Effect of Temperature Field on Mechanical Properties of Direct Laser Deposited Ti-6Al-4V Alloy

M O Gushchina¹, S Yu Ivanov¹,² and A M Vildanov²

¹Institute of Laser and Welding Technologies, St. Petersburg State Marine Technical University, 3, Lotsmanskaia, St. Petersburg, 190121, Russia
²Department of Laser Technologies, Peter the Great St. Petersburg Polytechnic University, 29, Polytechnicheskaya, St. Petersburg, 195251, Russia

E-mail: skmar.spb@gmail.com

Abstract. The mechanical and service properties of Ti-6Al-4V alloy parts produced by direct laser deposition (DLD) depend on the thermal cycle parameters. The temperature field during deposition is significantly affected not only by the parameters of the process, but also by the interpass dwell time and length of the deposited layers. The aim of the article is to establish the relationship between mechanical properties of deposited Ti-6Al-4V samples and DLD thermal cycle parameters. Numerical simulation was used in order to establish relationship between temperature field parameter and the process parameters. The nonlinear three-dimensional heat conduction problem was solved by the finite element method. It is shown that an increase in the dwell time between passes from 5 to 10 seconds leads to a significant decrease in the inter-pass temperature and an increase in the cooling rate. This leads to the metastable structure formation of the deposited layers of Ti-6Al-4V that consists mainly of a nonequilibrium α'-phase which hardness is higher than 390 HV. Without dwell time an equilibrium α + β structure with hardness of 360 HV and higher elongation is formed.

1. Introduction

Additive manufacturing (AM) of titanium alloys is one of the most interesting areas of 3D metal printing. Titanium alloys have unique properties that are combined with hard workability by mechanical methods and a tendency to grain growth during casting [1]. Additive manufacturing methods solve these problems, which leads to decreasing costs and efficiency increased [2]. Despite, the novelty of 3D printing technology requires solving the problems that arise during the transition to the AM [3]. For example, a large number of research works of laser AM of titanium α + β alloys confirm the metastable structures formation due to high heating and cooling rates [4, 5]. The formation of a nonequilibrium martensitic α'-structure reduces ductility and can significantly complicate the deposition of large-sized parts. Since during the deposition process there is a significant accumulation of residual stresses and failure of the part [6, 7].

The formation of the metastable phase in titanium alloys with β-stabilizers is associated with the diffusionless transformation of β-α’ from β-phase region when a cooling rate is higher than 20 °C/s [8, 9]. It has been established that the cooling rate in laser additive manufacturing can reaches 10⁶ K/s. However, subsequent heating from the higher and next layers also has a significant effect on the structure formation. For example, in work [10] was found that the initial completely martensitic structure, which forms at a cooling rate more than 200 °C/s during β transformation after thermal...
influence from the subsequent and next layers partially goes into equilibrium and the final structure consists of a mixture of \( \alpha' + \alpha + \beta \), and the content of the equilibrium component increases with a decrease in the cooling rate from the \( \beta \)-region. The formation of the thermal cycle during process AM depend on many different parameters.

It is shown that the shape and dimensions of Ti-6Al-4V products in the DLD process influence on the mechanical properties and structure [11]. The influence of beam oscillations on the structure and properties formation was demonstrated in [12, 13], as a result established that the use of a Z-shaped oscillation led to a change in the structure from nonequilibrium martensitic to equilibrium two-phase, which accordingly led to an increase in the mechanical characteristics of the deposited samples from Ti-6Al-4V.

The authors Jingjing Yang et al. [14] presented that in the SLM Ti-6Al-4V process, the content and morphology of the \( \alpha' \)-phase can be controlled by changing the distance between the bead as well as scanning speeds to control the time and type of thermal cycles. Additive DLD technology are most promising for the manufacturing of large-sized parts. Because of this, studies of thermal cycles are required that would correspond to different cooling times. As the dimensions of the part increase, the time between the application of adjacent and subsequent layers will increase, which will significantly change the thermal cycle [15]. Thermal cycle change will affect the structure, which will lead to a change in the properties of deposited samples from Ti-6Al-4V.

The aim of the article is to establish the relationship between mechanical properties of deposited Ti-6Al-4V samples and DLD thermal cycle parameters.

2. Materials and methods

2.1. Experimental procedure

The material used in this study is ASTM B 265 grade 5 Ti6Al4V titanium alloy powder with a fraction of 45-90 microns produced by PREP (Plasma Rotating Electrode Process). The experimental trials were carried out using a robotic complex for direct metal deposition based on IPG fiber laser. The laser system has the maximum power of 3000 W, a Gaussian beam profile. The complex also include a six-axis robot and two-axial positioner [16]. Working tool is a laser-weld head with coaxial four-jet nozzle for powder feeding. The process was carried out in chamber with argon atmosphere, the oxygen level in the chamber was 2000 ppm.

A 50 layers wall from Ti-6Al-4V powder was deposited on the 12 mm thick Ti-6Al-4V rolled plate (Figure 1). Seven passes formed each deposited layer of 80 mm length. Each layer in the plate build consisted of seven beads with a horizontal overlap distance of 2 mm. A vertical step size of 0.80 mm per layer was used. The powder, carried by the inert gas through four radially symmetrical nozzles, is injected into the molten pool. The process parameters were the following: a beam power of 2200 W, a beam diameter of 3 mm and a forward speed of 20 mm s\(^{-1}\), a coaxial gas flow of 25 l min\(^{-1}\), transport gas flow of 4 l min\(^{-1}\), powder flow rate of 14.84 g min\(^{-1}\). The layer height resulted to 0.73 mm leading to a total build height of 28 mm. Three different dwell times of 0, 5 and 10 s was analysed.

Mechanical properties were measured using a universal testing machine Zwick/Roell Z250 Allround series. Cylindrical samples of standard dimension were used for uniaxial tensile test. For detailed study of the defects location in structure, the samples were cut in a cross section, after there were etched in a reagent: 93 ml H2O + 2mlHF + 5ml HNO3. Metallographic studies of the samples were carried out using an optical microscope DMI 5000 (Leica) with the “Tixomet” software. Micro hardness tester FM-310 was used to study microhardness of the samples.

2.2. Simulation procedure

Deposition of material during DLD was simulated using the so-called element birth technique [17]. In this method, elements to be deposited are deactivated at the beginning and then gradually activated or “born” into the solution domain. The pass shape was as a cuboid. An 8-node
axisymmetric elements were employed in 3D model (Figure 1). A laser beam thermal efficiency was assigned a value of 0.45 based on [18]. An internal volumetric heat source with uniform density was applied to model heat input for each pass. To account for heat losses, convective heat transfer on the all surfaces exposed to air was modeled. The convective heat transfer coefficient is taken as 18 W m\(^{-2}\) K\(^{-1}\) [19]. The temperature-dependent thermophysical properties for Ti-6Al-4V including the enthalpy, thermal conductivity, density were taken from [20]. Solid-to-liquid phase transformation releases the latent heat of fusion, resulting in an increase in the enthalpy.

3. Results and discussion

3.1. Analysis of temperature field
Interpass dwell time has a decisive influence on the temperature field if the length of the compares parts is the same. As can be seen in Figure 1, the increase in the dwell time leads to a significant decrease in the interpass temperature. The average interpass temperature decreases by 300 °C from 540 °C when the dwell time increases to 10 s. The deposited pass undergoes multiple reheating from subsequent passes. Magnitude of the reheating temperature depends of distance between the point of interest and axis of newly deposited pass. As can be seen, the high interpass temperature provides a significantly higher peak reheating temperature. Thus, in the absence of dwell time, the peak values of reheating correspond to 1550-990-790 °C (Figure 1a) while if the dwell time equals 10 seconds: 1390-760-525 °C respectively (Figure 1b).

![Figure 1. Thermal cycles of the 40th layers deposited with 0 (a) and 10 s dwell time.](image)

Microstructure of the just deposited pass depends on the cooling rate. The analysis of thermal cycles showed a significant change in cooling rate with increasing distance from the substrate (Figure 2). The cooling rate of the first layer passes practically does not depend on the interpass dwell time. It is explained by the significant heat dissipation into the cold substrate, which prevents the heat accumulation. In this case an initial microstructure of the deposited layer must contain martensite, according to [21]. As the distance from the substrate increases, the dwell time effect becomes more noticeable. Cooling rate of the 40th layer deposited without dwell time is 1.7 time lower than that of the first layer.

The final microstructure is significantly affected by reheating of the subsequent passes. Reheating to high temperatures leads to activation of diffusion processes associated with phase transformation and tempering of nonequilibrium phases. The effect of diffusion processes can be indirectly estimated by the value of metal exposure time (Figure 3). As in the case of cooling rates, the holding time of the first layer higher than the different cut-off temperatures practically does not depend on dwell time (Figure 3a). A significant difference is observed at a distance from the substrate. Without dwell time the total exposure time above 600 °C is 54 s. If the dwell time equals to 2.5 s, it is only 7.5 s.
3.2. Microstructure of deposited Ti-6Al-4V samples

Reducing of the interpass dwell time leads to a significant change in the structure. In the sample without dwell time, an equilibrium structure is formed (Figure 4a). It is consisting of β grains with fine Widmanstätten α-phase structure, with plates widths on the order of one micron. This observation present that the cooling rate of the Ti-6Al-4V samples from temperature above the β transus, while rapid, was not sufficiently fast to allow the formation of martensite α’ phase. In samples with dwell time of 5 and 10 seconds, a nonequilibrium martensitic structure are observed unlike the microstructures of samples with dwell time of 0 seconds (Figure 4b,c). Thin acicular martensitic needles located orthogonal to each other. Moreover, reduce of a dwell time the ratio of the length and width of the martensitic needles decreases.

Based on diagram shown on figure 4 and prediction thermal cycles it is follow, that cooling rate low than 410 °C/s corresponding to the model sample deposited with dwell time of 0 seconds.

Comparison of the elongation values obtained in this study (Table1) for samples deposited with using different dwell time presented that with 0 second dwell time have value in two time higher respect to values for 10 second dwell time. Microhardness is reduce with dwell time decreasing and significantly
reduced when dwell time is 0 sec. This difference is likely due thermal cycles as well as cooling rate change.

![Image of optical micrographs](image.png)

**Figure 4.** Optical micrographs of deposited Ti-6Al-4V samples (a) dwell time=0 s, (b) dwell time=5 s, (c) dwell time=10 s

| Sample | Tensile strength, MPa | Yield strength, MPa | Elongation, % | Microhardness, HV<sub>0.03</sub> | Dwell time, sec |
|--------|-----------------------|---------------------|---------------|-------------------------------|-----------------|
| 1      | 1114                  | 1097                | 12.5          | 379                           | 0               |
| 2      | 1140                  | 1070                | 6.2           | 397                           | 5               |
| 3      | 1199                  | 1140                | 4.8           | 398                           | 10              |

**Table 1.** Mechanical tests result.

4. Results

A Ti–6Al–4V model samples was fabricated using a directed laser deposition AM process with using different value of interpass dwell time. The primary conclusions from this study are as follows:

The mechanical properties in the deposited samples improved when dwell time value is 0 second due to lower cooling rate, which allow to equilibrium α+β formation. Increasing dwell time value lead to higher cooling rate, that effect on metastable α’ phase formation with different relationship in α+β phase composition. Therefore, ductility values is increase in two times, microhardness is decrease at least on 40 HV.
References
[1] Banerjee D and Williams J C 2013 *Acta Mater.* 61 844–879
[2] Shamsaei Nima, Yadollahi Aref, Bian Linkan, Thompson Scott M 2015 *Add. Manuf.* 8 12–35
[3] Shunyu Liu, Yung C, Shin 2019 *Mater. and Design* 164 107552
[4] Kazantseva N, Krakhmalev P, Thuvander M, Yadroitsev I, Vinogradova N, Ezhov I 2018 *Mater. Character.* 146 101–112
[5] Kyung-Min Hong and Yung C. Shin 2016 *J. of Mater. Process. Tech.* 237 420–429
[6] Parry L, Ashcroft I A, Wildman 2016 R D *Add. Manuf.* 12 1–15
[7] Ivanov S, Zemlyakov E, Babkin K, Turichin G, Karpov I Em V, Rylov S. 2019 *Proc. Manufact.* 36 240–248
[8] Gil Mur F X, Rodriguez D, Planell J A 1996 *J. of Alloys and Comp.* 234 287–89
[9] Ahmed T and Rack H J 1998 *Mater. Sci. and Engineer. A* 243 206–211
[10] Keist Jayme S and Palmer Todd A 2016 *Mater. & Design* 106 482–494
[11] Shalnova S A, Klimova-Korsmik O G, Turichin G A, Gushchina M 2020 *Solid St. Phen.* 299 716–722
[12] Vildanov A M, Babkin K D, Zemlyakov E V, Gushchina M O 2018 *J. of Phys: Conf. Ser.* 1109 012059
[13] Jingjing Yang, Hanchen Yu, Jie Yin, Ming Gao, Zemin Wang, Xiaoyan Zeng 2016 *Mater. & Design* 108 308–318
[14] Stankevich S, Gumenyuk A, Strasse A, Rethmeier M 2019 *Key Engineer. Mater.* 822
[15] Turichin G A, Somonov V V, Babkin K D, Zemlyakov E V, Klimova O G 2016 *Equip.and Mater.* 125 012009
[16] Em V T, Ivanov S Y, Karpov I D, Rylov S A, Zemlyakov E V, Babkin K D 2018 *J. of Phys. Conf. Ser.* 1109 012049
[17] Kwon H, Baek W K, Kim MS, ShinW S, Yoh J 2012 *J Opt. Lasers Eng.* 50 114–121
[18] Gouge M and Michaleris P 2017 *Thermo-Mechanical Modeling of Additive Manufacturing* (Butterworth-Heinemann) p 294
[19] Mills K C 2002 *Recommended values of thermophysical properties for selected commercial alloys* (Cambridge: Woodhead Publishing)
[20] M. Majdic, G. Zeigler 1973 *Zeit. Metall.* 64 751–758

Acknowledgments
The reported study was funded by RFBR according to the research project №.19-38-50083\19.