JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

Studies on Wettability of Corrosion Resistant Stainless Steel 316L powder in laser melting process

Kurian Antony, N. Arivazhagan*, K.Senthilkumaran

School of Mechanical and Building Sciences, VIT University, India 632014

*Corresponding author: narivazhagan@vit.ac.in

Telephone Number-0416-220-2221,

Fax: 0416-224-3092, 224-0411.

Abstract

Laser sintering is one of the many mechanisms used in additive manufacturing processes. The main objective of the work is to study the effects of process parameters on wetting phenomenon and interfacial energy during laser melting of stainless steel powder. This paper reports wetting of laser melted powder particles and its use for the determination of surface energy of stainless steel powder under laser beam exposure. Process parameters such as laser power, scan speed and beam diameter are considered for study. This study also identifies the process parameters for better wettability which produces smooth surfaces

Keywords: Stainless Steel, Wettability, Interfacial Energy ratio, Macrostructure.

1. Introduction

Selective laser melting process enables the fabrication of components with complex shapes directly from metallic powder [1]. Laser melting process has aroused wide concerns and has been widely used in biomedical, aerospace and many other engineering fields, offering a series of advantages compared with traditional processing techniques due to its versatility in producing parts of both metals as well as polymer [2-5]. Moreover Stainless steel 316L (SS316L), is a widely used material in biomedical applications such as orthopedic pins, plates and hip replacements and is preferred over Ti Alloys for the cost advantage [6]. However, during the SLM process, the laser molten track possesses a shrinking tendency to decrease the surface energy under the action of surface tension. Thus, the balling phenomenon is easily observed during SLM process, which is detrimental to the quality of SLM processed part and hinder the further development of SLM technology [7-10]. Balling phenomena mainly occurs due to the poor wettability of the powder. Moreover wettability plays a major role in laser melting process which affects the mechanical as well as the corrosion behaviour of the laser melted parts [8]. Poor wettability in the surface produces cracks which will further cause corrosion of the part. Thus the laser melted surface with good wettability is less prone to corrosion and high wear resistance. To ensure good wetting and successful layer-by-layer consolidation the processing must be conducted in a vacuum or protective atmosphere using high purity inert gases [1]. For better wettability to take place, surface oxide reduction is necessary. De Gennes [11] has given an excellent review of the physical mechanisms governing the wetting. The wetting behavior of a molten liquid on a substrate of its own kind was investigated recently by Schiaffino and Sonin [12-14]. However this particular situation is known as “homologous wetting" and is inherently a non-equilibrium phenomenon involving simultaneous heat transfer, fluid flow and solidification [15]. Moreover poor

The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

wettability can leads to balling and crack formation which further leads to lower corrosion resistance and mechanical properties. This work mainly concentrates on the various process parameters which influence the wettability of the laser melted track.

2. Physical Model

2.1 Wetting

The interfacial energy of the solid-solid and the liquid-solid interfaces is related to wetting angle is as follows [16]:

$$\frac{¥_{SL}}{¥_{SS}} = \frac{1}{2\cos(\frac{\Theta}{2})} = {}^{2} \qquad (1)$$

γSL and γSS are the energies of the solid - liquid interface and solid-solid grain boundary respectively and θ is the wetting angle, τ interfacial energy ratio.

3. Experimentation

Experiments were conducted by melting of powder material and forming droplets onto prepared substrates of the similar material to investigate homologous wetting in SLS. Nd: YAG pulsed laser JK 300P (UK) of maximum peak power 5 KW, maximum pulse energy 40 J was used. Nitrogen atmosphere has been maintained in order to prevent oxidation. Schematic representation of the experimental setup is depicts in Fig.1. Stainless steel 316L was chosen as the material for investigation due to its ready availability in both powder and plate form and its virtue of enormous applications. The substrate was prepared

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

by polishing with 120, 240, 400 and 600 abrasive grits, followed by 3μm diamond paste and a final polish with 0.05μm alumina slurry, followed by ultrasonic cleaning in acetone. This preparation technique was necessary to provide as clean and smooth surface as possible since the presence of surface oxides will cause the material to spread poorly [9] and to reduce the influence of surface roughness to the wetting behavior. For conducting the experiments, taguchi L9 orthogonal array has been followed as shown in table 1. Initially, the stainless steel powder was spread over the substrate and maintaining the thickness of 100μm using scraper blade. Laser moves in x direction of the powder bed which produces melted track. Wetting angle is measured with image analyzer. In addition energy density of the laser beam is denoted by the equation [17].

$$E = \frac{P}{vd} \qquad (2)$$

Whereas P is the laser power used to scan a part; v is the scan speed or the velocity by which the laser beam moves over the powder surface, d is the beam diameter.

4. Results and Discussion

4.1 Experimentation

Sequential images from digital macroscopy of the experiment conducted with stainless steel powder on stainless steel plate are shown in Fig.2. Fig.2 (d, f, and g) schematically depicts the formation of continuous scan track, in general at relatively lower scanning speed the powder agglomeration and continuous melting normally occurs. In other words at lower scanning speed powder particles have much time for melting and solidification. Single layer tracks in fig.2 (a-c, e, g and h) reveals that the molten powder shows no tendency to spread and wet the underlying substrate. Instead, it formed a nearly spherical droplet having a point like contact with the substrate. Laser melted track which gives large semi-circle droplets as shown in fig.2 (i) which is having the highest contact angle. This effect justifies that increase in contact angle will leads to poor wettability and thus the quality of the part will get affected.

4.2 Wetting

Table 1 shows the wetting angle and interfacial energy ratio of the nine laser process parameters. Wetting angle is measured with the image analyzer; the contact angle for various process parameters is shown in table1. Fig.3. explains the relation between wetting angle and the energy densities of different process parameters. From the graph it is clearly understood that wetting angle increases at the lower energy density level. However it is noted that at lower energy density level the melting of the powder won't happen properly which will leads to distortion further cause's poor wettability. In the case of higher energy density as the laser power increases or the scan speed decreases, the amount of energy absorbed by the powders under the laser beam enhances, inducing a larger degree of melting which causes good wettability. Moreover the Wetting of the grain boundaries by a continuous liquid film occurs for τ less than 0.5($\theta < 60^0$) and for values above 0.5, the resistance to cracking increases which will leads to corrosion [18]. Fig.4 shows that interfacial energy ratio has an

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

influence on the energy density of the laser. Fig.5 reveals the effect of different process parameters on wetting; it is evident from the graph that as the laser power increases wettability also increases same as in the case of scanning speed. If the scan speed is higher, due to the pulse separation, the contact on all sides of the droplet becomes solid-liquid in nature. So the wettability is altered primarily because of the speed and pulsing of the laser. However it is noted from the fig.5 higher the beam size the tendency of wettability is very low, this mainly because of the larger beam which rarely melts the powder particles. From the experimental results the tracks which produce discontinuous as well as large droplets have τ more than 0.5 and θ more than 60^0. During wetting process the adhesion between the solid and liquid is greater than the cohesive force of the liquid. For laser melting, wetting implies that the molten powder spreads on the substrate or previously sintered layer, instead of balling up on its surface. The higher the solid-liquid surface energy, the greater is the tendency to minimize the liquid-solid interface by formation of isolated pockets of liquid instead of continuous films. Borland et al. [19] showed that the interfacial energy ratio for iron-iron sulphide films was close to 0.5, explaining the deleterious effect of sulphur in steels.

5. Conclusion

Optimum process conditions for laser melting process to achieve continuous track with good wettability have been investigated with stainless steel powder with different process parameters. Wettability and surface energies of the laser melted stainless steel powder has been found out experimentally. The laser melted track having low contact angle as well as interfacial energy gives good wettability. From all the nine laser parameters used in this study, the set of parameter which gave good wettability as well as smooth and continuous track is of laser power 150W, scan speed 2.4m/min, spot size 400μm. Moreover it is well understood from the ANNOVA study that the main process parameters that affects the wettability are laser power and scan speed of laser

Acknowledgement:

We would like to acknowledge the support extended to us by Optilase India Pvt. Ltd by providing access to their Nd:YAG pulsed laser and robot test facility for conducting experiments.

Reference

[1] 'Balling behavior of stainless steel and nickel powder during selective laser melting process,' Ruidi Li , Jinhui Liu ,Yusheng Shi , Li Wang , Wei Jiang, , International Journal of Advanced Manufacturing Technology, **59**,pp1025-1035, 2012.

[2] 'Parametric analysis of the selective laser melting process,' I .Yadroitsev, P .Bertrand, I .Smurov, Applied Surface Science, **253,** 19, pp8064-8069, 2007.

[3] 'Selective laser melting W-10 wt.% Cu composite powders,' Li RD, Shi YS, Liu JH, Xie Z, Wang ZG, International Journal of Advanced Manufacturing Technology, **48,**(5-8),pp597-605, 2010.

[4] 'An innovative method to build support structures with a pulsed laser in the selective laser melting process,' J .Jhabvala, E .Boillat, C .André, R .Glardon, International Journal of Advanced Manufacturing Technology, ,doi:10.1007/s00170-011-3470-8,2011

[5] 'Mechanical property study on rapid additive layer manufacture Hastelloy®X alloy by selective laser melting technology,' FD .Wang, International Journal of Advanced Manufacturing Technology, , doi:10.1007/s00170-011-3423-2, 2011

[6]'Influence of laser melting process parameters on surface roughness behavior for SS316L powder,' Kurian Antony, N .Arivazhagan, K .Senthilkumaran, Journal of Corrosion Science and Engineering ,**16**, ISSN 1466-8858, 2013

[7] 'Reducing Staphylococcus aureus biofilm formation on stainless steel 316L using functionalized self-assembled monolayers,' Kristen M. Kruszewski , Laura Nistico, Mark J. Longwell, Matthew J. Hynes c, , Joshua A. Maurer , Luanne Hall-Stoodley , Ellen S. Gawalt, , Materials Science and Engineering C **33** pp2059-2069,2013.

[8] 'Balling phenomena during direct laser sintering of multi-component Cu-based metal powder,' Gu DD, Shen YF , Journal of Alloys and Compounds, **432**,(1-2),pp163-166, 2007.

[9] 'Selective laser melting of iron-based powder,' JP. Kruth, L .Froyen, J .Van Vaerenbergh, P .Mercelis, M .Rombouts, B .Lauwers, Journal of Materials Processing Technology, **149**,(1-3),pp616-622, 2004.

[10] 'Instability of scan tracks of selective laser sintering of high speed steel powder,' HJ .Niu, ITH .Chang, Scripta Materilia, **41**,11,pp1229-1234, 1999.

[11] 'Wetting: statics and dynamics,' P. G. de Gennes, Reviews of Modern Physics, **57**,3, pp827-863,1985.

[12] 'Motion and arrest of a molten contact line on a cold surface: An experimental study,' Stefano Schiaffino and Ain A. Sonin, Physics of Fluids, **9**,8,pp2217-2226,1997.

[13] 'On the theory for the arrest of an advancing molten contact line on a cold solid of the same material,' Stefano Schiaffino and Ain A. Sonin, Physics of Fluids, **9,**8,2227-2233,1997.

[14] 'Molten droplet deposition and solidification at low Weber numbers,' Stefano Schiaffino and Ain A. Sonin, Physics of Fluids, **9,**11,pp3172-3187,1997.

[15] 'On Some Physical Aspects of Process Control in Direct Selective Laser Sintering of Metals|Part I,' Suman Das, symposium proceedings, Department of Mechanical Engineering University of Michigan, USA, pp85-93, 2001

[16] 'Grains, phases and interfaces: an interpretation of microstructure,' C S. Smith Transaction of American Institute of Mining, Metallurgical Engineers, **175,**pp15-51, 1948.

[17] 'Laser-Induced Materials and Processes for Rapid Prototyping,' Lu, L.; Fuh, J.Y.H. & Wong, Y.S., Kluwer Academic Publishers, ISBN 0792374002, Norwell, USA 2001

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

[18] 'Generalized theory of super-solidus cracking in welds (and castings),' J C .Borland, British Welding Journal, **7**, pp508-512, 1960.

[19] 'Some aspects of cracking in welded Cr-Ni austenitic steels,' J C .Borland, R N .Younger, British Welding Journal, **7**,pp 22-59, 1960.

Trial No	Laser Power (W)	Laser Speed (m/min)	Beam Dia (μm)	Energy Density (j/mm2)	Interfacial Energy Ratio (τ)	Wetting Angle (θ)
1	100	2.4	300	8.33	0.52543	35.8040
2	100	8.4	400	1.785	0.61812	72.0230
3	100	12	500	1	0.52069	32.4130
4	150	2.4	400	9.375	0.5514	24.9360
5	150	8.4	500	2.142	0.52377	34.6530
6	150	12	300	2.5	0.52465	35.2680
7	200	2.4	500	10	0.51635	28.9180
8	200	8.4	300	4.761	0.57257	58.3250
9	200	12	400	2.5	1.37627	137.3940

Table.1. The selected process parameters for laser melting for making single layer track.

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

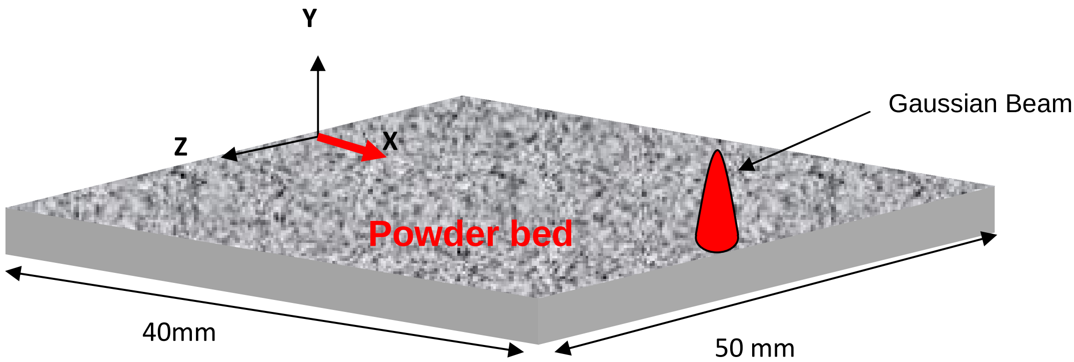

Figure.1

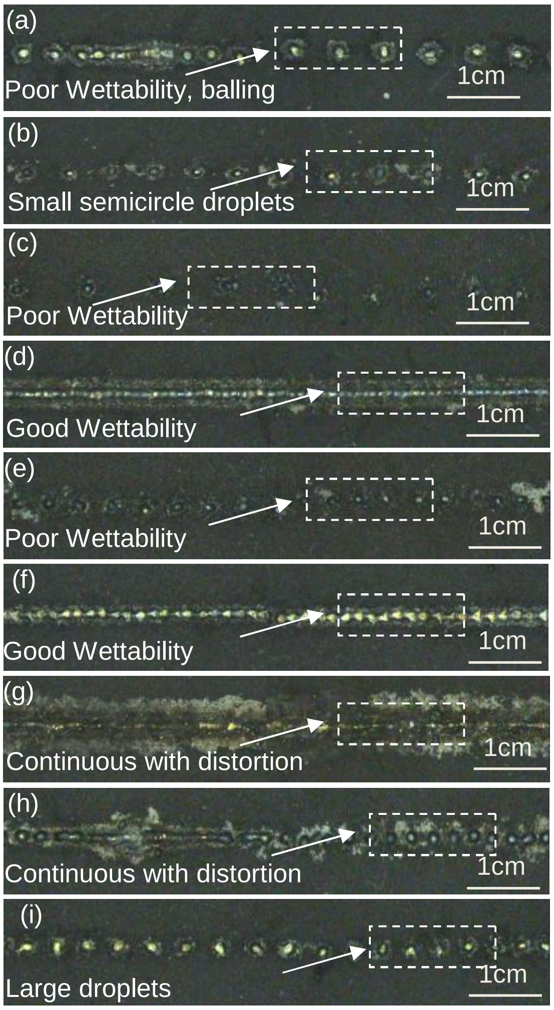

Figure.2

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

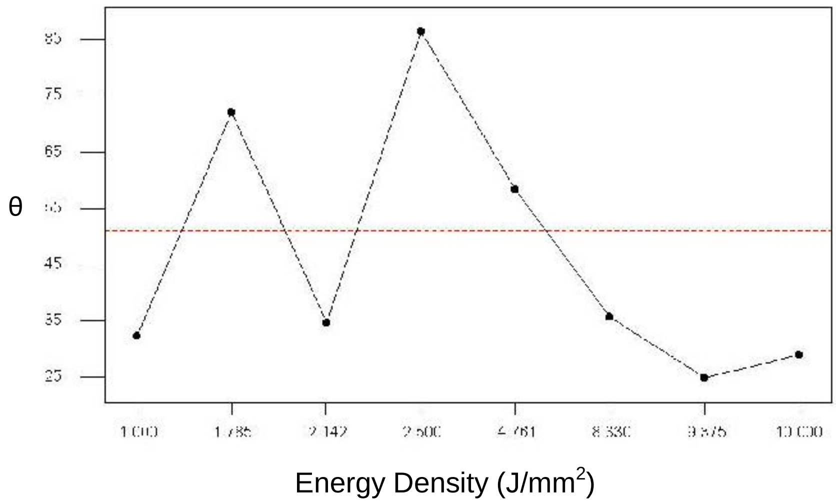

Figure.3

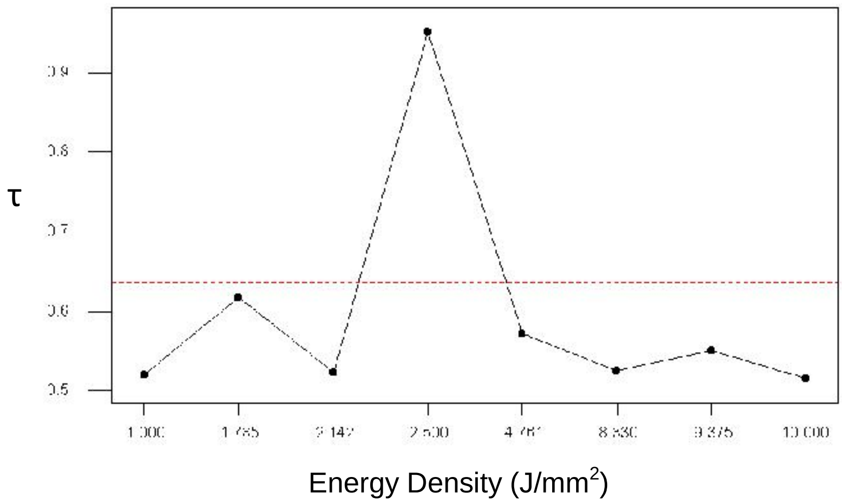

Figure.4

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

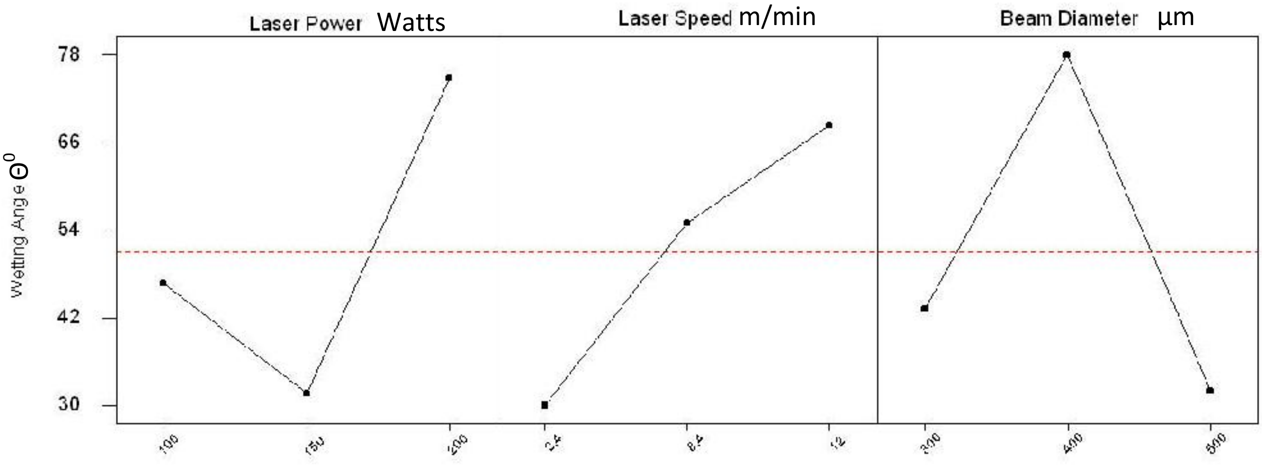

Figure.5

Legends for Figures

Fig. 1. Specimen for SS316L powder bed irradiated by Nd-YAG laser beam.

Fig. 2.The macrograph of single track formation of SS 316L powder on SS 316L substrate

((a) P 100 W; V 2.4 m/min; d 300 μm; (b) P 100 W; V 8.4 m/min; d 400 μm; (c) P 100 W; V 12 m/min; d 500 μm; (d) P 150 W; V 2.4 m/min; d 400 μm; (e) P 150 W; V 8.4 m/min; d 500 μm; (f) P 150 W; V 12 m/min; d 300 μm(g) P 200 W;

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 44 submitted 28 June 2013

V 2.4 m/min; d 500 μm; (h) P 200 W; V 8.4 m/min; d 300 μm; (i) P 200 W; V 12 m/min; d 400 μm.

Fig.3 Energy Density Vs Wetting Angle.

Fig.4 Energy Density Vs Interfacial Energy Ratio.

Fig.5 Effect of process parameters on Wetting