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In-situ optical emission spectroscopic investigation of direct laser melting process during fabrication of Ti-6Al-4V parts

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Abstract

Direct laser melting (DLM) of Ti-6Al-4V micropowders of average size about 75 µm is investigated by optical emission spectroscopy during fabrication of three-dimensional parts using DLM machine [BeAM (Mobile 1.0). Emission from melt pool and vaporized materials is monitored at different laser powers. At lower laser powers, emission spectra are dominated by continuum emission from melt pool. At higher laser powers, neutral titanium (Ti I) and aluminum (Al I) atomic emissions appear along with the continuum emission. Temperatures of the melt pool and evaporated species obtained using the continuum emission and Ti I emission lines, respectively are studied as function of laser power to establish a correlation with the microstructural properties and chemical composition of the fabricated parts. Mechanical properties and microstructure of fabricated Ti-6Al-4V parts are investigated. The density of fabricated parts is about 4.4 g/cm^3 and the hardness is found to be about 370 HV for all investigated conditions.

Keywords: Direct Laser Melting; Optical Emission Spectroscopy; Ti-6Al-4V

1. Introduction

Ti-6Al-4V, an α+β – type titanium alloys, has attracted increasing attention in aviation, aerospace, chemical, shipbuilding and other industrial sectors due to its high strength, low density, high fracture toughness, fatigue strength and resistance to crack propagation, superior biocompatibility, good low-temperature toughness and excellent corrosion resistance [Chunxiang et al., 2011, Liu and Shin, 2019].

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Fabrication of Ti-6Al-4V parts remains challenging due to its poor thermal conductivity, the propensity to strain hardening, and active chemical reactivity to oxygen [Liu and Shin, 2019]. Recently, Powder based additive manufacturing techniques have widely been used for building different metal parts. In laser additive manufacturing processes, a high power laser beam heats and melts the deposited powder material to form a molten pool which then solidifies rapidly to form the desired three dimensional objects [Shin et al., 2018]. High thermal gradient due to highly localized heating, cooling and short interaction time can cause residual stress and distortions that can further lead to deformations, cracks or delamination in the fabricated parts [Alimardani et al., 2009, Katinas et al., 2018]. Moreover, heat accumulation effect can also induce defects in the material [Martin et al., 2019]. Thus, it is imperative to carry out in-situ process investigation during fabrication of metal parts by laser additive manufacturing. Photodiodes are widely used to monitor the in-situ laser additive manufacturing processes during fabrication of metal parts which gives some information about the state of the process [Bisht et al., 2018, Lough et al., 2018]. In addition, investigation on the spectral features of the light emitted from the melt pool and plume can provide useful information about the chemical ingredients of the evaporated species, and temperature of both melt pool and plume. Optical emission spectroscopy (OES) is an efficient in-situ monitoring technique which has been used to characterize the light emitted during laser manufacturing process [Mohanta and Leparoux, 2019]. In the present study, we have performed in-situ investigation of direct laser melting process of Ti-6Al-4V micropowders of average size about 75 µm by optical emission spectroscopy during fabrication of three-dimensional parts.

2. Experimental details

Three dimensional (3D) parts having length of 21.2 cm, width of 11.5 cm and height of 11.2 cm were fabricated by direct laser melting (DLM) of Ti-6Al-4V micropowders of average size about 75 µm using BeAM machine (Mobile 1.0) under the argon environment where oxygen content is < 50 ppm and water content is < 150 ppm.   A photograph of the BeAM machine is shown in Fig 1(a).

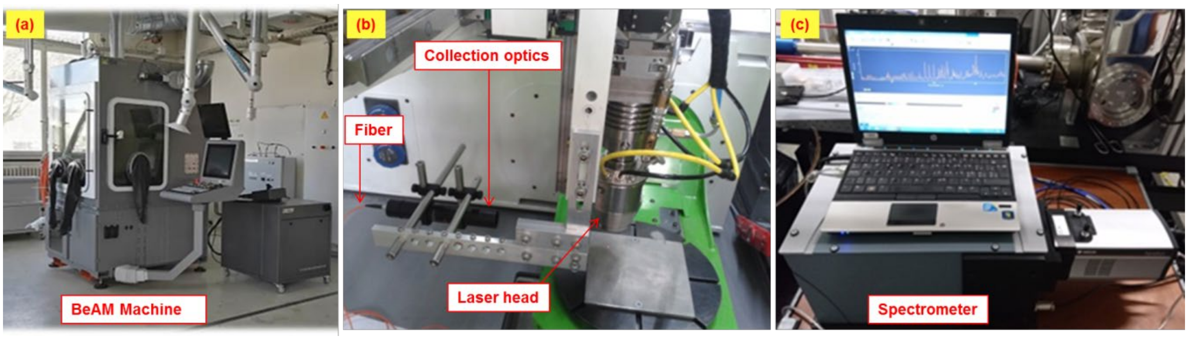

Fig. 1. (a) Photograph of BeAM machine used to fabricate three dimensional (3D) Ti-6Al-4V parts by direct laser melting of feedstock powder; (b) Photograph of Laser head of BeAM machine, and collection optics with fiber mounted with the laser head; and (c) photograph of spectrometer used to record emission spectra from melt pool and plume.

A fiber laser (IPG) of wavelength 1070 nm operated in CW mode mounted in BeAM machine was focused to a diameter of 800 µm for DLM of the injected Ti-6Al-4V micropowders. The printing speed, hatch spacing and z increment were kept at 2000 mm/min, 0.5 mm and 0.2 mm, respectively. The emission from the melt pool and plume is collected using two lenses [Part number: AC254-150-A-ML and AC254-100-A-ML, THORLABS] and is coupled to one end of the fiber. The other end of the fiber is aligned with the entrance slit of the spectrometer [Andor Technology (Shamrock Spectrograph, Model No. SR-303i-A and Newton CCD, Model No. DU940P-BU)] which records the spectra in time integrated manner during the DLM process. A photograph of collection optics with fiber mounted with laser head is shown in Fig 1(b) and of the spectrometer is shown in Fig. 1(c). The spectrometer is comprised of three gratings: (i) 150 lines/mm with blaze wavelength of 500 nm, (ii) 1200 lines/mm with blaze wavelength of 500 nm, and (iii) 2400 lines/mm with blaze wavelength of 300 nm.

3. Results and discussion

Fig. 2 shows a representative image of the three-dimensional Ti-6Al-4V parts fabricated using BeAM machine by direct laser melting. Several parts are built by varying laser power from 275 to 460 W. The density of fabricated parts is about 4.4 g/cm^3 and the hardness is found to be about 370 HV for all investigated conditions.

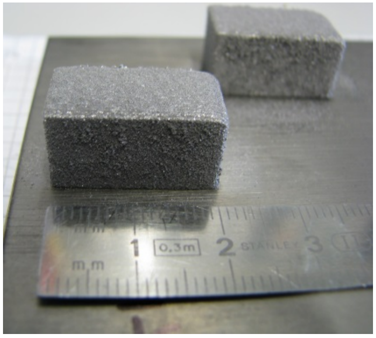

Fig. 2. A representative picture of the three-dimensional Ti-6Al-4V part fabricated using BeAM machine by direct laser melting.

Emission spectra are recorded during the fabrication of Ti-6Al-4V three-dimensional parts at diffferent laser powers varying from 275 to 460 W. Fig 3(a) shows the spectrum in the spectral region between 480 and 925 nm at lowest laser power of 275 W used in this experiment which shows a broad band continuum emission from the melt pool. Considering the continuum emission as Planck's radiation spectrum, the temperature of the melt pool (T_m) can be determined by using the following relation for the emission intensity, I(λ) [Amoruso et al., 2005]:

$$I(\lambda) \propto \lambda^{-5} \exp\left(-\frac{hc}{\lambda k_B T_m}\right) \quad (1)$$

where λ is the emission wavelength, *h* is the Planck's constant, *c* is the velocity of light, and k_B is the Boltzmann constant. Fig 3(b) shows a plot between $1/\lambda$ and $I\lambda^5$ obtained from the spectral response corrected continuum emission where the red solid line is the exponential fit that gives T_m of 2200 K at 275 W of laser power which is higher compared to the melting temperature of Ti-6Al-4V (1877 – 1933 K). Above 325 W of laser power, line emissions from the plume are detected in the spectral region between 481 and 545 nm along with the continuum emission from the melt pool. The line emission intensity is found to be increased with increase in laser power. Fig 4(a) shows the emission spectrum recorded at highest laser power of 460 W used in this experiment in the spectral region between 481 and 545 nm which contains the spectral information from both the melt pool and the plume.

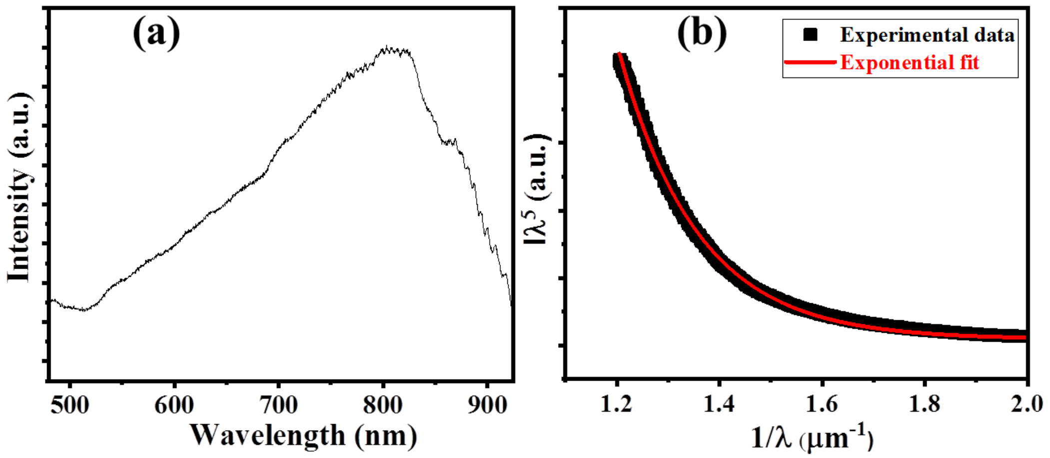

Fig. 3. (a) Emission spectrum recorded during direct laser melting of Ti-6Al-4V micropowders using 150 lines/mm grating at laser power of 275 W; and (b) A schematic plot between $1/\lambda$ and $I\lambda^5$ at laser power of 275 W where the red solid line is the exponential fit to the data points.

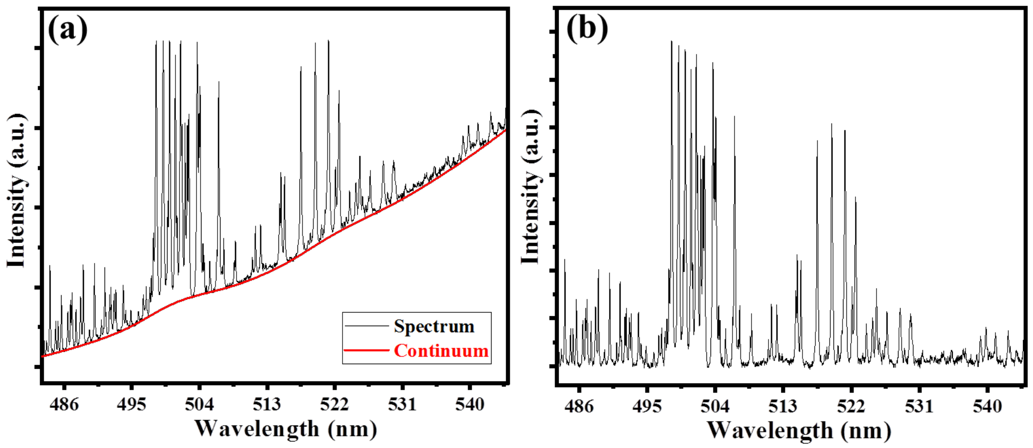

Fig. 4. (a) Emission spectrum recorded during direct laser melting of Ti-6Al-4V micropowders using 1200 lines/mm grating at laser power of 460 W; and (b) Emission spectrum of plume after separation of continuum emission from (a).

The continuum emission in Fig 4(a) is used to determine the melt pool temperature at laser power of 460 W following Eq. (1) and is found to be 2900 K. The melt pool temperature increases as the laser power increases. The spectrum in Fig. 4(b) is dominated by the neutral titanium (Ti I) emission lines. Under the assumption of local thermodynamic equilibrium (LTE), Boltzmann plot method can be used to determine the plume temperature (T_p) using the following relation [Mohanta and Leparoux, 2019, Griem, 1964]:

$$ln\left(\frac{I_{ki}\lambda_{ki}}{g_k A_{ki}}\right) = -\frac{E_k}{k_B T_p} + constant \qquad (2)$$

where I_{ki} is the intensity of the emission line at wavelength of λ_{ki}, g_k is the statistical weight of upper level k, A_{ki} is the transition probability, E_k is the energy of the upper level k and k_B is the Boltzmann constant. Fig 5 shows the plot between E_k and $ln\left(\frac{I_{ki}\lambda_{ki}}{g_k A_{ki}}\right)$ obtained using the spectral response corrected Ti I emission lines where the red solid line is the linear fit to the data points which gives T_p of 6000 K at laser power of 460 W. T_p is found to be increased from 4000 to 6000 K as the laser power increases from 360 to 460 W.

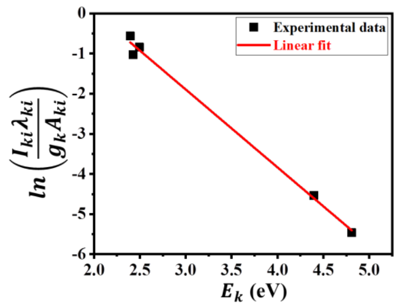

Fig. 5. Boltzmann plot between E_k and $ln\left(\frac{I_{ki}\lambda_{ki}}{g_k A_{ki}}\right)$ for the determination of T_p at laser power of 460 W.

Neutral aluminum atomic transitions (Al I) are identified in the optical emission spectrum along with Ti I lines recorded at laser power of 460 W in the spectral region between 390 and 405 nm as shown in Fig 6(a). Similarly, emissions due to neutral vanadium atomic transitions (V I) are also observed in the spectral region between 545 and 566 nm along with other Ti I emission lines as shown in Fig. 6(b).

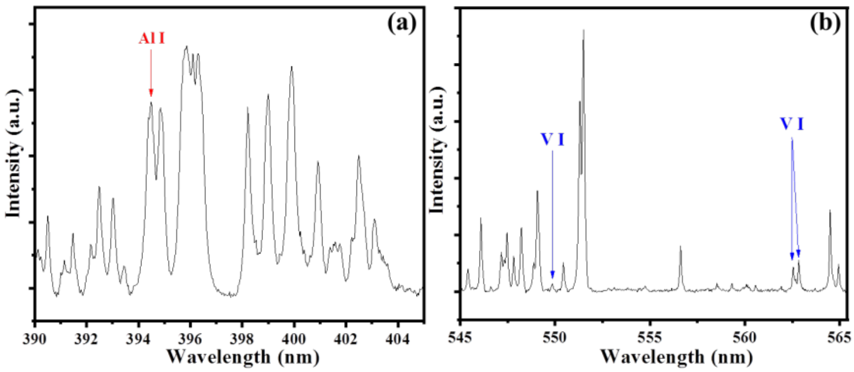

Fig. 6. Emission spectra from plume recorded during direct laser melting of Ti-6Al-4V micropowders using 1200 lines/mm grating at laser power of 460 W in the spectral region between 390 and 405 nm (a) and between 545 and 566 nm (b).

4. Summary

Optical emission spectroscopy experiment is successfully conducted during the fabrication of three dimensional Ti-6Al-4V parts by direct laser melting of Ti-6Al-4V micropowders of average size about 75 µm in BeAM machine (Mobile 1.0). Neutral aluminum, titanium and vanadium atomic transitions are observed in the optical emission spectra. The temperature of both the melt pool and plume is determined. Both melt pool and plume temperatures are found to be increased with increase in laser power. Such study on optical emission spectroscopy can further be extended to correlate the microstructural properties and chemical composition of the fabricated parts at different process conditions with the optical emission characteristics of both melt pool and the plume during laser based additive manufacturing processes. Mechanical properties and microstructure of fabricated Ti-6Al-4V parts are also investigated. The density of fabricated parts is about 4.4 g/cm^3 and the hardness is found to be about 370 HV for all investigated conditions. This study is ongoing and further work is necessary to implement in different laser based additive manufacturing machines for in-situ monitoring and process investigation.

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