

performances of the welded specimens as well as SLMed Ti-6Al-4V specimens were investigated.

2. Materials and methods

SLMed Ti-6Al-4V plates with a thickness of 5 mm were built using optimized parameters (laser power of 300 W, scan speed of 1000 mm/s, hatch spacing of 0.12 mm, layer thickness of 40 μm and hatch angle of 90°) in a self-developed SLM system (LSNF–2) [12]. During the SLM process, the oxygen content in building chamber was strictly kept below 50 ppm by argon. Then the SLMed specimens were stress-relieved at 500 °C for 2 h followed by furnace cooling. Commercial 5-millimeter-thick wrought annealed Ti-6Al-4V plates were also prepared.

Before welding, the SLMed and wrought Ti-6Al-4V plates were fine milled and sandblasted. The welding system mainly consists of an IPG YLR-6000 fiber laser and a FANUC M-710ic/50 six-axis industrial robot [13]. During laser welding, the top and bottom surfaces of the welding zones were shielded by argon. In the optimization on welding parameters of SLMed Ti-6Al-4V, six groups of welding parameters were utilized, as listed in Table 1. Then the relatively optimal parameters were used to join both SLMed to SLMed and SLMed to wrought Ti-6Al-4V specimens. Part of the SLMed to SLMed welded specimens were heat-treated at 850 °C for 2 h followed by furnace cooling [14]. The other welded specimens were stress-relieved at 500 °C for 2 h followed by furnace cooling. As shown in Table 2, the welded and SLMed Ti-6Al-4V specimens were divided into four groups.

After welding, fatigue, fatigue crack growth rate (FCGR) and tensile specimens were sampled from the #1–#4 specimens as schematically shown in Fig. 1a. Fig. 1b–d show the configurations of the fatigue (ASTM E466–07), FCGR (ASTM E399–12$^{\varepsilon 3}$) and tensile (ASTM E8/E8M–15a) specimens, respectively. Microhardnesses were examined by an HVS-1000 tester at a load of 1.96 N and a holding time of 20 s. Tensile tests were carried out using a Shimadzu AG-100 kN tester at room temperature. Fatigue and FCGR tests were conducted on a Shimadzu EHF-UV100k2-040-1A fatigue tester with uniaxial sinusoidal cyclic loading at room temperature. The stress ratio and frequency in the fatigue and FCGR tests were –1, 20 Hz and 0.4, 10 Hz respectively. The fatigue fractures were observed by an FEI Quanta 200 scanning electron microscope (SEM). Microstructure observations were performed on a Nikon Epiphot 300 optical microscope (OM) and an FEI Sirion 200 SEM equipped with an electron backscatter diffraction (EBSD). The grain maps acquired by EBSD were used to measure the dimensions of the grains. Fifteen randomly selected grains in each specimen were measured to calculate the average dimension.

Table 2
The classification of the welded and SLMed Ti-6Al-4V specimens.

No.	Classification of the Ti-6Al-4V specimens
#1	SLMed to SLMed laser welded specimens followed by stress relieving
#2	SLMed to wrought laser welded specimens followed by stress relieving
#3	SLMed to SLMed laser welded specimens followed by heat treatment at 850 °C for 2 h, furnace cooling
#4	Stress-relieved SLMed specimens

3. Results and discussion

3.1. Weldability

Fig. 2 shows the cross-section micrographs of the SLMed to SLMed Ti-6Al-4V joints under #a–#f laser welding parameters. Obviously, the 5-millimeter-thick SLMed specimens can be fully penetrated welded under all the parameters except the #d, as #d parameters have the lowest laser energy density due to the highest welding speed of 2.5 m/min. No crack is found in all the six groups of specimens. The results imply that a relatively wide range of parameters can be applied to laser-weld SLMed Ti-6Al-4V and the martensitic microstructure does not exhibit a high cracking tendency in the welding.

The red arrows in Fig. 2 indicate the voids in the welding zones. Most of the voids are spherical with diameters of less than 200 μm and distribute at the interfaces between the welding zones (WZs) and heat affected zones (HAZs). The spherical shape of the voids indicates gas type pores, which are usually caused by absorbed hydrogen in the molten pool [15]. Among the six groups of welded specimens, the specimen under #a parameters has the smallest amount and average size of pores.

Fig. 3a summarizes the widths of the WZs under the six welding parameters at the sites shown in Fig. 2 (top–bottom). The widths of the WZs at top and bottom sites are larger than those at middle sites (‘1 mm’–‘4 mm’). Therefore, in order to compare the dimensions of the six WZs, the average widths of the WZs at ‘1 mm’, ‘2 mm’, ‘3 mm’ and ‘4 mm’ sites were calculated, as shown in Fig. 3b. Clearly, the average widths decrease with the increased welding speed. For the specimens under #c, #e and #f parameters, the average widths of the WZs are almost equal of ~950 μm by using the same welding speed of 2 m/min, implying that the beam defocused distances of +2 mm and −2 mm play limited roles in the widths of the WZs. The specimen under #a parameters has the smallest width standard deviation of 86 μm, showing the highest size stability of WZ at the perpendicular direction. As a consequence, considering both the size stability of WZ and the amount and sizes of pores in WZ, #a parameters were selected as the relatively optimal welding parameters in this study.

Then #a parameters were also successfully used to join SLMed to wrought Ti-6Al-4V specimens. As displayed in Fig. 4, the specimens are fully penetrated welded without crack. A few spherical pores can also be found in the WZ as the red arrows indicated.

Obviously, it can be concluded that the stress-relieved SLMed Ti-6Al-4V has a good laser weldability. Laser welding of both SLMed to SLMed and SLMed to wrought Ti-6Al-4V can be successfully achieved, which implies a promising future of fabricating large Ti-6Al-4V parts by combining traditional and additive manufacturing techniques.

3.2. Microstructural characteristics

Fig. 5 displays SEM metallographs and EBSD orientation maps of the two welding base materials (BM), namely SLMed and wrought Ti-6Al-4V. In Fig. 5a and b, the epitaxially-grown columnar structures with inside near-fully acicular structures can be observed in SLMed Ti-6Al-4V. The columnar and acicular structures should be prior β grain boundaries and hexagonal close-packed α′ martensites, respectively, which form as a result of high temperature gradients (10^6 K/m) and rapid cooling rates (10^3–10^8 K/s) during SLM [9,10,12]. The widths of α′ martensites in SLMed Ti-6Al-4V (#4) were measured and listed in Table 3. In Fig. 5c and d, wrought Ti-6Al-4V are mainly composed of equiaxed α and intergranular β phases [16].

Microstructures of #1, #2 and #3 welded specimens were then characterized, as shown in Fig. 6. In Fig. 6a–c and d–f, the microstructures in WZs of #1 and #2 specimens are the directionally-grown columnar prior β boundaries with inside acicular α′ martensites formed during the rapid cooling of weld pools, which exhibit the similar features as those in SLMed Ti-6Al-4V (#4) or laser-welded traditional Ti-