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Porosity and microstructure in pulsed Nd:YAG laser welded Ti6Al4V sheet

Xiao-Long Gao, Lin-Jie Zhang*, Jing Liu, Jian-Xun Zhang

State Key Laboratory of Mechanical Behavior for Materials, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

The overlapping factor of pulsed laser welding is used to help understand the correlation between welding parameters and the quality of Ti6Al4V welded joints. The number of porosity decreases with the increase in overlapping factor, and the welded joints are almost completely free of porosity when overlapping factor is greater than 75%. This can be attributed to the fact that the remelted volume of the spot region increases with the increase of overlapping factor, which assists porosity formed in the previous pulse wave in escaping from molten pool formed by the subsequent pulse. With the increase of overlapping factor, the weld microstructure becomes much coarser and the width of the fully transformed region of heat affected zone increases, which reduces the microstructure gradient and microhardness gradient from the fusion zone to heat affected zone. A method to evaluate the porosity susceptibility of a specific welding condition prior to actual welding process is presented.

1. Introduction

Matsunawa et al. (1998) showed that two types of porosity formed in laser welding, intrinsic or metallurgical and characteristic or welding specific. Kutsuna and Yan (1998) determined that the formation of metallurgical pores mainly depends on the amount of hydrogen or other gases dissolving in a melt, the cooling speed of a melt pool and the temperature-dependent solubility of gas in a melt. Yu et al. (2010) found that metallurgical pores were usually relatively small and spherical in shape and can be reduced by eliminating hydrogen or other gas sources. Characteristic pores are relatively large and irregular in shape, and their formation is closely related to the instability of keyholes during laser welding, as reported by Matsunawa et al. (2003).

Finding a solution to the problem of characteristic porosity formation is especially crucial to improve welding quality because of their larger size and irregular shape compared with metallurgical porosity. Therefore, numerous studies have been performed to suppress characteristic porosity formation by improving keyhole stability. Katayama et al. (2001) found that vacuum laser welding exerts a beneficial effect on the reduction or prevention of pores or porosity. Haboudou et al. (2003) proved that the dual laser beam configuration is adequate method for reducing porosity formation tendency in laser welds of A356 and AA5083 aluminum alloys. Porosity in pulsed laser welding can be prevented by an applied electromagnetic force as described by Zhou and Tsai (2007). Blackburn et al. (2010) showed that modulating amplitudes and laser beam focal plane position reduced the resultant porosity levels when laser welding Ti6Al4V alloy.

Compared with CW CO_2 and Nd:YAG lasers, pulsed Nd:YAG lasers are particularly well suited for microwelding applications, such as the seam welding of small electromechanical components, fine cutting and welding thin sheets as described by Tzeng (2000). In pulsed laser welding, the energy pumped to an area comes not only from a single pulse but also from overlapping pulses on the same spot. To characterize the nature of pulsed laser welding, a cumulative factor is introduced to take into account this phenomenon, as reported by Malek Ghaini et al. (2007). Since several laser pulses come down on one spot, each pulse reheats and remelts a portion of the pervious spot. The fraction of the remelted volume of the spot region can be calculated through the overlapping factor, as described by Torkamany et al. (2006). Torkamany et al. (2014) proved that a relatively continuous dissimilar butt joint of Ti6Al4V and Nb can be obtained under higher overlapping factor. Torkamany et al. (2012) showed that weld porosity was formed in the pulsed laser welded joints of pure Ti. However, the influence of the overlapping factor of melt pools on porosity elimination, metallurgical and mechanical modifications is still poorly understood in the pulsed laser welding process of Ti6Al4V alloys. In this work, the overlapping factor is used, to aid in the

* Corresponding author. Tel.: +86 029 82663115; fax: +86 29 82668807.
E-mail addresses: gaoxiaolong503@163.com (X.-L. Gao), zhanglinjie@mail.xjtu.edu.cn (L.-J. Zhang).

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Table 1
The composition of Ti-6Al-4V (wt%).

Material	Ti	Al	V	Fe	Si	C	N	H	O
Content	Balance	5.5–6.8	3.5–4.5	<0.3	<0.15	<0.1	<0.05	<0.015	<0.2

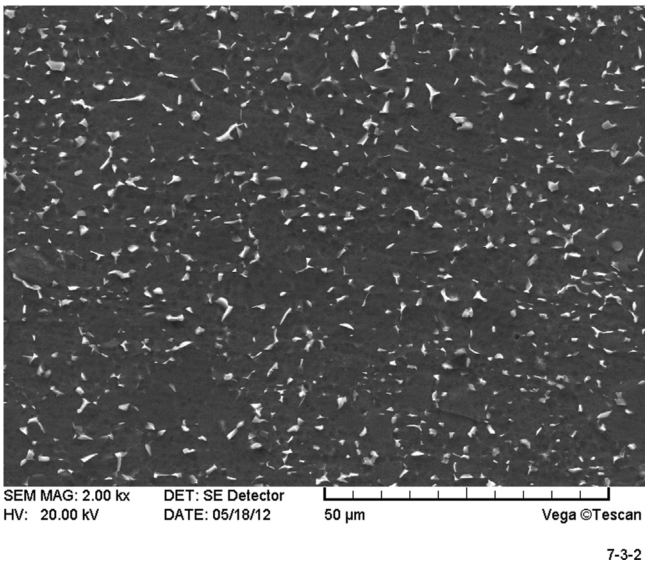

Fig. 1. Microstructure of Ti6Al4V.

Table 2
Factors and levels of orthogonal experiment.

Factor	Level 1	Level 2	Level 3	Level 4
Pulse energy I/J	7.8	8.5	9.0	9.7
Pulse duration t/ms	5.5	5	4.5	6
Pulse frequency f/Hz	16	18	20	22
Welding speed v/(mm/min)	300	400	500	600
Defocus ΔF/mm	−1	−2.0	−1.5	−2.5

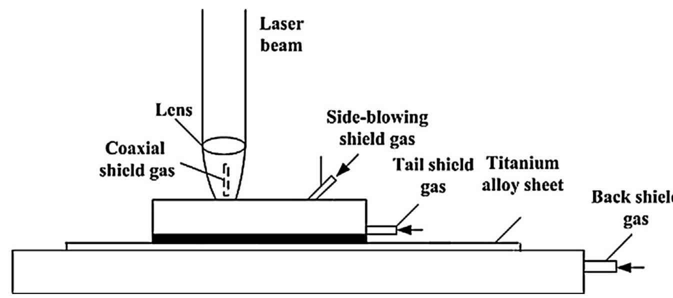

Fig. 2. Shielding gas device.

interpretation of the influence of the characteristic pulsed laser welding on weld quality. This paper aims to provide fundamental insights into the mechanism of porosity formation, metallurgical and mechanical modifications via the model of the overlapping factor and targeted experimentation, and provide the method of porosity elimination.

2. Materials and experimental methods

2.1. Experimental setup

In the study, bead on plate (BOP) welding was carried out on Ti6Al4V alloy sheets with dimensions of 260 mm × 110 mm × 0.8 mm using a JHM-1GXY-400X Nd:YAG pulsed laser system. The chemical composition of Ti6Al4V is listed in Table 1. Fig. 1 shows that the base metal (BM) consists of black equiaxed α and white granular β phases. During BOP welding, a rectangular pulse shape was used and the laser beam was focused on the surface of titanium sheets by a convex lens with a focal length of 75 mm.

The plates were mechanically wire brushed, acid pickled in a HF solution and then cleaned with acetone prior to welding. To protect the fusion zone and heat affected zone from contamination, argon was used as a shielding gas. Fig. 2 shows that coaxial, side-blowing, tail and back shielding gas flow were delivered to the high-temperature zone at flow rates of 7 L/min, 10 L/min, 15 L/min and 20 L/min, respectively.

After welding, the weld beads were analyzed by X-ray spectroscopy to quantify the porosity. The cross sections of weld seams were measured by a VMS-1510 standard video measuring instrument. Vickers microhardness measurements were performed on the base metal, heat affected zone (HAZ) and fusion zone (FZ) using a diamond pyramid indenter under a load of 100 g with a dwell time of 10 s. Scanning electron microscope (SEM) observation of the porosity and microstructure along the weld cross section was carried out. In addition, the elemental composition of the inner

Table 3
L16 (4^5) matrix and experimental results.

Case no.	I (J)	t (ms)	f (HZ)	V (mm/min)	ΔF (mm)	P_N	W_T	W_B
1	7.8	5.5	16	300	−1	1	1.26	1.11
2	7.8	5	18	400	−2.0	14	1.10	0.53
3	7.8	4.5	20	500	−1.5	27.6	1.10	0.56
4	7.8	6	22	600	−2.5	20	1.06	0.91
5	8.5	5.5	18	500	−2.5	23	1.23	0.89
6	8.5	5	16	600	−1.5	89.67	1.09	0.77
7	8.5	4.5	22	300	−2.0	1	1.29	1.11
8	8.5	6	20	400	−1	1.67	1.39	1.38
9	9.0	5.5	20	600	−2	17.67	1.25	1.19
10	9.0	5	22	500	−1	7	1.25	1.14
11	9.0	4.5	16	400	−2.5	13	1.15	0.78
12	9.0	6	18	300	−1.5	1.67	1.45	1.43
13	9.7	5.5	22	400	−1.5	0.67	1.40	1.32
14	9.7	5	20	300	−2.5	1	1.37	1.27
15	9.7	4.5	18	600	−1	84	1.05	0.91
16	9.7	6	16	500	−2	17	1.24	1.19