Effect of Process Optimization Parameters and Hot Isostatic Pressing on Microstructure and Hardness of Additively Manufacture Co-Cr 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. Commercially, it was 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 in the as-built coupons when compared to the recommended OEM's benchmark parameters. However, after HIP, the % volume fraction of defects reduces significantly, and the microstructure is homogenized. Furthermore, the hardness value (strength) of the test coupons manufactured using the recommended OEM's laser parameters is comparable to those obtained in the low ED input test coupons after HIP; which could be utilized to enhance productivity. In addition, the surface roughness of the low ED input parameter coupons after HIP is similar to the coupons produced using the OEM's laser parameters assessed with light optical magnification image evaluation. HIP can be an excellent post-processing method to reduce internal Co-Cr defects for a given range of laser energy densities in metal additive manufacturing at increased build speeds.

Keywords: Additive manufacturing, DMLS, Defect, Hot Isostatic Pressing, Energy Density, CoCr, Hardness, Laser parameters

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 that are almost impractical to fabricate by other manufacturing processes. This process involving the sequential adding 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 [1]

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 [2-11]. Different techniques are currently being used for AM of metallic products and one of these is the powder bed fusion (PBF) process technologies. In this technology, the additive material (powder form) 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 [12].

Since material properties are inherently controlled by their microstructure, an in-depth understanding of how material microstructure is influenced by AM process parameters is fundamental to engineer desirable properties by this emerging technology. It has been found that one of the key microstructural features in metallic products produced by powder bed fusion (PBF) and which could have dire detrimental effects on mechanical properties, such as, tensile, fatigue and impact toughness is porosity [13-16]. Accordingly, an adequate understanding of microstructure in terms of processing parameters variables that can affect pore formations and possible effective measures that can be taken to eliminate and or reduce porosity are crucial to producing metallic products with reliable properties and performance by the AM technique.

Precision ADM is a Canadian company that helps their customer companies to take advantage of advanced technologies that enable manufacturing of parts that are stronger and lighter and at higher production rate and lower costs without undue burden to the environment. One of these key advanced technologies is the additive manufacturing (AM) process. Precision ADM have used laser metal powder bed fusion (PBF) AM method 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.

Materials and Methodology

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 (LED) parameters, OEM recommended parameters and High Energy Density parameters. The Co-Cr powder with proprietary chemical composition was sourced from 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 (Fig. 2) and then an identical build was reprinted to undergo Hot Isostatic Pressing (HIP). After production and subsequent HIP of one set (150 coupons), both the as-built and HIP coupons were EDM machined and subjected to one of the oldest, simplest but reliable non-destructive test (NDT) methods, Liquid Penetrant Inspection (LPI) at Magellan Aerospace, Winnipeg, Manitoba. Three cross-section image each were capture using a Light Optical Microscope (OM) and Scanning Electron Microscope (SEM) at 200X and 500X magnification respectively from transverse sections across the built (Z) direction of selected coupons. 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. Microhardness 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 microhardness were determined from an average value of 20 data points.

Table 1. Design of Experimental Parameters

Energy Densities Parameters	LED	OEM	HED
Part Thicknesses (t) (inches)	0.03/0.035/0.04	0.03/0.035/0.04	0.03/0.035/0.04
Stripe Scan Power (P) (Watts)	145 – 245		
Stripe Scan Speed (V) (mm/s)	400 – 1200		
Energy Densities (P/V)	0.5	1	2.5

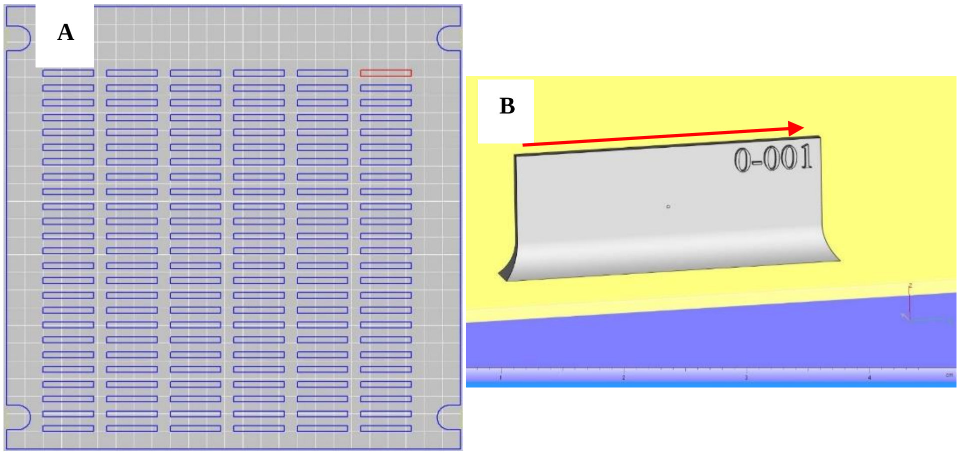

Figure 1: (A) shows the built plate design/layout, and (B) typical coupon design with an identification mark (arrow show the scanning direction)

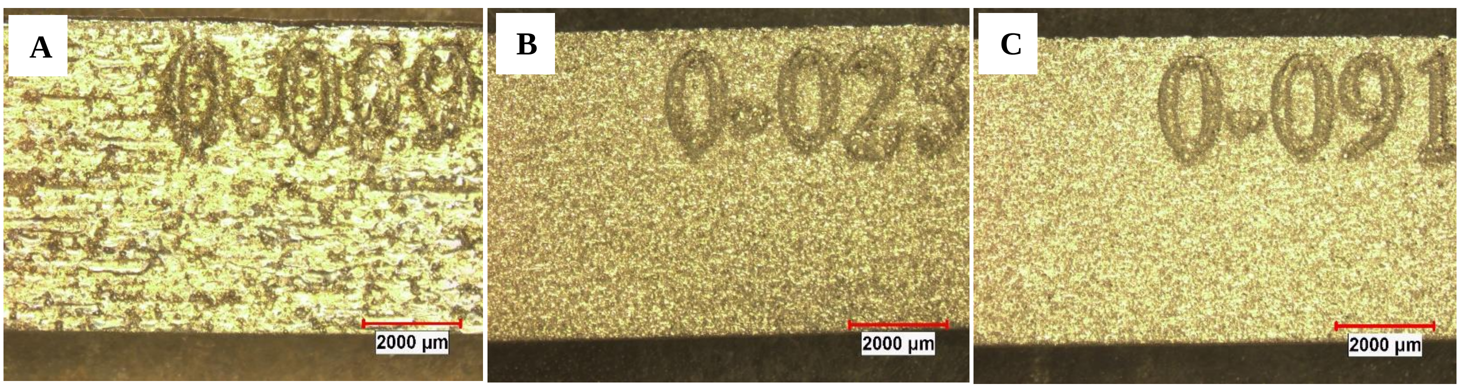

Figure 2: Typical Optical Image of the as-built coupon after EDM removal from build platform (A) HED, (B) OEM (C) (C) LED, all at baseline thickness of 0.035 inches

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 at Magellan Aerospace passed the LPI test. Liquid penetrant inspection method was used to reveal surface discontinuities by bleed-out of a colored or fluorescent dye from the flaw based on the ability of a liquid to be drawn into a clean surface discontinuity by capillary action [17-18]. 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 further, microstructural issues that have been previously reported in the literature [13-16] 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 [19-21], however, limited information has been reported on the post-processing AM treatment effect of HIP.

Selected coupons from the as-built and HIP AM coupons were section transversely to the built direction and examined using a light optical microscope (OM) and scanning electron microscope (SEM) for microstructural features. Irrespective of the energy densities process parameter used, defects ranging from porosity to incompletely melted powder was noticed at different volume fraction in all sectioned coupons. It is generally accepted in AM techniques that porosity can result from unstable melt pool (keyhole) formation, causing the melt pool to collapse in, and resulting in pores of inert gas or voids [22].

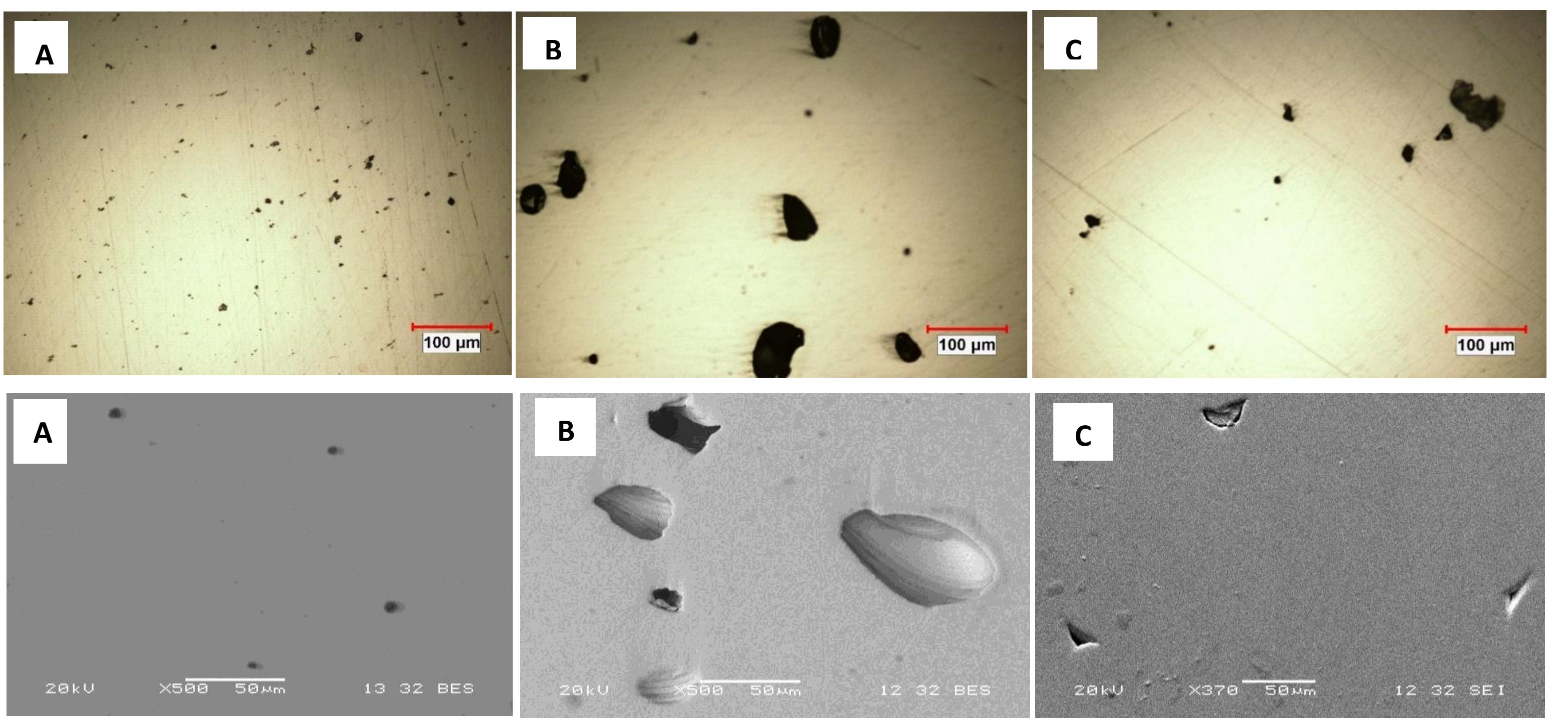

Figure 3: shows typical Optical and SEM Images of Defects in (A) OEM (B) HED and (C) LED coupons, all at constant thickness 0.035 inches

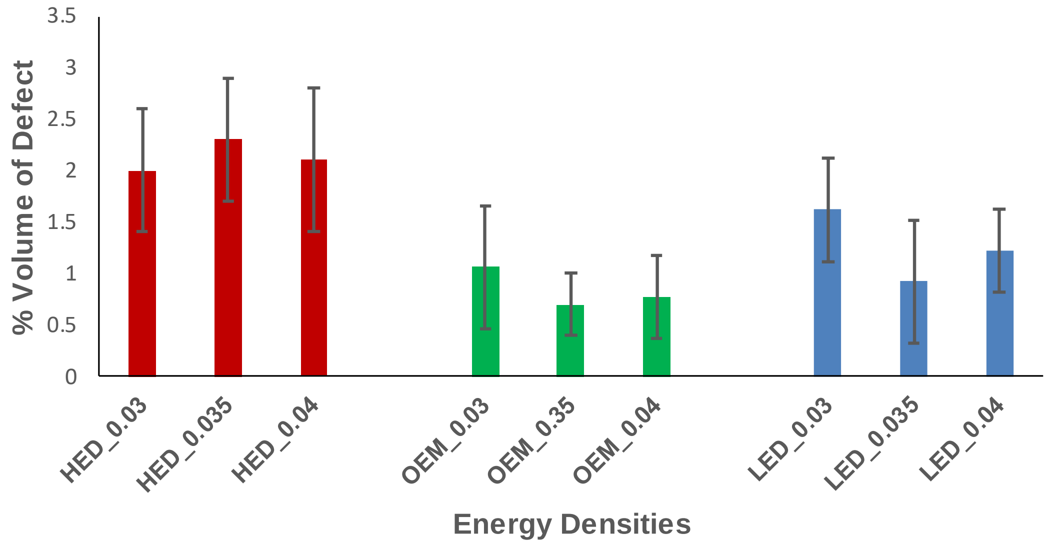

Figure 4: Summary of the combined effect of Energy Densities and Thickness variation on % Volume of defects in Co-Cr Alloy

Figure 4 illustrates the combined effects of energy densities and thickness variation. Evidently, the OEM standard parameters induce the lowest % volume of defects compared to the LED and HED parameters, involving processing at low speed and laser power or high speed and high laser power, respectively. In addition, the thickness variation of the coupons has no well-defined effect on % volume of defects.

As previously mentioned, the as-builts coupons were subjected to Hot Isostatic Pressing (HIP), and subsequent to the HIP treatment, the coupon was LPI tested and passed. Remarkably, the % volume fraction of defects reduced significantly, more so, the effect of HIP treatment appears more pronounced in the HED and LED AM coupons compare to the OEM baseline parameters (Fig. 5 & 6). While the reduction in % volume fraction of defects in the OEM baseline parameters is barely significant based on the standard deviation, the reductions are most significant in the HED and LED processing parameters, such that, the % volume fraction of defects are essentially comparable to the values obtained in the OEM baseline processing parameters. Hot isostatic pressing (HIP) is a manufacturing procedure used in reducing porosity of metals and increase density which ultimately improves the material's mechanical properties and workability [23]. The HIP process subjects a component to both elevated temperature and isostatic gas pressure in a high-pressure containment vessel at between 7,350 psi (50.7 MPa) and 45,000 psi (310 MPa). An inert gas at high pressure is used so that the material does not chemically react during the process as pressure is applied to the material from all directions (isostatic). During processing, soaking temperatures ranges from 900 °F (482 °C) to 2,400 °F (1,320 °C) depending on alloy type. The simultaneous application of heat and pressure (HIP) eliminate/reduces considerably, internal voids and micro-porosity through a combination of plastic deformation, creep and diffusion bonding.

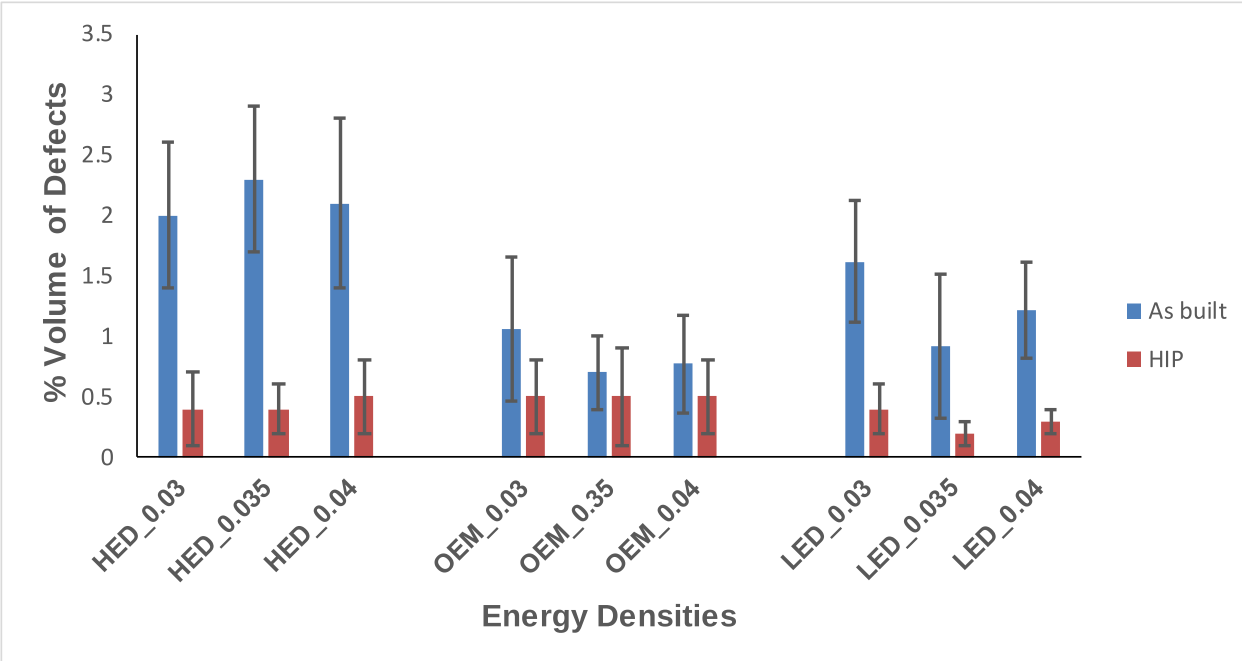

Figure 5: Effect of HIP on % Volume Fraction of Defects

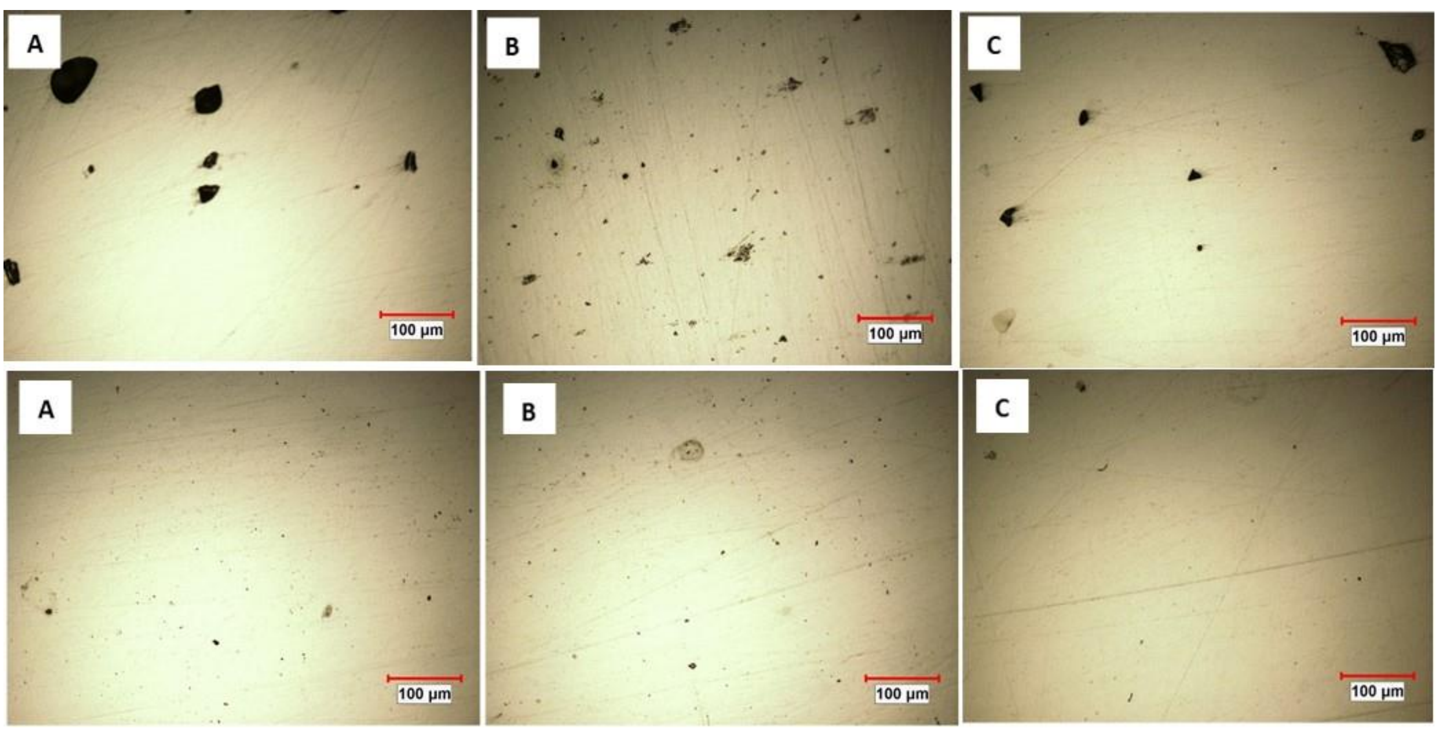

Figure 6: As polished Optical Images of Defects in the as-built and HIP coupons at different Energy Densities in (A) HED, (B) OEM and (C) LED, all at constant thickness 0.03 inches

3.2 Effect of Optimization parameters on Microstructure and Hardness

Material properties, strength (hardness) inclusive, are inherently controlled by microstructure, therefore 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. 7a-b showed the microstructures of the As-built and HIP alloy.

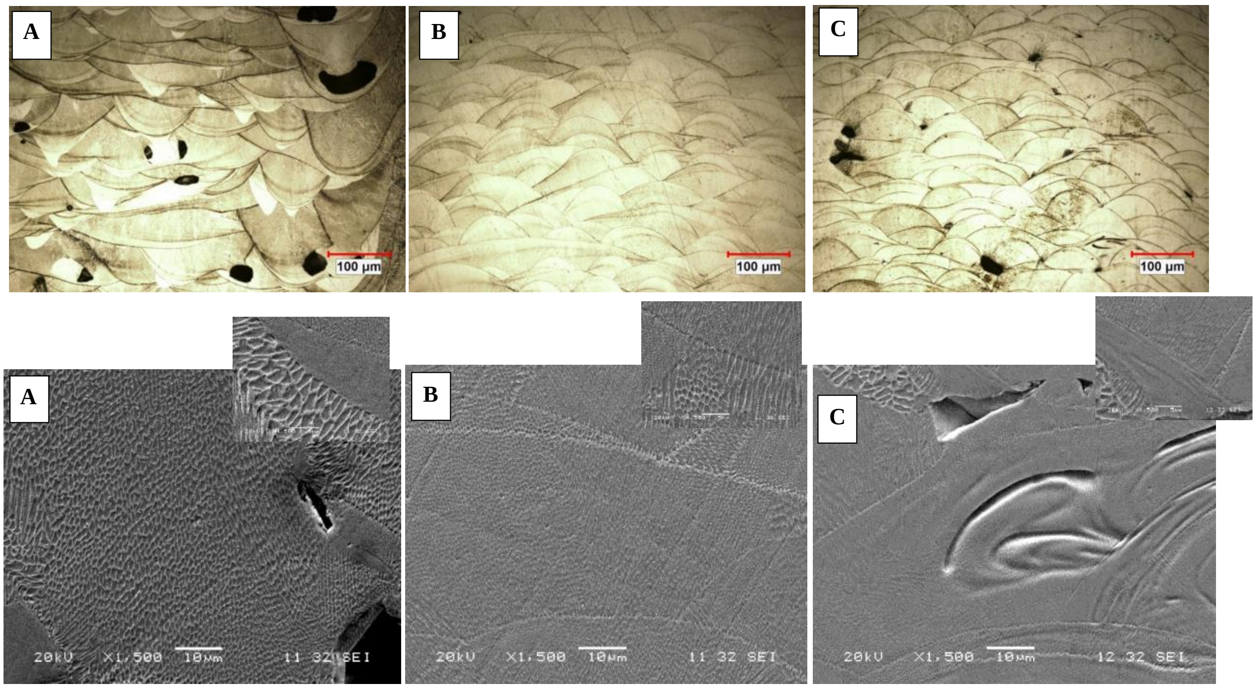

Figure 7a: Typical Optical & SEM Images of the microstructure in as-built coupons at different Energy Densities in (A) HED, (B) OEM and (C) LED, all at constant thickness 0.035 inches (inserts are high magnification SEM image of As-built coupons)

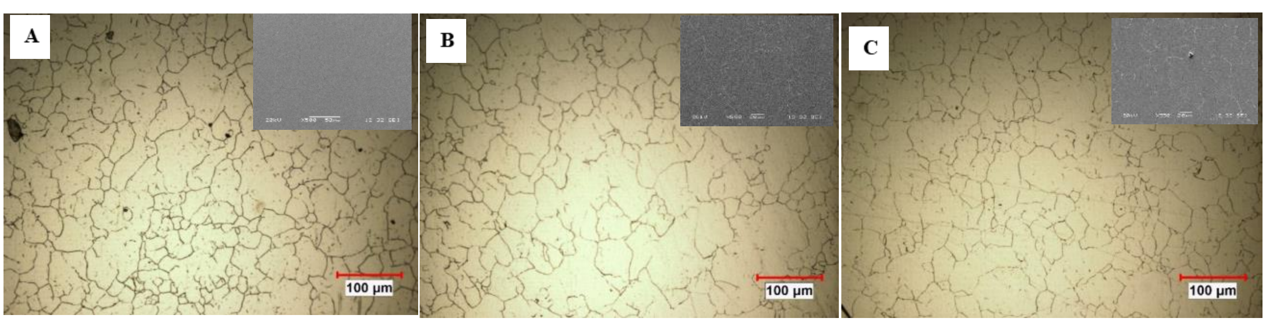

Figure 7b: Typical Optical & SEM Images of the microstructure in HIP coupons at different Energy Densities in (A) HED, (B) OEM and (C) LED, all at constant thickness 0.035 inches (inserts are high magnification SEM image of HIP coupons)

The relatively small molten pool formed during PBF processing of the alloy and the consequent fast solidification in a shielding vacuum environment may be attributable to the more uniform solidification profile observed in this work. In the current study, the built direction of the different energy densities is the same (Z-direction) and as such there is no major difference in the morphology of the as-built microstructure aside the dendritic spacing, which is coarse in the HED as-built coupon and much finer in the LED (SEM insert) processing parameters while the OEM processing parameter is intermediate. Samples built with different built direction have been reported to have elongated grains along different built direction resulting in anisotropic properties [1]. Furthermore, after the post-processing HIP treatment, the microstructure of all the coupons having different initial processing parameters is homogenised and the grain size are comparable irrespective of the initial energy density in the as-built AM coupons.

Microhardness evaluation of the various energy densities processing parameters coupon showed that hardness of the HED, OEM and LED as-built coupons are generally comparable and after post-treatment HIP, the hardness are also comparable (Fig. 8). In essence, there is no microhardness variation in the homogenised grain microstructure of solid solution strengthening Co-Cr alloy and as such, the mechanical properties (strength) of the AM LED as-built and HIP coupon can favourably compare and or serve as a good substitute to the OEM baseline processing parameters properties with enhanced productivity.

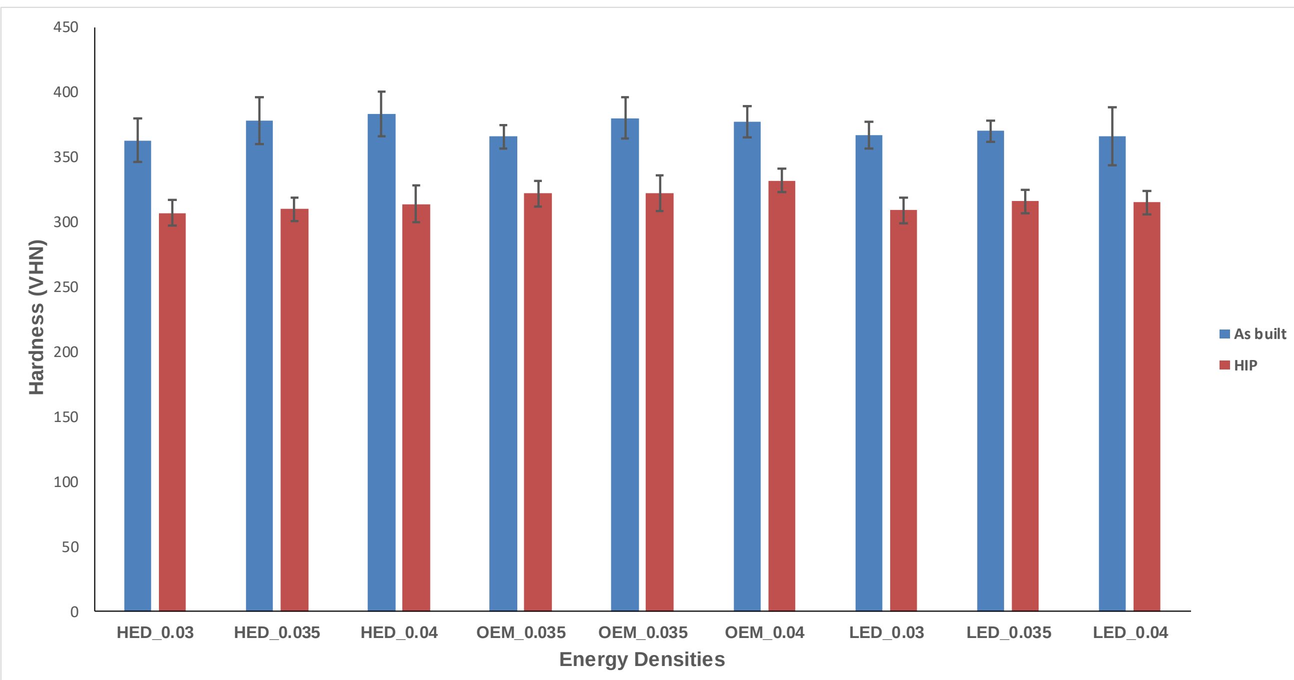

Figure 8: shows the Microhardness profile of the as-built and HIP coupons at HED, OEM and LED, at various thicknesses.

Surface preparation in term of roughness is the most critical step during liquid penetrant inspection (LPI) testing. As previously mentioned, LPI is a simple but reliable non-destructive test (NDT) method commonly used in ensuring/certifying the quality of AM components [18]. Therefore, the effect of the different energy densities on the surface roughness of the Co-Cr alloy was evaluated in the study. Figure 9 showed the effect of the different energy densities on the surface roughness of the Co-Cr alloy in As-built and HIP condition.

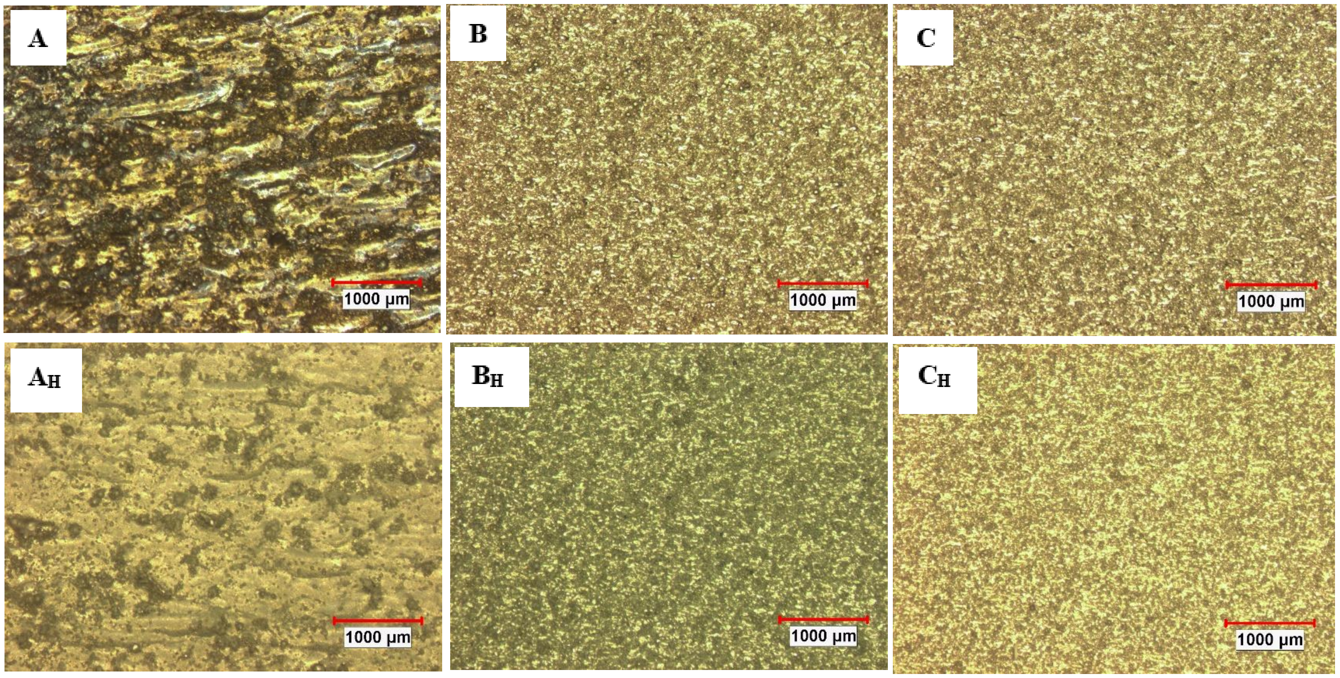

Figure 9: Effect of Energy densities on Surface Roughness of as-built and HIP coupon in (A) HED (B) OEM, and (C) LED, all at baseline thickness of 0.035 inches

Surface roughness in the HED (A) is high and significantly poor compared to that in the OEM and LED coupons (B & C) where the surface roughness is appreciably finer and comparable based on Light Optical Magnification Image evaluation. Post-processing treatment, HIP, of the AM coupons, moderately improved the surface roughness in the HED (A_H). Although HIP appears relatively effective to achieve reduced porosity, homogenized microstructure, and normalised grain size in the as-built coupons, it is however not sufficient to normalise the surface roughness in all coupons irrespective of the initial 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, microhardness, and surface roughness. Major conclusion from the evaluation include:

1. Based on thin walled manufactured AM coupons (ranging from 0.030in to 0.040in), LPI test did not detect through-part porosity in all the 300 coupons tested
2. Although porosity is not detected by LPI, careful microstructural analysis of selected coupons based on process optimization parameters reveals defects of various sizes, shapes, and morphology.

3. Based on the variation in coupons thickness at constant energy density, there is no evidence to suggest that thickness has a well-defined effect on % volume of defects in the AM Co-Cr alloy.
4. The magnitude of Energy Densities (ED) is the most important factor that influences the % volume of defects in AM Co-Cr alloy. The baseline OEM standard processing parameters induce the lowest % volume of defects in the AM Co-Cr alloy.
5. 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.
6. HIP had the greatest affect on the High Energy Density (HED) and Low Energy Density (LED) optimization parameters compared to minimal affect it has on the baseline OEM processing parameters.
7. HIP homogenised the microstructure and normalised the grain size such that they are comparable irrespective of the initial energy densities or coarse/fine dendritic structure in the as-built AM coupons
8. HIP designed to reduce porosity/defects is not sufficient to normalise the surface roughness in all coupons irrespective of energy densities.
9. There is no microhardness variation in the as-built and homogenised grain microstructure of solid solution strengthened Co-Cr alloy. Therefore the mechanical properties (strength) of the AM LED as-built and HIP coupon compares favourably and serves as good substitute to the OEM baseline processing parameters properties with enhanced productivity.

5.0 Acknowledgment

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