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Effect of travel speed and stress relief on thin Ti-6Al-4V laser wire deposits

N. Chekir[a], Y. Tian[a], R. Gauvin[a], N. Brodusch[a], J.J. Sixsmith[b], M. Brochu[a,*]

[a] Department of Mining and Materials Engineering, McGill University, Montreal, Quebec, Canada H3A 0C5

[b] Liburdi Automation Inc., Dundas, Ontario, Canada L9H 7K4

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ABSTRACT

The effect of two travel speeds on thin Ti-6Al-4V buildups produced by Laser Wire Deposition (LWD) has been investigated. A travel speed set at 1.4 mm/s promoted recrystallization of columnar prior β grains into horizontal prior β grains. It was associated with lower strength hardly meeting minimum wrought requirements as set by the AMS4911. On the other hand, it was shown that by increasing the travel speed to 7.2 mm/s, sufficiently high cooling rates are occurring creating a fine $\alpha + \beta$ basket weave structure, while no recrystallization of the prior β grains has been observed. Tensile properties were improved with strength consistently exceeding minimum wrought requirements. An additional stress relief cycle preserved the effect of deposition parameters on material properties. A strong anisotropy in elongation was associated with the slower travel speed where higher values were derived along the Z direction. While the faster travel speed exhibited isotropic properties. Strengthening of the deposits has been observed following a stress relief cycle.

1. Introduction

Additive Manufacturing (AM) of titanium alloy Ti-6Al-4V is a promising process for the aerospace industry in order to substantially reduce part cost and waste generation [1–3]. However, and as of today, producing functional parts with properties meeting or exceeding the industry requirements remains extremely challenging mainly due to the variability in the generated properties induced by the different processes [4–9].

The high interest of the aerospace industry in Ti-6Al-4V is in part due to the excellent strength to weight ratio and corrosion resistance properties that the alloy can develop [10–12]. Aluminum and vanadium are the main alloying elements, stabilizing the hcp α phase and the bcc β phase respectively at room temperature. During the deposition processes and upon cooling from above the melting temperature (about 1660 °C [10]), Ti-6Al-4V starts to solidify into columnar grains of the β phase as a consequence of highly directional heat extraction. Upon subsequent cooling, an allotropic transformation occurs at 1000 °C ± 20 °C: platelets of the α phase precipitate starting at the β grain boundaries and develop into a complex arrangement of α platelets in a β matrix at room temperature [10]. β grains will then be referred to as prior β grains. This final typical microstructure is referred to as $\alpha + \beta$ basket weave. If temperature of the part is above the martensitic start temperature (M_S = 575 °C) and cooling rates exceed the critical rate of 410 °C/s, a fully martensitic type of structure can be developed usually referred to as α′ [13]. Eventually and due to the complex thermal history of a deposit induced by the cyclic behavior of the addition of new layers, a gradient in the properties of the resulting microstructure may characterize the print as pointed out by Kelly et al. [14] affecting in turn the generated mechanical properties. This becomes extremely important in Direct Energy Deposition (DED) Additive Manufacturing (AM) processes. Many studies have investigated the structure/properties relationship of DED processes by primarily focusing on room temperature static tensile properties and hardness values. From these studies, three different processes are mainly encountered: Laser Wire Deposition (LWD) [7,15–20], Laser Powder Deposition (LPD) [8,9,14,21–30] and the so-called Shape Metal Deposition (SMD) [7,15,31–35] that uses a Tungsten Inert Gas (TIG) torch as a focused thermal energy source to fuse the deposited material.

Travel speed, material deposition rate and laser power are among the most investigated parameters in DED processes [16,18,23,24,32,36–38]. Brandl et al. [16] have shown for instance that by decreasing the laser power, decreasing the deposition rate, or by increasing the travel speed, columnar prior β grains tended to decrease in size affecting in turn mechanical properties. Deposits are also usually reported to display an anisotropic behavior regarding their static tensile property. Tensile samples extracted orthogonal to the build direction have been found in most cases to exhibit higher strengths but lower ductility than samples extracted along the build direction [7–9,15,22,27,31,33]. It was mainly explained with the additional strengthening induced by the presence of columnar prior β grains boundaries orthogonal to the testing direction and the associated grain

* Corresponding author.
E-mail address: mathieu.brochu@mcgill.ca (M. Brochu).

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boundary allotriomorphs α_{GB} [7–9,15,22,27,31,32]. Selection of parameters inducing larger prior β grains such as slow travel speed or higher laser power would reduce tensile strength and increase ductility for samples extracted orthogonally to the build direction. This was explained by the reduced number of macro boundaries through the presence of the larger prior β grains inducing a less important strengthening mechanism [7,8,32]. Regarding LWD microhardness measurements, Brandl et al. [16] have shown that the hardness of the deposited material was always higher than the one of the feedstock. This was reported to be the consequence of an increased solid solution strengthening induced by the enrichment of the melt pool with oxygen and nitrogen. Deposition parameters have also been shown to affect material's microhardness. An increase in travel speed or reduced material feed speed would eventually increase the measured microhardness [16,19].

Stress relieving or aging thermal cycles have been attempted to remove residual stresses while maintaining the developed microstructure [39]. This thermal cycle has been found to not substantially affect the developed microstructure post deposition [7,17,18]. A strengthening of the material has often been reported though [17,18]. One of the common recurrent hypotheses is provided by means of precipitation strengthening of Ti_3Al [15,18]. But this hypothesis lacks experimental evidence such as TEM observations. This would also require important gradients in chemical distribution of aluminum in order to reach Al concentrations that enable the precipitation of the Ti_3Al intermetallics [12]. Such gradients were not reported in the literature [18,39]. Another more plausible hypothesis is through solid solution strengthening by diffusion of Al, V, Ti, O and N. This is supported by the study of Brandl and al. [18]. The reported effect of stress relief cycles on static tensile properties is not clear. While some studies imply an increase in strength and a decrease in elongation [15,17], other investigations suggest no real impact of such a thermal cycle on tensile properties [7]. Anisotropy in properties is still reported as in the as-built condition [7,15,17,19,29].

This paper takes advantage of the fully dense microstructure developed by LWD. A simple thermal model is presented to provide a basic understanding on the thermal history experienced by the deposits for the two travel speeds investigated in this study. Structural development mechanisms are then discussed for the two conditions. The beneficial effect of an increase in travel speed on the generated microstructure and the anisotropy in materials properties will then be discussed. A typical stress relief is performed in an attempt to keep the effect of deposition parameters on the developed microstructure and properties.

2. Experimental methods

AM samples were built using a Liburdi LAWS 1000 automated deposition system. The robot is controlled by WinLAWS; an in-house software allowing the operator to program axes movements along with defining customized deposition parameters. An IPG Yb:YAG fiber laser reaching up to 1 kW power is used to fuse the material. To prevent excessive oxidation, all deposits are completed in an argon inert environment with oxygen levels below 60 ppm.

Wrought Ti-6Al-4V plates are used as substrates. A Ti-6Al-4V wire spool with Extra-Low Interstitials (Oxygen weight percentage being below 0.13%), manufactured by Lancaster Alloys Company Inc., is used to deposit the material. Single stringers are deposited layer after layer on top of the substrate. Two travel speeds are used in this study: 1.4 mm/s and 7.2 mm/s. A predefined increment of 0.660 mm was set between each deposited pass along the buildup direction. Deposited material is characterized by a thickness of about 2.5 mm. Dimensions of the deposits changed in order to accommodate the extraction of tensile specimens Printed plates are subsequently used for structure characterization and mechanical properties evaluation.

Macrostructure, microstructure and fractographs were observed using a Nikon light optical microscope equipped with a Clemex vision system, a Hitachi SU-8230 cold field FE-SEM and a Hitachi SU-3500 cold field FE-SEM.

Phase composition was investigated using a Bruker D8 Discovery X-Ray Diffractometer with a copper source for XRD analysis and a FlatQuad X-Max SDD EDS detector from Bruker assembled with the Hitachi SU-8230 for the chemical element distribution.

Structure evaluations were conducted in two different areas: The top region, associated with a transitional region, where each of the deposited layers did not experience the same thermal history and where structure development is still affected by the process. And the steady state region defined by cyclic macroscopic features usually associated with the same thermal history but where some of the deposited layers may still have experienced a different one.

All samples are extracted in a plane containing both the travel and buildup directions. Flat samples combining the top region and the steady state region are mounted in Bakelite. These samples were ground up to 1200 SiC grit, followed by polishing with 3 µm and 1 µm diamond suspension and a finish with 0.05 µm colloidal silica. Grinding and polishing were done using a Buhler Ecomet-3 autopolisher equipped with an Automet-2 head. These samples were used as is for XRD analysis. A Kroll's Reagent etchant with 91% deionized water (H_20), 6% nitric acid (HNO_3) and 3% hydrofluoric acid (HF) was then used on the mounted samples to reveal the structural features using the optical microscope or the SEM.

The previous flat specimens were then ground to a thickness of about 150 µm with a 1200 SiC grit finish on both sides. 3 mm disks were punched out from top and steady state regions. Final thinning of the disks was done using a Struers TenuPol-5 automatic electrolytic thinning unit set at 25 V and using a solution consisting of 95% methanol (CH_3OH) and 5% sulfuric acid (H_2SO_4) cooled at −25 °C. These thin samples were used for STEM characterization and EDS mapping.

A stress relief (SR) cycle according to AMS2801 standard was performed to reduce the residual stresses while keeping the effect of deposition parameters on the developed structure.

The Vickers hardness was measured by means of a Clark Microhardness (CM-100AT) indenter, using a 100 g load. A minimum of 25 measurements was done along the build direction for each of the reported values.

Machined samples proportional to the ASTM E8 standard with a thickness of 0.5 mm, a gage width of 2.5 mm and a gage length of 4.7 mm were extracted in the as-built condition to prevent excessive distortion. Machined subsize specimens meeting ASTM E8 requirements with a thickness of 1.4 mm, a gage width of 6.35 mm and a gage length of 25.4 mm have been extracted for SR condition. Numbers of samples tested in each condition are summarized in Table 1. Heat treated samples were tested at room temperature with a crosshead speed of 2.54 mm/min until fracture using a United SFM-20 kN load frame equipped with a calibrated load cell and an extensometer. Finally, average values of wrought tensile properties produced from five specimens extracted from the base plate and reproducing the subsize specimen geometry previously described have been used to normalize all the results.

Table 1
Number of static tensile samples tested per condition.

Travel speed:	1.4 mm/s		7.2 mm/s	
Testing direction:	X	Z	X	Z
AB	3	3	3	3
SR	3	5	4	4