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Microstructural evolution and mechanical property of Ti-6Al-4V wall deposited by continuous plasma arc additive manufacturing without post heat treatment

Jianjun Lin[a,b,*], Yaohui Lv[b], Yuxin Liu[b], Zhe Sun[b], Kaibo Wang[b], Zhuguo Li[a], Yixiong Wu[a], Binshi Xu[a,b]

[a] *Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China*

A R T I C L E I N F O

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A B S T R A C T

Plasma arc additive manufacturing (PAM) is a novel additive manufacturing (AM) technology due to its big potential in improving efficiency, convenience and being cost-savings compared to other AM processes of high energy bea\m. In this research, several Ti-6Al-4V thin walls were deposited by optimized weld wire-feed continuous PAM process (CPAM), in which the heat input was gradually decreased layer by layer. The deposited thin wall consisted of various morphologies, which includes epitaxial growth of prior β grains, horizontal layer bands, martensite and basket weave microstructure, that depends on the heat input, multiple thermal cycles and gradual cooling rate in the deposition process. By gradually reducing heat input of each bead and using continuous current in the PAM process, the average yield strength (YS), ultimate tensile strength (UTS) and elongation reach about 877 MPa, 968 MPa and 1.5%, respectively, which exceed the standard level of forging. The mechanical property was strengthened and toughened due to weakening the aspect ratio of prior β grains and separating nano-dispersoids among α lamellar. Furthermore, this research demonstrates that the CPAM process has a potential to manufacture or remanufacture in AM components of metallic biomaterials without post-processing heat treatment.

1. Introduction

Titanium alloys, particularly Ti-6Al-4V, have been widely used in aerospace, aircraft, automotive, biomedical and chemical industries due to their excellent combination of strength, fracture toughness, low density, and very good corrosion resistance (Peters and Christoph, 2003; Donachie, 2000; Banerjee and Williams, 2013). However, material cost is regarded as the biggest barrier for further application considered the output of lower value and high price sensitive products (Lujering and Williams., 2007), the main reason is their poor machinability caused by the low thermal conductivity and high chemical reactivity with cutting tool materials (Davim, 2014). Fortunately, additive manufacturing (AM) technologies offer the potential to reduce cost, energy consumption and carbon footprint (Brooks and Molony., 2016; Paydas et al., 2016; Ding et al., 2015).

Typical AM technologies include Tungsten Inter Gas welding process (TIG) (Brandl et al., 2010; Szost et al., 2016), Electron Beam Melting (EBM) (Edwards et al., 2013; Murr et al., 2009; Zhao et al., 2016), Laser Beam Deposition (LBD) (Brandl et al., 2011; Miranda et al., 2008; Kelly and Kampe 2004), as well as Plasma Arc Additive Manufacturing(PAM).

EBM and LBD processes are characterized by large temperature gradient and high cooling rate, and suit for precise parts or particular applications. Generally, the width of a certain thin component is larger than the spot diameter of laser beam or electrical beam, thus both processes need multiple passes for such components, which will result higher residual stress (Szost et al., 2016). Besides, a rapid solidification gives rise to the occurrence of segregation and the presence of coarse prior β-grain (Edwards et al., 2013; Brandl et al., 2011; Tan et al., 2015; Qiu et al., 2015a). Particularly, narrow prior β-grain with large aspect ratio always grows up to the top surface of deposited parts, which results in obvious anisotropy. Therefore, the parts normally need to be heat treated after deposition or hot isostatically pressed (Zhu, et al., 2015; Qiu et al., 2015b).

With a big potential in improving efficiency, convenience and being cost-savings, PAM and TIG process are the kind of significant for AM

* Corresponding author at: Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: jianjunin@outlook.com (J. Lin).

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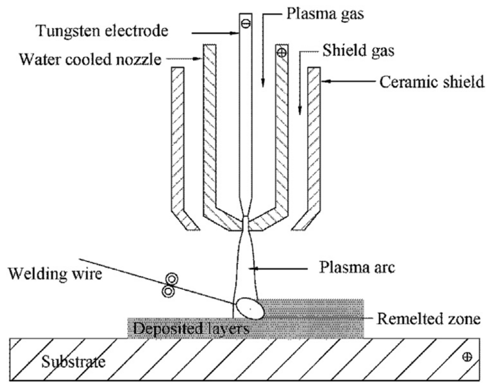

Fig. 1. Schematic representation of the plasma arc deposited process.

Table 1
Summary of reported advantages of PAM compared with other technologies.

AM technology	β grains	Cost	Utilization ratio	Precision
Laser beam	0.5–1.5 mm (0)	$500,000 (-)	(- -)	(+)
Electron beam	1.4–5.0 mm (-)	$1,000,000(- -)	(- -)	(+)
TIG	15–35 mm (- -)	< $7000 (+)	(+)	(- -)
Plasma arc	(Maybe +, 0, or -)	$7000 (0)	(+)	(0)/ (+)

(+)=good, (0) = neutral, (-) negative, and (- -) more negative.

technology. PAM process has advantages of high efficiency for the manufacture of high-cost structural components, such as disks and blades of aircraft gas turbine, which are normally produced by costly titanium alloys. These components can be fabricated by using one beam only of PAM process. In addition, the temperature zone of plasma arc transferred to the work piece in the concentrated beam can reach about 10000–16000 K (Aiyiti et al., 2006), so the energy density of plasma arc is much higher than gas tungsten arc welding and close to the lower limit of laser, which helps deposit in better precision compared to TIG process. Fig. 1 shows schematic representation of the plasma arc deposited process. Moreover, the price of plasma arc power source decreases to 1/7 of that of Laser Beam or 1/15 of Electron Beam (Stavinoha, 2012), as is shown in Table 1 (Stavinoha, 2012; Antonysamy, 2012; Martina et al., 2012).

Table 1 gives a summary of reported advantages of PAM in comparison with other technologies. From the data of measured length of columnar β grains in samples deposited by AM technologies, it clearly shows that LBM is the best deposition process, and EBM is much better than TIG, and the PAM process needs further investigation.

In PAM process, wire or powder is fed into the melt pool produced by constant plasma arc, pulsed plasma arc, or variable polarity plasma arc which is usually used in welding aluminum alloys in order to wipe off the oxide (Jiang et al., 2013). In addition, previous researches have confirmed that it can refine the structure by pulsed plasma arc welding, of which the reason is that the process enables the melt pool to agitate more tempestuously during welding (Correa et al., 2008). However, using constant parameters deposited by the pulsed plasma arc process needs to set more parameters, which increases the complexity in controlling and cooling time. Additionally, the heat input value of each deposited layer will easily result in heat accumulation (Stavinoha., 2012; Xu et al., 2013; Lin et al., 2016). Moreover, the first lot of layers were excluded because of the thermal effect of the base plate after finish deposited part (Martina et al., 2012), which will spent time, waste material and impel anisotropy. Hence, decreasing the heat input between deposited layers can help keep heat balanced, so that the molten pool size is controlled.

Using AM technologies to fabricate components will experience complex cyclic thermal history, thus there is necessity to understand the relationship of microstructure, processing and properties. However, continuous PAM process (CPAM) is rarely reported before, in especial, the effect of microstructural evolution on mechanical property remains unclear for Ti-6Al-4V alloy deposited by the CPAM.

In this research, several Ti-6Al-4V thin walls were deposited by optimized weld wire-feed CPAM, in which the heat input was gradually decreased layer by layer. The microstructural evolution and mechanical properties of Ti-6Al-4V wall deposited by wire-feed CPAM has been studied. The interactive effects between microstructural evolution, deposition process and mechanical properties should be clarified for the deposited thin wall without cooling substrate. It is expected that the mechanical properties of directly deposited walls at room temperature to be equal to or to exceed the standard level of forging. Furthermore, the results of the CPAM process can be added in development of an AM database of materials processing.

2. Experimental procedure

2.1. Experimental material and equipment

A 1.0 mm diameter Ti-6Al-4V wire (ERTi-5) was used in deposition process, and namely chemical composition was 0.02 C, 0.14 O, 0.01 N, 0.007 H, 0.0 7 Fe, 6.11 Al, 3.95 V, Bal.Ti (in weight %), which is below the maximum content recommended by ASTM F1108–04 (2009). The substrate was 2000 × 1500×8 mm (length×width×height) hot rolled plate. The plates were grounded by 150 to 400 grit SiC papers and then degreased by acetone and ethanol before being used. A TransTig 4000 Job G/F and A Plasma module 10 were used as the power supply with a KD7000 D-11 wire feeder. The plasma arc welding torch was attached to a 6-axis KUKA robot linked to a 2-axis table. The PPAM process was carried out under inter gas (argon) shield.

2.2. Research methodology

After 16-layer deposition, the total height with one bead width is shown in Fig. 2. In each specific trial, Ti-6Al-4V wire was deposited layer by layer onto the substrate by CPAM. The scanning direction of each layer was set X-coordinate, moreover, each additive height (ΔZ) was set at 1.5 mm in positive Z-coordinate direction.

To prevent air oxidation, heat input of bead was gradually decreased layer by layer, and each layer would be deposited only if the temperature of the previous layers fell below 300 ℃. Thermocouple probes were inserted into the substrate, of which the distance from the deposited surface was 5 mm. The main processing parameters were constant: Travel Speed(Ts) was 0.25 m/min, Wire Feed Speed(WFS) was 3.5 m/min, Plasma gas was 0.2 L/min, and Argon atmosphere was

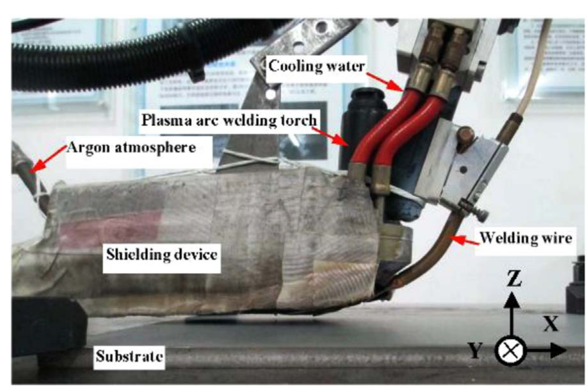

Fig. 2. Photograph of CPAM process deposited components.