Process Optimization, Microstructure and Hardness of Aerospace Alloy

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Abstract
In the current study, the effect of carefully designed Powder Bed Fusion (PBF) laser parameters on the microstructure and hardness of Co-Cr alloy straight, thin-wall additively manufactured test coupons that are as-built or have undergone Hot Isostatic Pressing (HIP) was investigated. For enhanced productivity, it is important to evaluate the relationship between energy density (ED) input (laser power, scan speed) and the microstructure developed in the Co-Cr alloy coupons for an aerospace application. Both the High ED and Low ED input processing laser parameters induce a higher percent (%) volume of defects i In addition, the surface roughness of the Low ED input parameter coupons after HIP is similar to the coupons produced using the manufacturer recommended laser parameters assessed with light optical magnification image evaluation. Hot Isostatic Pressing is therefore an excellent post-processing method to reduce internal defects for a given range of laser energy densities in metal additive manufacturing at increased build speeds.

Keywords: Additive manufacturing, Defect, Hot Isostatic Pressing, Energy Density, Hardness.

1.0 INTRODUCTION

Over the last decade, additive manufacturing (AM) technology has consistently evolved as a sophisticated rapid manufacturing tool that allows direct fabrication of an end-usable part with complicated shapes e.g. complex vanes and air ducts that are almost impractical to fabricate by other manufacturing processes. This process involving the sequential addition of ultra-thin layers of material without extensive tooling, has been recognized and predicted as a key tool that will revolutionize manufacturing processes for many industries (Sankaranarayanan *et al.*, 2016).

Although AM, which is also known as 3D printing, has become relatively popular for fabricating parts from plastics, the use of AM to produce metallic components, which faces a much higher level of design challenges and post processing requirements, is expected to have its most commercial impact in aerospace and biomedical applications (Zhang *et al.*, 2006; Williams *et al.*, 2015; Thompson *et al.*, 2015; Syed *et al.*, 2005; Kinsella, 2008). Different techniques are currently being used for AM of metallic products and one of these is the powder bed fusion (PBF) process technology. In this technology, the additive material (powder) is used to produce metallic part directly from 3D model data. PBF can be performed with either laser or electron beam as the thermal source to melt the powder. The process also includes a mechanism to pre-spread a smooth powder layer on the bed and control the powder fusion to a specific region during each layer scan (Choi and Chang, 2005).

In this current study, laser metal powder bed fusion (PBF) AM method was used to produce thin-wall Co-Cr alloy samples part typically used in aerospace application with the view of evaluating the relationship between energy density (ED) input (laser power, scan speed) and the microstructure developed in the Co-Cr alloy coupons. The objective of this study is to perform systematic microstructural analyses and hardness evaluation on test coupons that are as-built and those that have undergone Hot Isostatic Pressing (HIP). The ultimate goal of this study is to enable a better understanding on the influences of energy density on as-built

defects in the Co-Cr alloy and the consequential role of HIP on the as-built defects in order to develop optimal processing parameters that will enhance fabrication of better quality Co-Cr parts by laser metal PBF.

2.0 MATERIALS AND METHOD

Carefully designed energy densities process optimization parameters were developed as shown in Table 1, to produce the Co-Cr AM coupons. These included Low energy density parameters, manufacturers' recommended parameters and High energy density parameters. The Co-Cr powder with proprietary chemical composition was sourced from Original Equipment Manufacturer (OEM). Figure 1 shows the design plan and the 3D printing layout plate of the design of experiment. A total of 75 parameters (in duplicate – 150 coupons) were produced in an as-built configuration (Figure 2) and then an identical build was reprinted to undergo Hot Isostatic Pressing (HIP). The images from OM and SEM were then converted into de-noised, black-and-white micrographs using Image J porosity analysis software to quantify % volume fraction of internal defects (Figures 3). Micro-hardness tests were performed using a Buehler Micromet 5100 series hardness tester on a load setting of 300 gf and a step size of 0.5 mm. The values of the micro-hardness were determined from an average value of 20 data points

Table 1. Design of the Experiment

Energy Parameters	High	Recommended	Low
Part Thicknesses (t) (mm)	0.0762/0.889/1.016	0.0762/0.889/1.016	0.0762/0.889/1.016
Stripe Scan Power (P) (Watts)		245 – 145	
Stripe Scan Speed (V) (mm/s)		1200 – 400	
Energy Densities (P/V)	2.26	1.01	0.59

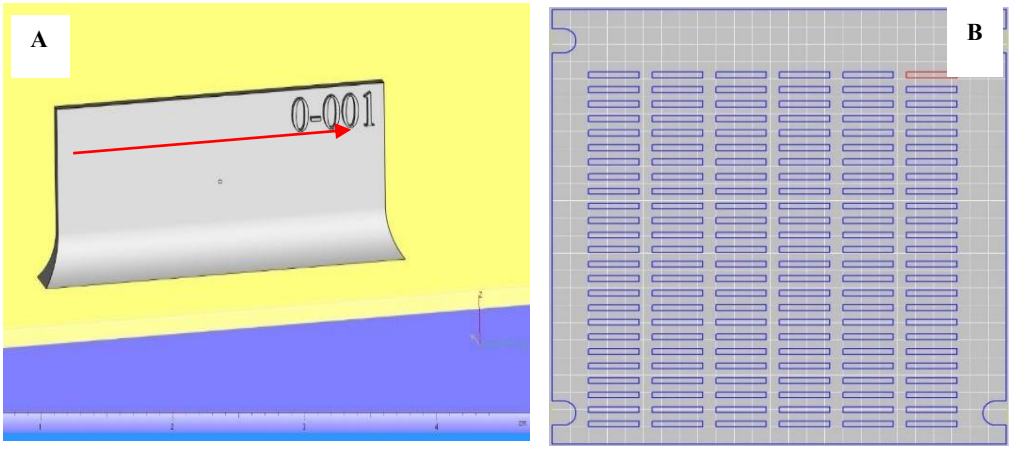


Figure 1: (A) typical coupon design with an identification mark (arrow show the scanning direction), and (B) shows the built plate design/layout

3.0 RESULTS AND DISCUSSION

3.1 Effect of Optimization parameters on Defects and Porosity Evaluation

All the as-built and HIP coupons subjected to LPI testing passed the LPI test. Liquid penetrant inspection method was used to reveal surface discontinuities by bleed-out of a coloured or fluorescent dye from the flaw based on the ability of a liquid to be drawn into a clean surface discontinuity by capillary action (Lu and Wong, 2017; Sharratt, 2015). The advantage over an unaided visual inspection is that it makes defects easier to see by producing a flaw indication that is much larger and improves the detectability of a flaw due to the high level of contrast between the indication and the background. Although all the experimental coupons passed LPI test, nevertheless, there was a need to further investigate microstructural issues that have been previously reported in the literature (Kim *et al.*, 2017; Asala *et al.*, 2017; Zhong *et al.*, 2015; Gong *et al.*, 2015) as common to AM components. Defects such as cracks and porosity have been reported, including the influence of thickness, powder particles sizes, morphology and energy densities (Kong et al., 2007; Karapatis et al., 1999; Cleary and Sawley, 2002), however, limited information has been reported on the post-processing AM treatment effect of HIP.

3.2 Effect of Optimization parameters on Microstructure and Hardness

The microstructure of the AM Co-Cr alloy in the as-built and HIP condition were analyzed with respects to its influence on the strength of the Co-Cr alloy. Fig. 8a-b showed the microstructures of the as-built and HIP alloy.

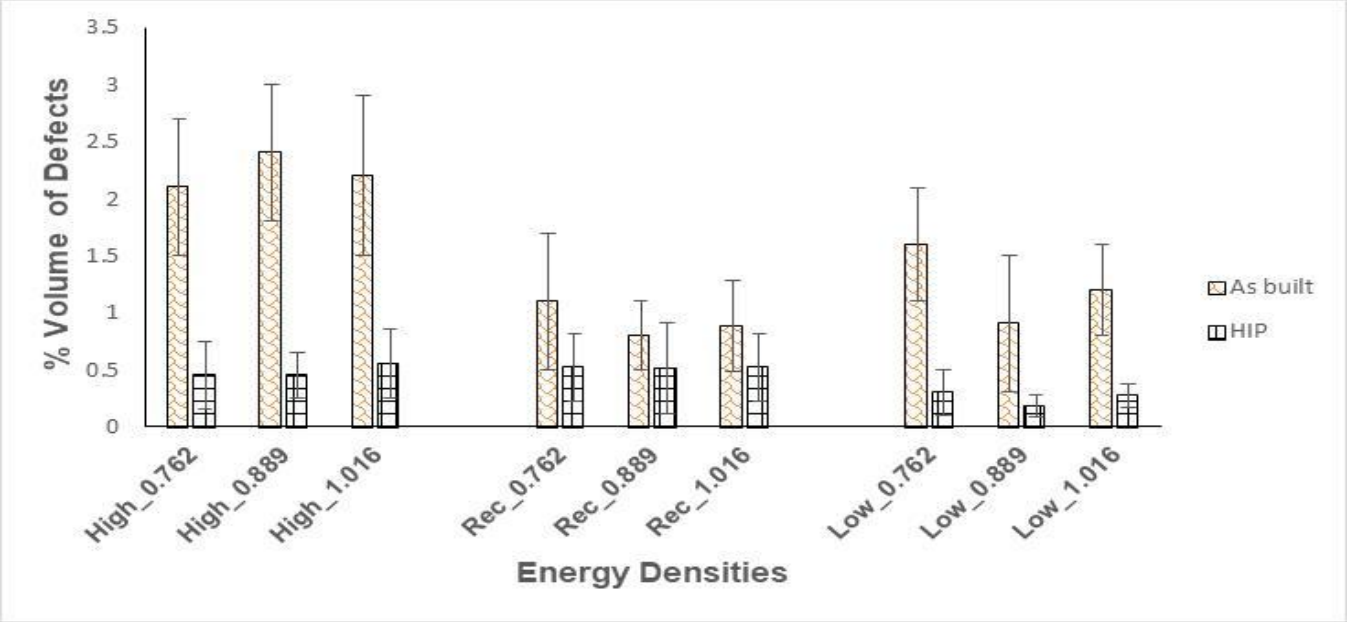


Figure 2: Typical Optical & SEM Images of the microstructure in HIP coupons at different Energy Densities

4.0 CONCLUSIONS

The effect of carefully designed process optimization parameters on AM manufactured straight wall Co-Cr Alloy has been microstructurally evaluated for defects, micro-hardness, and surface roughness. Major conclusion from the evaluation includes:

1. Although porosity is not detected by LPI in thin wall coupons produced, careful microstructural analysis of selected coupons based on process optimization parameters reveals defects of various sizes, shapes, and morphology.

2. The magnitude of Energy Densities (ED) is the most important factor that influences the % volume of defects in AM Co-Cr alloy. The baseline manufacturer recommended processing parameters induce the lowest % volume of defects in the AM Co-Cr alloy.
3. Post-processing treatment, HIP, designed to reduce porosity/defects is highly effective in reducing % volume of defects in the AM Co-Cr alloy irrespective of the initial Energy Densities in the as-built AM coupons.

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REFERENCES

Asala, G., Khan, A. K., Andersson, J., & Ojo, O. A. (2017). Microstructural analyses of ATI 718Plus® produced by wire-ARC additive manufacturing process. *Metallurgical and Materials Transactions A*, *48*(9), 4211-4228.*Atkinson, H.V., Davies, S. Fundamental aspects of hot isostatic pressing: An overview. Metallurgical and Materials Transactions. A. 31 (12): 2981–300.*

Choi, J., & Chang, Y. (2005). Characteristics of laser aided direct metal/material deposition process for tool steel. *International Journal of Machine Tools and Manufacture*, *45*(4-5), 597-607.

Cleary, P. W., & Sawley, M. L. (2002). DEM modelling of industrial granular flows: 3D case studies and the effect of particle shape on hopper discharge. *Applied Mathematical Modelling*, *26*(2), 89-111.

Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, *81*(1-4), 465-481.

Frazier, W. E. (2014). Metal additive manufacturing: a review. *Journal of Materials Engineering and Performance*, *23*(6), 1917-1928.

Gong, H., Rafi, K., Gu, H., Ram, G. J., Starr, T., & Stucker, B. (2015). Influence of defects on mechanical properties of Ti–6Al–4 V components produced by selective laser melting and electron beam melting. *Materials & Design*, *86*, 545-554.

Karapatis, N. P., Egger, G., Gygax, P. E., & Glardon, R. (1999). Optimization of powder layer density in selective laser sintering. In *1999 International Solid Freeform Fabrication Symposium*.

Kim, F. H., Moylan, S. P., Garboczi, E. J., & Slotwinski, J. A. (2017). Investigation of pore structure in cobalt chrome additively manufactured parts using X-ray computed tomography and three-dimensional image analysis. *Additive Manufacturing*, *17*, 23-38.

Kong, C. Y., Carroll, P. A., Brown, P., & Scudamore, R. J. (2007, May). The effect of average powder particle size on deposition efficiency, deposit height and surface roughness in the direct metal laser deposition process. In *14th International Conference on Joining of Materials*.

Zhang, Y., Wei, Z., Shi, L. and Xi, M. (2008). Characterization of laser powder deposited Ti–TiC composites and functional gradient materials. *Journal of materials processing technology*. 206, 438–444.

Zhong, C., Gasser, A., Schopphoven, T., & Poprawe, R. (2015). Experimental study of porosity reduction in high deposition-rate Laser Material Deposition. *Optics & Laser Technology*, *75*, 87-92.