Post-processing of direct metal deposited AlCrCoCuFeNi HEA using centrifugal barrel finishing

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Abstract. Stainless steels, Ni-based alloys, Ti-based alloys, and more recently high entropy alloys have been used in the aerospace industry to improve the exterior properties of components and coatings that require a fine surface finishing with over high temperature range. High- entropy alloys (HEA) have become a ground-breaking research field that provides solutions for structural/ functional materials in the aerospace industry. These alloys, fabricated via direct metal deposition, have better properties than those produced by arc melting. However, the poor surface finish acquired by the layer-by-layer laser deposition process fails to meet the industrial requirements. The implementation of surface treatment by centrifugal barrel finishing is employed to improve the surface roughness of AlCoCrCuFeNi laser deposited HEA. The results have shown a minimum surface roughness decrease of 40%. Thus, an improved surface finish was achieved.

1. Introduction

Conventional alloys such as Cu-based alloys, stainless steels, Ni-based alloys, and Ti-based alloys have been used for years but with time they have been found to have limitations, including restrictions in the number of possible compositions [27]. Today, High entropy alloys (HEA) are becoming a recognisable phenomenon in the material science fraternity. HEA is novel concept, designed to supersede conventional alloys' potential [4]. Aluminium alloys have been used over the years in aircraft engines by virtue of its low-density characteristics, but the inability to withstand high temperatures has limited its application [3]. Dada *et al.*[6] conducted a comparative microstructural and corrosion behaviour HEA study between AlCoCrFeNiCu and AlCoCrFeNiTi. The study revealed that even though Ti-based HEA displayed high corrosion resistance compared to Cu-based HEA, the resistance of both these alloys was still higher than that of traditional alloys. Yeh *et al.*[31] defined HEAs as metallic materials that consist of five or more principal elements in equiatomic or close to equiatomic atomic ratios, with an atomic percentage ranging between 5 % and 35 %. HEAs have become a ground-breaking research field that provides solutions to complex problems in the aerospace industry [28]. The industry requires improvement in the application of structural materials that are well-functioning at a low cost, for example, in turbine blades [3].

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This results in the deployment of functional coatings, which are applications driven, particularly for surface protection resulting in an improved mechanical and chemical properties [18].
Environmental degradation of the surface subjected to high temperature, abrasion, fatigue, erosion, gas and hydro-abrasion etc. leads to surface wear damage, causing a reduction of the service life [10]. Laser surface cladding of HEA alloys has been shown to improve and/or enhance surface properties in tribological applications. Functional components by means of laser additive manufacturing (AM) using HEAs materials, have also been receiving great attention in recent times [20, 21]. The fabrication of metal parts obtained using laser-based additive manufacturing (LBAM) techniques such as selective laser melting (SLM), direct metal deposition (DMD), laser engineering net shaping (LENS) and wire-laser additive manufacturing (WLAM) usually produce a poor-quality surface finish, resulting from the layer-by-layer process which fails to fulfil industrial requirement [13,25]. Guo *et al.*[12] machined CoCrFeMnNi HEA, following fabrication using a selective laser melting (SLM) process. The surface finish could however not fulfil industrial requirements. Poor surface quality often deteriorates over time due to environmental factors such as the oxygen present in air and temperature [15]. The deployment of post-processing methods creates a reflective surface to prevent the contamination on the surface created by environmental substances [15]. There are various post-processing treatments used in AM metallic components to reduce surface roughness, such as electropolishing (EP), sandblasting, chemical polishing, centrifugal barrel finishing (CBF), ultrasonic polishing and oxidation polishing [13, 19].
CBF post-processing treatments have shown promising results in the deburring of compounds. The CBF operation requires the loading of a component in a rotating barrel that consists of ceramic media, polishing liquid and water. The rotation of the barrel generated an abrasion action that permits the micro-removal of the material [1]. The CBF operation enables the polishing of complex shapes and sizes with the added benefit of low maintenance costs [11,30]. De Beer *et al.*[9] polished low surface manufactured Alumide® jewellery in a tumbler using an abrasive media and obtained a smooth attractive metallic lustre surface. Tokarewicz *et al.*[27] developed barrel finishing methodologies to condition Ti6Al4V and inconel718 for complex geometries fabricated using SLM processes. The study confirmed a successful reduction of the surface roughness. Tsai *et al.*[28] investigated barrel finishing on wire arc additive manufactured (WAAM) components and found that their barrel finishing setup could successfully be used for material cleaning, material removal, deburring, and descaling of WAAM parts. However, in this process of polishing, there is a need for the operator to be highly involved, due to the manual loading and unloading of the sample(s).
The purpose of the study is to demonstrate the application of the CBF method for surface improvement on DMD AlCrCoCuFeNi HEA at different scanning speed. Optimum barrel finishing parameters were determined based on previous studies [13]. There is limited scientific research and mathematical model publications in the area of mass finishing with respect to HEAs.

2. Methodology and Materials

2.1 Materials

The chemical composition of commercially available AlCrCoCuFeNi HEA powder, used in this study, shown in Table 1. The as-received powder was supplied by F.J. BRODMANN & CO., L.L.C SUPPLIERS with each element purities above 99.9% and particle size distribution in the range of 32-140 µm. Figure 1 illustrates the scanning electron microscope

(SEM) image of the AlCrCoCuFeNi HEA powder. Before deposition, the Ti6Al4V baseplate was sandblasted to promote bonding between the alloy and the baseplate.

Table 1. Chemical Composition of AlCrCoCuFeNi Powder (wt. %)

Al	Cr	Co	Cu	Fe	Ni
25.52	12.28	27.57	1.29	30.02	3.32

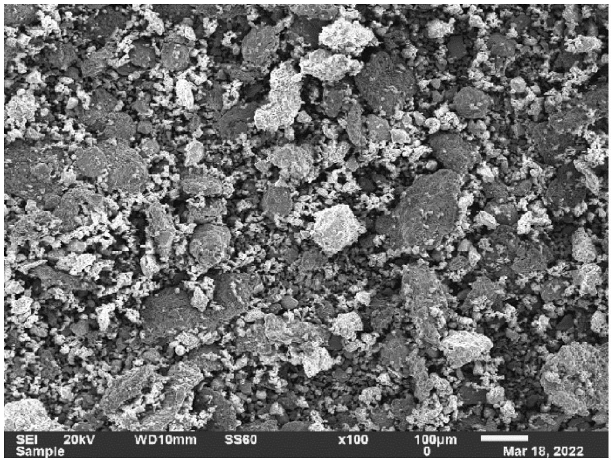

Figure 1. SEM Image of AlCrCoCuFeNi Powder

2.2 DMD Process

A KUKA robot [4, 26] with a 3 kW IPG [26] continuous fibre laser was used to deposit the AlCoCrCuFeNi HEA powder into an argon-controlled system, in order to protect the surface from oxidation. Six cubic DMD samples in the size 20 mm × 20 mm ×15 mm were fabricated at the National Laser Centre Council for Scientific and Industrial Research, South Africa. These samples will serve to demonstrate the application of the CBF method for surface improvement. Optimised parameters (see Table 2) based on previous studies were used [4]. The deposition process was carried out in a double crucible electric lifting melting furnace preheating furnace with model number RR3-50K at 600˚C [4].

Table 2. Laser process parameters of AlCrCoCuFeNi [4]

Sample	Laser Power (W)	Scanning speed (m/min)	Powder feed rate (rpm)	Beam diameter (mm)
a_2	1200	0.48	2.5	2
a_3	1200	0.48	2.5	2
b_2	1200	0.60	2.5	2
b_3	1200	0.60	2.5	2
c_2	1200	0.72	2.5	2
c_3	1200	0.72	2.5	2

2.3 Post-processing

The primary objective of this experiment is to determine the barrel finishing process for AlCrCoCuFeNi HEA parts. An industrial barrel finishing machine, CB320-CBF from the National Laser Centre Council for Scientific and Industrial Research, South Africa, was used to treat sample a_2, b_2 and c_2 using fixed machine parameters of 85 rpm for 14 hours. The finishing operation is performed on account of rotary movement with abrasive tumbling media to create a high centrifugal force and sliding friction. Angle cut ceramic media, with nominal dimensions of 10 mm x 10 mm was used. Figure 2 shows images of the CB320-CBF and the ceramic media used. The total quantity of the samples (a_2, b_2 and c_2), abrasive media, LC-13 polishing lubricant and water put in the tumbler is 11kg, accounting for the load of 50% volume in the tumbler. The change of water and LC-13 polishing liquid was executed after 14 hours to further improve the surface finish of the samples.

I

II

Figure 2. CB320-CBF Machine (I) and ceramic media (II)

2.3.1 Surface analysis

The surface roughness of the treated (a_2, b_2, c_2) and untreated (a_3, b_3, c_3) samples were measured before (a_3, b_3, c_3) and after (a_2, b_2, c_2) polishing and further analysed using a Taylor Hobson Strutronic S-100 series – roughness tester [24]. The surface morphology and composition were examined JEOL-JSM-6010PLUS/LA Analytical Scanning Electron Microscope (SEM) equipped with Energy dispersive X-ray spectroscopy (EDS) [7]. In addition, Gwyddion 2.9.32 software [29] characterised SEM images to obtain the topography and roughness profile of the samples.

3. Results and Discussion

Three samples were manufactured with DMD at three different scanning speeds. One sample at each scan speed was kept untreated (samples a_3, b_3, c_3) and the other samples were treated with CBF (samples a_2, b_2, c_2). The surface roughness of the untreated samples were measured to be a_3 = 13.78 µm, b_3 = 13.36 µm and c_3 = 17.36 and the treated sample a_2, b_2, c_2 was measured to be 7.63 µm, 5.59 µm and 5.68 µm respectively. The average surface removal trend per 3.5 hour is estimated to be 2 µm for a_2, 2 µm for b_2, and 3 µm for c_2 (see Figure 3). Insignificant improvement of the surface was observed after 14 hours of polishing time, consequently leading to a negligible surface progress. This was attributed to the excessive impact caused by the centrifugal force which sequentially accumulated abrasiveness at the boundary of the barrel. Thus, a change of water and LC-13 polishing liquid was implemented however the samples showed an insignificant improvement in the surface finish. Boschetto *et al.*[1] barrel finished selective laser melting (SLM) Ti6Al4V parts, the processing time took 24 hours to give sufficient result. Khan *et al.* [16] used CBF to polish wire + arc additive manufactured samples, the water induced the samples to corrode thus more time was required to remove the corrosion. The samples experienced an insignificant improvement in the surface finish after 8 hours. The polishing of AlCrCoCuFeNi HEA gave an improved surface quality while experiencing low disorientation as opposed to the conventional alloys.

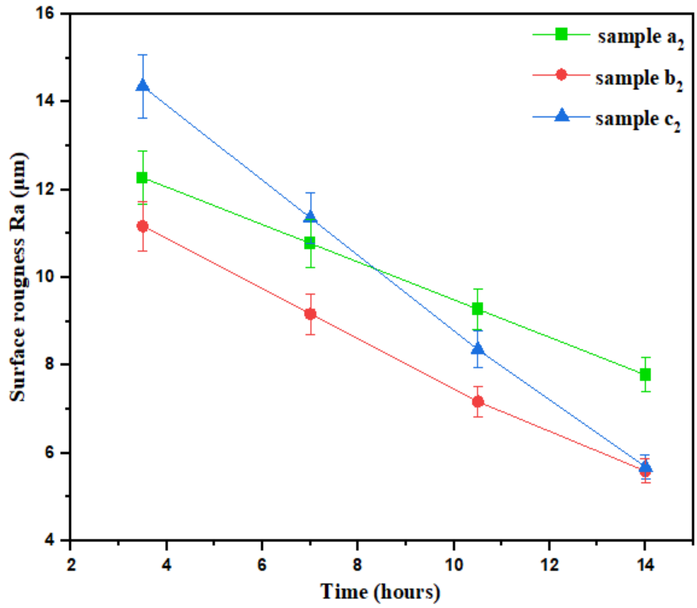

Figure 3. Surface roughness variation development with time at 85rpm

Figure 4 (i,) (ii) shows images of the treated CBF and untreated as-built samples. The barrel finishing process removed sloping plane 3i (A) (C) on the sides caused by the balling-effect. It could be seen that the finishing process removed the oxides effectively and additionally removed the some spatters 3i (A) (B).

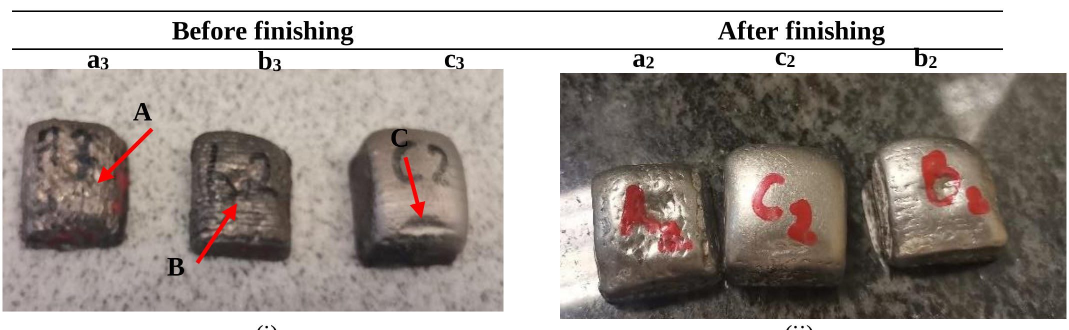

Figure 4. DED untreated as-built samples (i) and CBF treated samples (ii)

Figure 5, presents the average surface roughness comparison between as-build and CBF post-processing samples. From Figure 5 it can be observed that the as-built samples had a higher surface roughness, Ra, in comparison to the CBF polished samples. The low scan speed sample produced a higher surface removal and the high scan speed removal resulted in a lower surface removal. Hardinnawirda *et al*. [14] found that cooling rate have a significant effect on the mechanical integrity of the joint and as the cooling rate increase, the strength increases. Therefore, the increase in scanning speed is associated with an increase in the rapid cooling rates [5]. Thus, sample c_2 producing a lower surface removal because of the acquired strength.

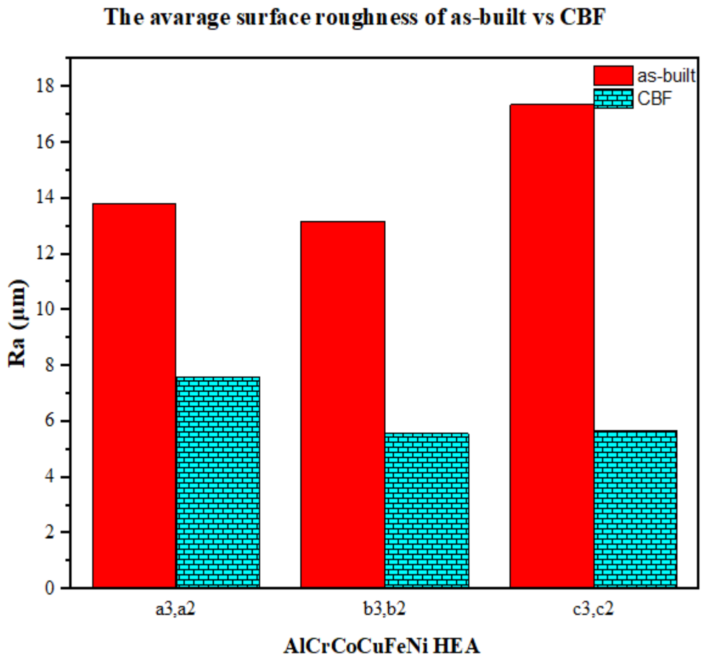

Figure 5. Graphical comparison between as-built to CBF

Figure 6 exhibits SEM images of CBF treated and untreated as-built samples. The untreated surface is affected by the balling effect which is more evident in sample c_3, thus leading to a greater Ra value. The polished samples contain embedded scratches Figure 6 (A, B, C), since the surface removal action is based on rubbing and deburring. The CBF process produced reduced surface roughness therefore smooth surface was obtained. The EDS analysis of the CBF polished samples confirms the chemical composition established in Table 1.

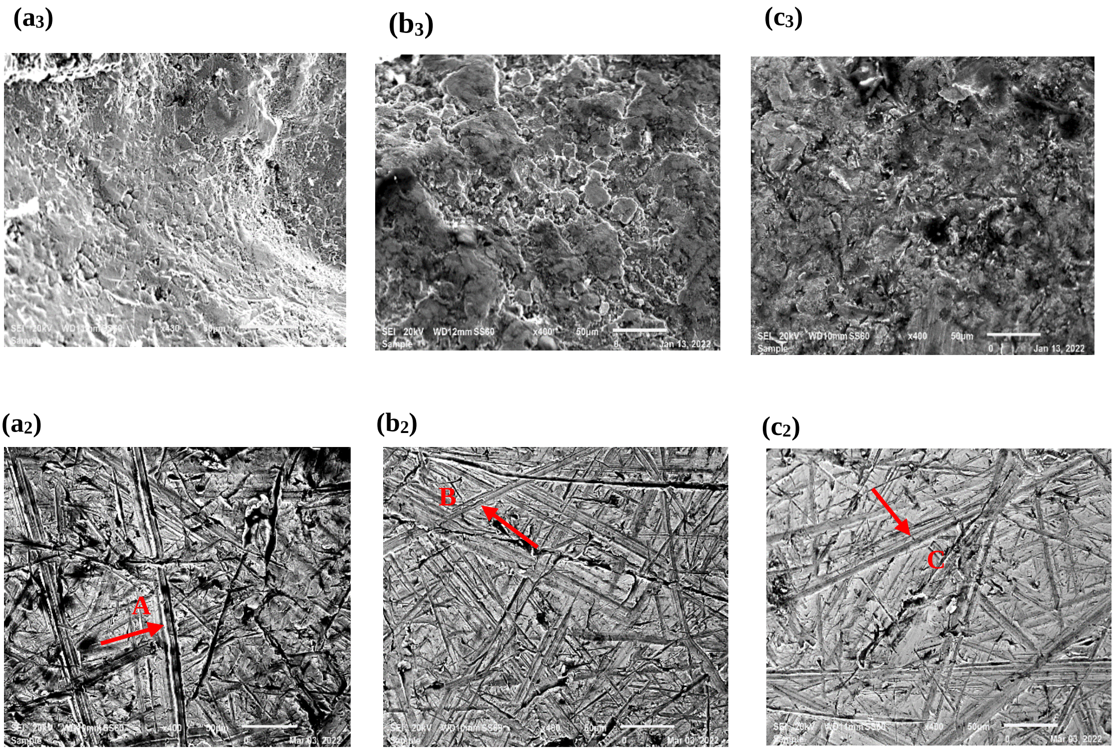

Figure 6. SEM images of untreated as-built samples (a_3,b_3,c_3) and treated CBF samples (a_2,b_2,c_2)

In Figure 6, samples a_3 and a_2 average surface roughness Ra is 13.78 µm and 7.63 µm respectively with the peak-to-valley, Rt, of a_3 = 159.55 µm and a_2 = 83.34 µm. The average roughness, Ra, was decreased by 55% Rt. Samples b_3 and b_2 had an Ra improvement of 13.17 µm to 5.59 µm for b_3 and b_2 respectively with Rt values of b_3= 131.85 µm and b_2= 74.49 µm amounting to a decrease of 42%. For samples c_3 and c_2 the Ra values decreased by 33% with the Ra values of 17.36 µm and 5.68 µm for c_3 and c_2 respectively. The Rt value was found to be: c_3= 168.47 µm and c_2= 64.06 µm. The as-built surface contains higher peak-to-valleys which dissolves to a lower surface area valley causing a polishing effect on the CBF surface [23].

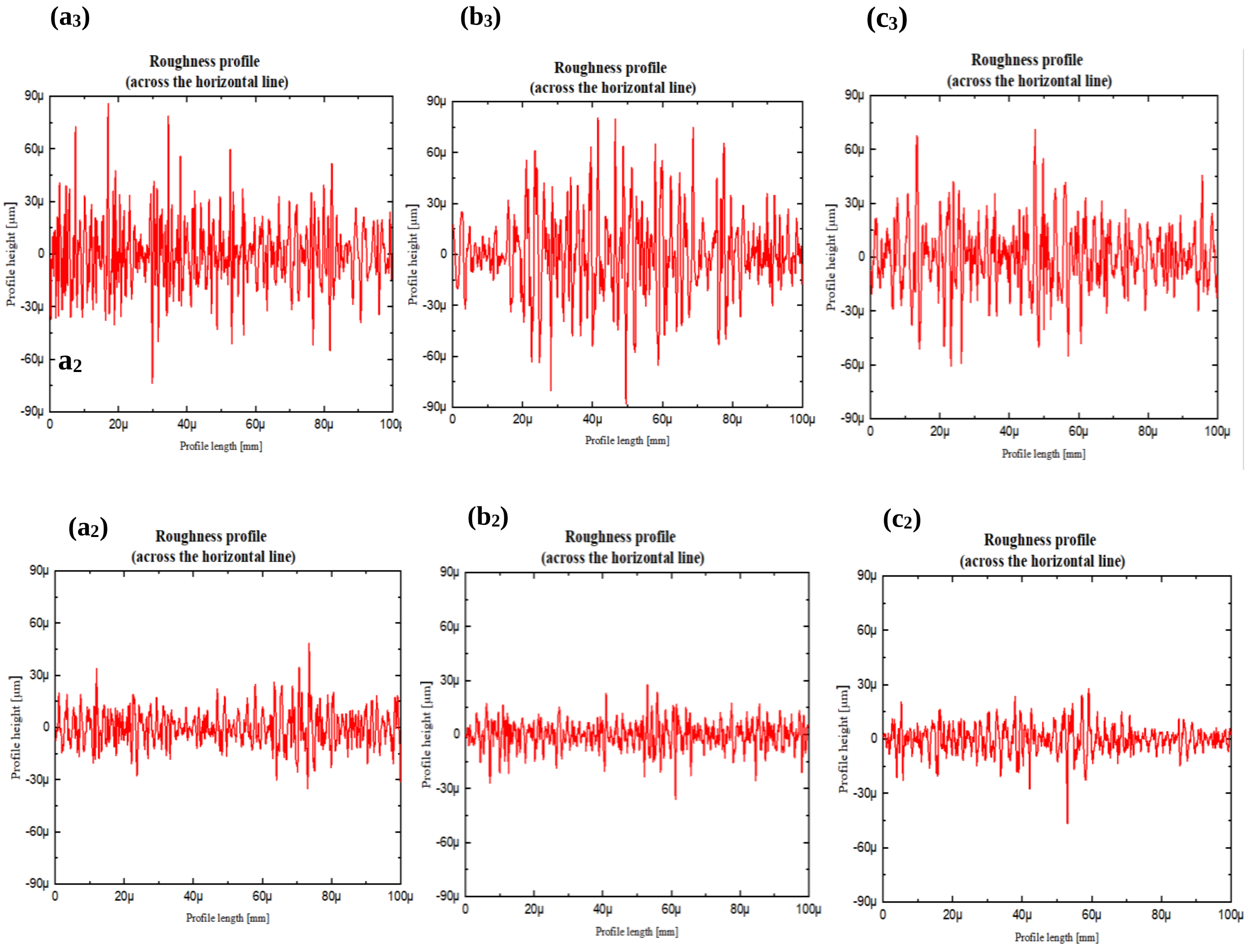

Figure 7. Roughness profile of the as-built (**a$_3$,b$_3$,c$_3$**) and CBF samples (**a$_2$,b$_2$,c$_2$**)

Figure 8, illustrates 3D topographical analysis for the as-built and CBF samples. There is a considerable difference in the peak-to-valley of the post-processing and as-built surface. The as-built sample a$_3$, b$_3$ and c$_3$ are characterised by the very high peaks-to-valley height rough surfaces are observed. After the 14 hour processing time CBF maps appeared to have an overall decreased peak-to-valley were a decrease of over 33% was observed. CBF produced samples which resulted in the smooth and improved surface quality of AM AlCoCrCuFeNi.

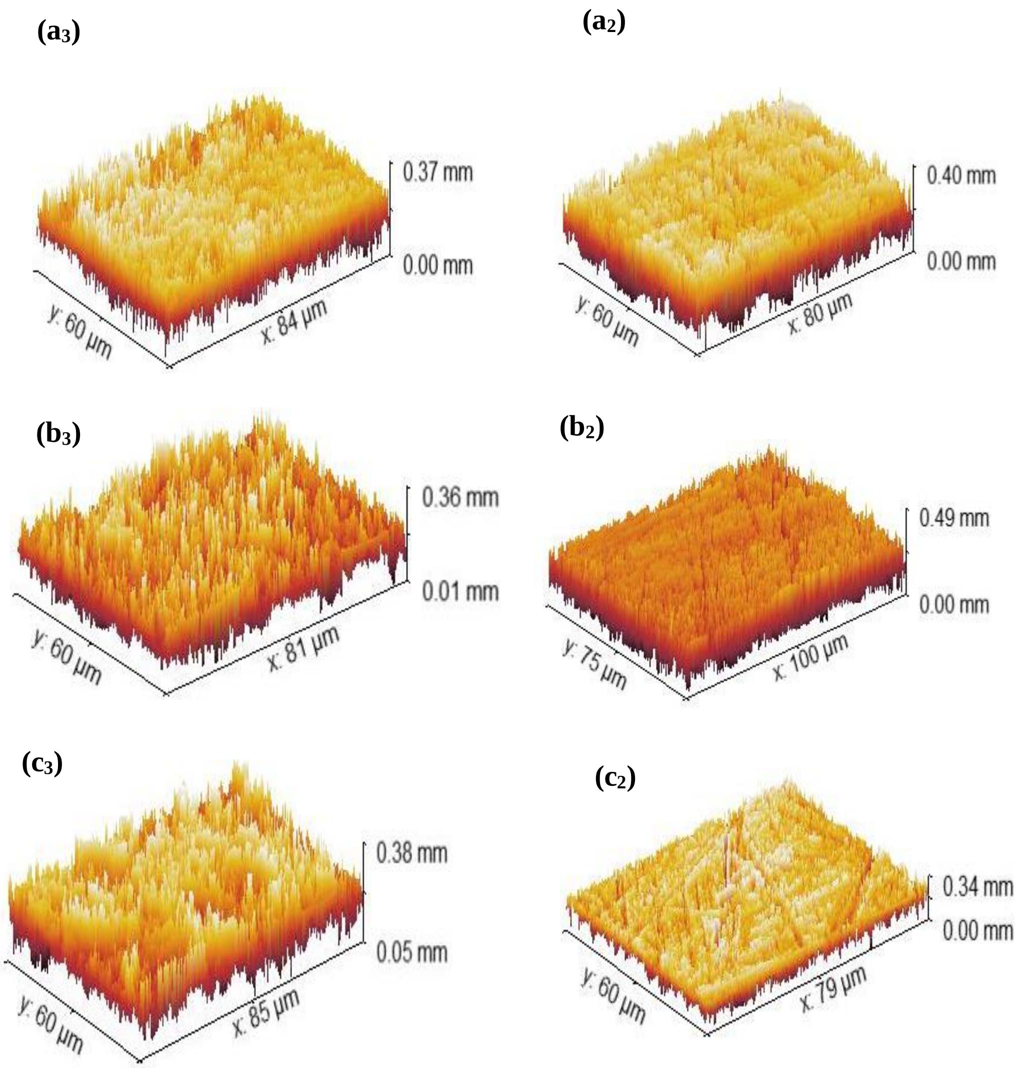

Figure 8. Three-dimension topographical representation of as-built (**a_3,b_3,c_3**) and CBF samples (**a_2,b_2,c_2**)

4. Conclusion

DMD plays a critical role in the production of complex parts, but the fabrication of surface quality remains a crucial aspect. This study investigated and analysed the CBF process of HEA samples.

The AlCrCoCuFeNi HEA fabricated at different scan speed and laser power, were treated using CBF post-processing methods to improve the external surface quality of the HEA. An improvement of 55% for a_2, 42% for b_2 and 33% for c_2 is observable. The CBF process on AlCrCoCuFeNi HEA has been found to produce an improved surface finishing with minimum complexity. CBF process produced smooth fine surface finish attributed to the process' easy sliding to all corners of the external surface. The scratched surface observed were caused by the ceramic media which could be avoided by changing to a less abrasive media (such as plastic media) at the final stages of polishing. The lower scan speed sample produced an improved post surface finish due to lower cooling rates. More parameter variation such as laser power range and time interval is recommended for future work to observe polishing development.

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