Corrosion Behaviour of Laser Additive Manufactured Titanium Alloy

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The influence of process parameter on corrosion behavior of the most widely used titanium alloy-Ti6Al4V, produced using laser metal deposition process was studied. The processing parameters: scanning velocity, the powder flow rate and gas flow rate were kept at constant values of 0,005m/s, 1.44 g/min and 4 l/min while the laser power was varied between 0.8 to 3.0 kW. Electrochemical corrosion test was conducted on each of the samples produced at each set of processing parameters. The corrosive media used is the solution of sodium chloride (NaCl) desolved in deionized water. The results of this study indicate that the as the laser power was increase, the corrosion behaviour was found to be improved. The better corrosion resistance performance of the additive manufacture part can be attributed to the higher cooling rate that is associated with this type of manufacturing process. This high cooling rate results in the higher hardness of the material which could also contribute to the improved corrosion resistance behaviour.

Keywords: Corosion rate, Laser metal deposition, Laser Engineered Net shaping, Microhardness, Open circuit potential.

Highlights*:*

- The influence of Laser power on the resulting corrosion resistance was studied.
- The laser power was varied between 0.8 kW and 3.0 kW while other processing parameters were kept constant.
- Electrochemical analysis was conducted using aqueous solution of sodium chloride.
- The study revealed that, as the laser power was increased, the corrosion resistance was also increased

1.0 INTRODUCTION

Ti6Al4V is an important titanium alloy that has been favoured in many applications and it is referred to as the workhorse in the industry because of its superior properties [1]. The excellent properties includes it high corrosion resistance and high strength to weight ratio [2]. Ti6Al4V is the most widely used titanium alloy in the world due to its exciting properties [3]. This important

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alloy is used areas such as, for critical structural component of aerospace parts that includes the landing gear; the exhausts ducts; and some aircraft engine parts such as Rotors and compressor blades and frames. Ti6Al4V is the most used alloy in the aerospace industry. Ti6Al4V also finds its applications in the biomedical industry because of its compatibility with the human body. It is used to produce orthopedic and dental implants. Ti6Al4V is also used in other industries such as the chemical and petrochemical industries, Jewelry, as well as in nuclear power plants for storing nuclear waste [4]. Ti6Al4V has the highest strength-to-weight ratio that makes them an indispensable materials in many indistries.

In spite of the excellent properties, machining titanium alloy is challenging because it results in frequent tool failure [5]. The tool frequent tool failure occur as a result of the chemical reaction between the titanium and the cutting tool material when they come in contact with one another. It becomes more challenging when the material is used to fabricate aerospace parts that are more complex. Additive manufacturing process is an important manufacturing technology that can off-set most of these short comings of the conventional machining process.

Laser metal deposition process is an additive manufacturing technology, that is use to produce parts by adding materials in layer wise manner. This manufacturing technology helps to improve buy to fly ratio in the aerospace industry and can also be used to repair high valued parts [6]. Laser metal deposition process is an excellent manufacturing process for fabricating titanium and its alloys and other difficult to machine materials amongst other materials because it is a contactless manufacturing technology [7]. Laser metal deposition process is an important technology for producing new components, remanufacturing process and for manufacturing metals, composites and functionally graded materials [8, 9]. Different material has been processed using LMD process and have been reported in the literature [10-16] It is important to access the influence of processing titanium alloy using additive manufacturing method on the corrosion resistant behaviour so as to ascertain if the manufacturing process does not compromise the corrosion resistance performance. A number of studies has been carried out by researcher to establish this important characteristics of additive manufacturing process. Buciumeanu et al. [17] studied the influence of manufacturing process on trobocorrosion behaviour of titanium alloy grade 5. The manufacturing processes that were studied are casting, hot pressing and laser engineered net shaping (LENS)- a laser metal deposition process. The result of this study showed that the samples produced using LENS displayed a better corrosion resistance than the other two manufacturing processes that were studied. The reason for the improved corrosion resistance was attributed to the high localized cooling rates that is experienced in the LENS process. Chandramohan et al, Dai et al and Yang et al [18, 19 20] also demonstrated that additive manufactured Ti6Al4V has superior corrosion resistance properties.

The literature is still very scarce when it comes to the effect of process parameters on corrosion resistance study of additive manufactured components [20, 21] . Also, laser metal depositon process has been proof to be sensitive to processing parameters [22]. In this study, the influence of laser power on the corrosion resistance behaviour of laser metal deposition Ti6Al4V was studied.

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2.0 MATERIALS AND EXPERIMENTAL METHODS

The materials used in this study are Ti6Al4V substrate and powder. The powder is gas atomized powder that is spherical in shape. The powder is of particle size range between 150 and 250 µm. The substrate was a sheet of dimension 100 × 100 × 5 mm. The substrate was prepared by roughening the surface through sandblasting as and subsequently rinsed in acetone to help aid the laser absorption.

The laser metal deposition (LMD) process was achieved through the experimental set-up available at the National Laser Center (NLC) at CSIR Pretoria as shown in Fig. 1. Nd-YAG laser was used in this experiment due to its better penetration properties in metals due to its wavelength of 1.06µm. Argon gas was used as powder carrying gas as well as deposit shielding gas by filling the improvised shield box shown in Figure 1. The LMD process is achieved by the laser beam firstly creating a melt pool on the substrate and then the powder is delivered into the melt pool.

Fig. 1. Experimental-setup [23]

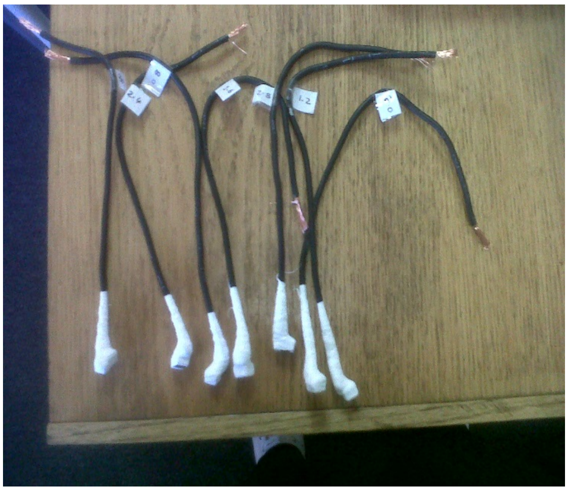
As the melt pool solidifies, a track of solid melted powder is seen along the laser path. The laser spot size of approximately 2mm was maintained throughout the experiments with the laser focal length maintained at a distance of 195 mm above the substrate. The scanning speed, the powder flow rate and gas flow rate were maintained at a value of 0.005 m/s, 1.44 g/min and 4 l/min respectively. The laser power was varied from 0.8 kW to 3.0 kW. The processing parameters are presented in Table 1. The laser metal deposition process is very sensitive to processing parameter which makes the process to be difficult to understand. By understanding the influence of single process parameter, it will help to simplify the control of the properties of the material produced. This understanding can then be extended to the variation of two or more processing parameters. Initial experiments were conducted to establish the process window for the process. The results of preliminary investigation gave better metallurgically bonded sample at the laser power of 0.8 kW, the sample at this laser power has less porosity. The range used in this study was based on this preliminary experiment.

Table 1. Experimental Matrix

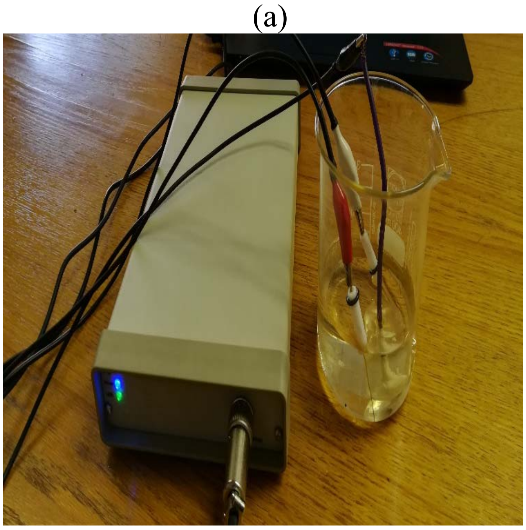
Sample No.	Laser power (KW)	Scanning speed (m/s)	Powder mass flow rate (g/min)	Gas flow rate (1/mm)
1	0.8	0.005	1.44	4
2	1.2	0.005	1.44	4
3	1.6	0.005	1.44	4
4	2.0	0.005	1.44	4
5	2.4	0.005	1.44	4
6	2.8	0.005	1.44	4
7	3.0	0.005	1.44	4

After the deposition process, the samples were cut across the deposition direction to reveal the cross section of the deposited samples. The samples for microstructural studies are mounted in hot resin, ground, polished and etched using Kroll reagent. The etched samples were studied under Olympus BX51M Optical Microscope. The samples for the corrosion testing are prepared by attaching an electrical wire onto the sample while the whole samples were mounted in cold resin and revealing the deposited area of approximately 0.5 X 0.5 cm.

Corrosion test was performed through open circuit potential and potentiodynamic polarization tests. The samples were prepared by grinding the surface using a 1200-grit SiC paper together with 3-µm diamond suspension. The samples are then cleaned with ethanol before starting the corrosion test. The cleaned samples are then immersed in the 3.5% NaCl aqueous solution with pH of 6.24. The test was carried out at room temperature of 23 ± 2 °C. The electrochemical tests were performed using a three-electrode system. The samples is used as the working electrode while the a platinum rod was used the counter electrode and the silver/silver-chloride electrode (Ag/AgCl) 3 M KCl was the reference electrode using the potentiodynamic polarization method according to the ASTM G-3-89 and ASTM 5-94 standards. The measurements were taken using the Autolab PGSTAT30 potentiostat as shown in the experimental set up in Figure 2. Tafel plots were obtained and analyzed using the General Purpose Electrochemical Software Version 4.9. The open-circuit potential (OCP) scan was first performed for each of the samples followed by the linear polarization scan and at a scan rate of 1 mV/sec starting from − 0.25 V based on the OCP value for the sample and up to to + 0.25 V of the OCP value. The experiments were conducted three times.



(a)



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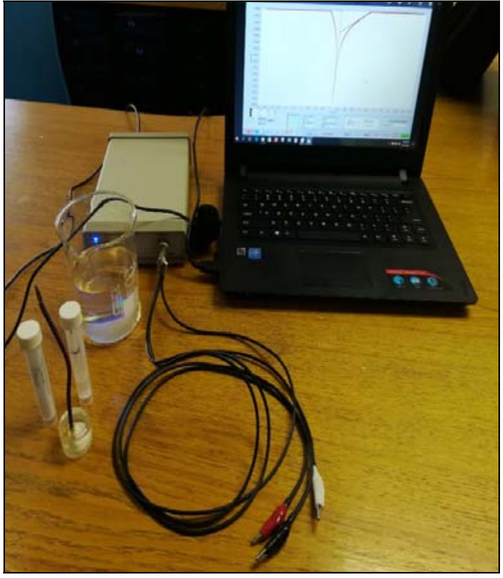
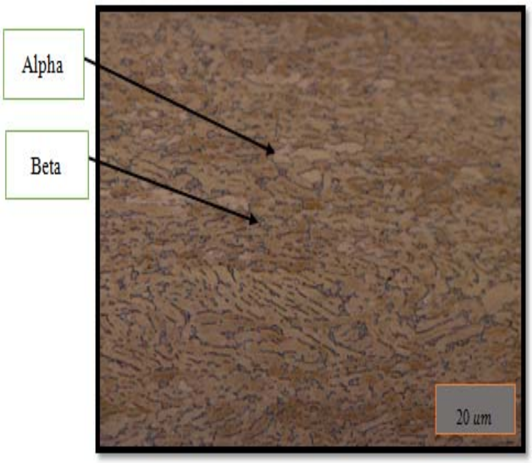


(c)

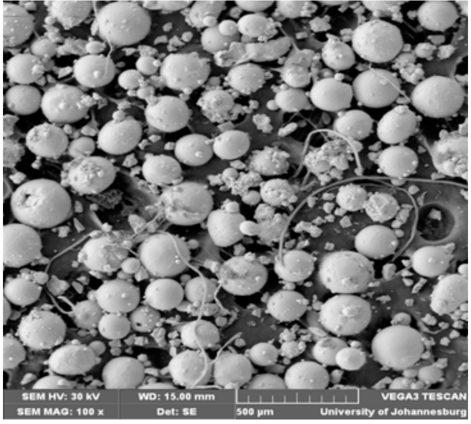
Fig. 2. Pictures of the (a) prepared corrosion samples (b) potentioststat for electrodes connection and (c) Experimental set up for corrosion test

3 RESULTS AND DISCUSSION

The micrograph of the Ti6Al4V substrate and powder are shown in Fig. 3a and 3b respectively. The Ti6Al4V substrate consists of alpha and beta grains. The Ti6Al4V powder is a spherical shaped gas atomized powder. The microstructure of a deposited sample is shown in Fig.4 with the three distinct zones typical of laser metal deposited material. The microstructure of the heat affected zone is characterized by globular grains and the deposit zone is characterized by columnar grains that grow epitaxially on the globular grains. The direction of growth is due to the directional solidification of the melt pool which is directed opposite of the substrate material. This is because; the substrate is cold and acts as a heat sink.



(a)

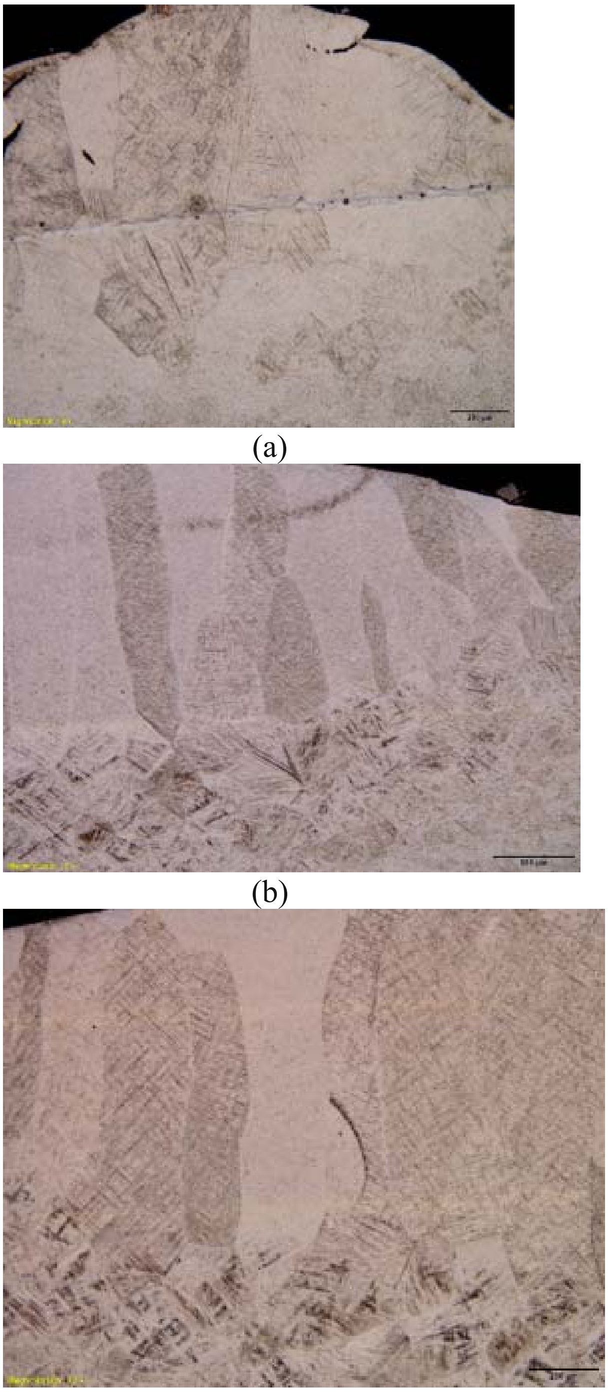


(b)

Fig.3 The micrograph of Ti6Al4V (a) substrate (b) Powder

The micrograph of samples produced at laser power of 0.8kW, 1.6 kW and 3.0 kW are shown in Fig. 5a, 5b and 5c respectively. The sample at 0.8 kW show porosity in the fusion region where the powder joined with the substrate. This is as a result of insufficient laser power for the set of processing parameters used. The higher the laser power, the larger the melt pool created on the substrate and the longer it takes the molten metal to solidify. This results in the formation of larger globular grains in the heat affected zone that in turn causes the columnar grains to be larger at higher laser power as shown in Fig. 5a and 5c. More of Widmanstätten alpha is seen at higher laser power that makes the microhardness to be lower at higher laser power. The microhardness reduces with increasing laser power as shown in Fig 6.

Fig. 4. The microstructure of sample at a laser power of 1.2 kW showing the deposit zone, and heat affected zone.


(a)

(b)

(c)

Fig. 5. Microstructure of samples produced at laver power of (a) 0.8 kW (b) 1.6 kW (c) 3.0 W

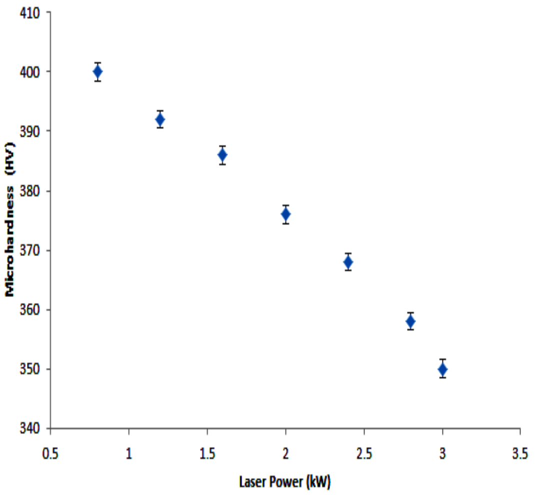


Fig. 6. The plot of average microhardness against the laser power.

The open circuit potential results also indicate similar result. It reduces with increasing laser power as shown in Fig.7. The OCP of sample at a laser power of 0.8 kW is higher than that of the substrate because of the porosity in the sample. The graph of the corrosiuon current density (icorr) versus the laser power is shown in Fig 8. The icorr was found to reduce as the laser power was increased as shown in Fig. 8. The very high values recorded in the sample at a laser power of 0.8 kW because of the inherent porosity that cause the total surface area that is exposed to the corrosion media to be higher. The tafel of al the samples are shown in Fig.9. The bar chat of corrosion rate against the laser power is shown in Fig. 10. The corrosion rate was found to reduce as the laser power was increased. This could be due to moderate hardness that is seen at higher laser power. Though the hardness seen at lower laser power was higher which could be as a result of improper melting of the metal power? The sample at a laser power of 0.8 kW is the highest but lack of fusion porosity is seen in the micrograph and hence insufficient melting of the powder. The higher laser power promotes higher corrosion resistance by helping to increase the formation of stronger protective oxide layers on the samples as shown in Figure 11 thereby inhibiting further corrosion processes.

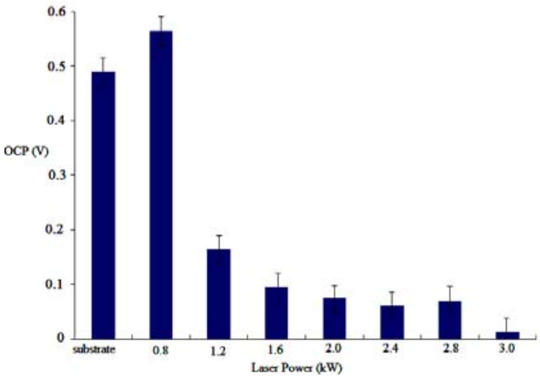


Fig. 7. Open circuit potential (OCP)

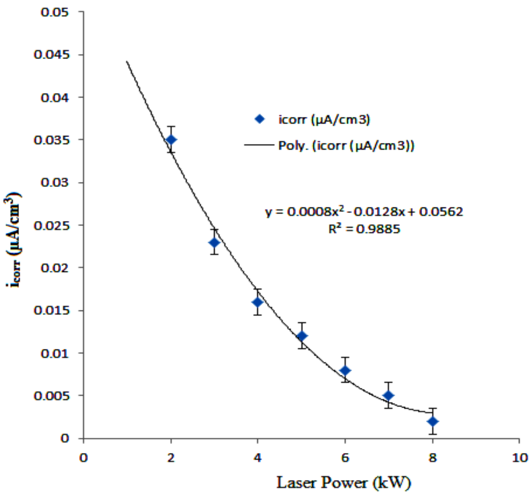


Fig. 8. The plot of Corrosion current density against laser power

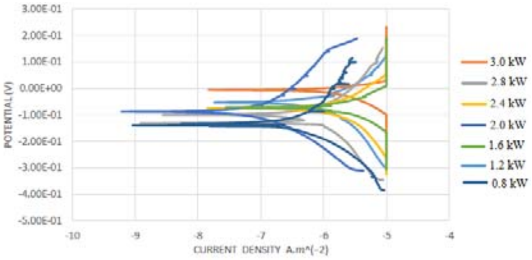


Fig. 9. Tafel plot of all the sample

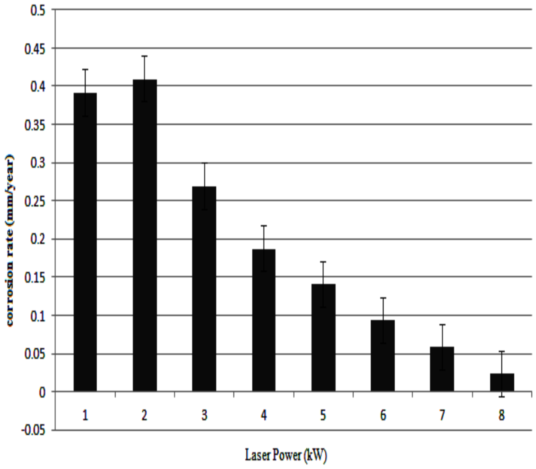
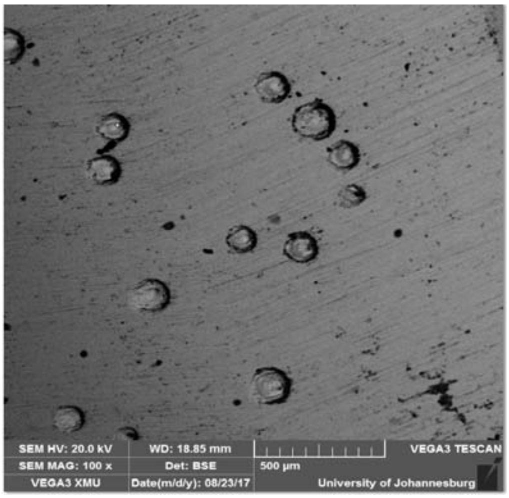
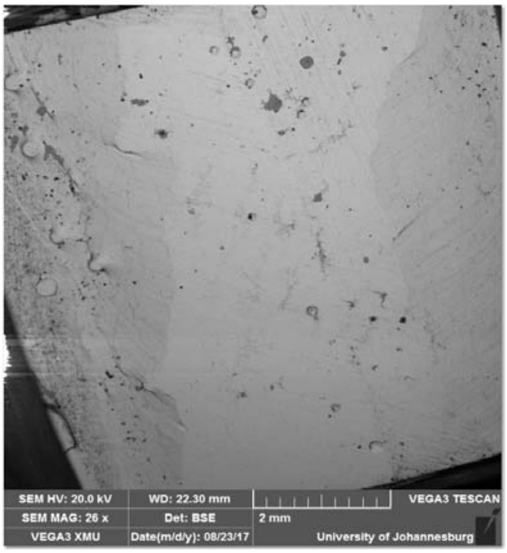


Fig. 10. Bar Chat of corrosion rate per year versus laser power



(a)



(b)

Figure 11. SEM Micrograph showing whitish protective layer on corroded samples at (a) 0.8 kW (b) 2.6 kW

4.0 CONCLUSIONS

The influence of laser power on the corrosion resistance properties of laser metal deposited Ti6Al4V. Electrochemical analysis was performed on samples in 3.5 % NaCl solution. The results showed that as the laser power was increased, the corrosion rate was reduced. The corrosion resistance performances of the laser metal deposited samples are better than that of the parent material. This could be attributed to the rapid solidification that is associated with the laser metal deposition process. Also, the moderately higher microhardness seen at higher laser power helps to improve the corrosion performance of the laser metal deposited Ti6Al4V.

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