HIGH ENTROPY ALLOYS FOR AEROSPACE APPLICATIONS

Modupeola Dada, Patricia Popoola, Samson Adeosun and Ntombi Mathe

ABSTRACT

In the aerospace industry, materials used as modern engine components must be able to withstand extreme operating temperatures, creep, fatigue crack growth, cyclic and translational movements of parts at high speed and erosion. Therefore, the parts produced must be lightweight, have good elevated-temperature strength, fatigue, wear and oxidation resistance and resistant to chemical degradation. High Entropy Alloys (HEAs) characterizes the cutting edge of high-performance materials. These alloys are materials with complex compositions of multiple elements and striking characteristics in contrast to conventional alloys; their high configuration entropy mixing is more stable at elevated temperatures. This attribute allows suitable alloying elements to increase the properties of the materials based on four core effects. A slow diffusion rate, an increased lattice strain, high entropy of mixing and a cocktail effect gives tremendous possibilities as potential structural materials in jet engine applications. Researchers fabricate most of these materials using formative manufacturing technologies; arc melting, where the molten alloys are cast in a vacuum-sealed argon environment. However, the challenges of heating the elements together have the tendency to form hypoeutectic that separates itself from the rest of the elements and defects reported are introduced during the casting process. Nevertheless, Laser Engineering Net Shaping(LENS™) and Selective Laser Melting(SLM); a powder-based laser additive manufacturing process offers versatility, accuracy in geometry, rapid prototyping and fabrication of three dimension dense structures layer by layer avoiding wastes and human production errors. Fabrication of high entropy alloys as an advanced material for aerospace applications using laser additive manufacturing can ease the challenges of aero engines producing noise, large fuel consumption, emissions, thus, reducing repair and maintenance costs.

1. INTRODUCTION

There are three major components of the turbine engine; the compressor, the combustor, the turbine blade and the nozzle. In recent years, the aeronautic trade demands the advancements of new material for the aero-engine components characterized by thrust, weight, safety, fuel utilization, life cycle costs and environmental necessities[1]. Contemporary innovative advances and evolution in the aerospace industry require improvement and application of structural materials that would provide higher performance and will be cost-effective in fabrication and maintenance compared with existing parts. The choice of material relies upon the working conditions and an ideal alloy that could withstand an environment with extreme temperatures while lightweight. Consequently, the aero engine material distribution comprises steels, titanium alloys, nickel superalloys, aluminium alloys and more recently high entropy alloys[2].

The avionic trade utilizes low-alloy steels, maraging steels and highly alloyed secondary stainless steels in commercial and military aircraft for their resistance from erosion, oxidation and the capacity to withstand high temperatures. However, a lot of strength is required for the steel to reduce the weight of its parts and the fracture mechanism of the material are not well understood reducing its usage for aerospace applications. Aluminium alloys were at a point fascinating to use on aero engines due to its low density but the inability to withstand elevated temperatures limited its applications. On the other hand, Ti-6Al-4V and other titanium alloys including nickel superalloys, chromium super alloys, tantalum and rare earth metallic alloys are used for their ability to withstand high temperatures, low density and lightweight[3]. However, failure of these materials has been inevitable because of extreme operating temperatures, cyclic and translational movement of the part, mode of fabrication of parts and nature of the material. Material improvements and technological advancements in the mode of synthesis led to the discovery of high entropy alloys.

2. HIGH ENTROPY ALLOYS AS AERO-ENGINE MATERIALS

High Entropy Alloys (HEAs) are alloys with at least five metallic components and every one of these components has a molar atomic concentration somewhere between 5 and 35%[4].

Reports on most HEAs show the amalgams contain a basic Face-Centred Cubic(FCC) or Body-Centred Cubic (BCC) or Hexagonal Closed Pack (HCP) solid solution phases without intermetallic phases because of their high-entropy impact[5]. These solid solution phases empower high entropy alloys combinations to have remarkable properties, for example, increased hardness, high fracture strength, yield stress, and plastic strain. HEAs exhibit good ductility, they have a superb work hardenability and high-temperature oxidation resistance[6]. They contain particular attractive magnetic properties, have high wear resistance and exhibit good erosion opposition[7]. As a result of these properties, HEAs are remarkable refractory materials, fatigue resistant materials, and have a corrosion–resistant surface layers and diffusion obstruction layers for various structural jet engine applications. However, most HEAs were fabricated using conventional techniques and an enhancement in the manufacturing process of the alloys will upgrade the mechanical properties of these alloys.

When designing high entropy alloys, the components in the blend need not be equivalent or near equal. The structure does not separate a minor or major element in its composition rather, the major consideration for designing high entropy alloys amalgams is; the elements in the mix ought to be at least 5 in number and additionally, their atomic concentrations should be between 5-35%. Higher configurational entropy is achieved by having no less than five elements in the composition because an increment in the number of components increases the mixing entropy and best explains the high entropy effect which is an important factor to the designing of high entropy alloys [8-10].

$$N_{\textit{Major}\ \text{elements}} \geq 5\text{at.\%} \leq 35\text{at.\%} \ \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$N_{\textit{minorelements}} \geq 0 \geq 5\text{at.\%} \ \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

When the Gibbs free energy (ΔG_{mix}) is at its base, the system is said to be at equilibrium.

$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where the enthalpy of mixing is the ΔH_{mix}, ΔS_{mix} is the entropy of mixing and T is the temperature. From the Boltzmann hypothesis on the entropy of mixing, the molar configuration entropy design (ΔS_{Conf}) gives more prominent outcomes of forming a multi-element solid solution phase through statistical thermodynamics determined by:

$$\Delta \boldsymbol{S}_{\boldsymbol{conf}} =- KInw = -RIn\tfrac{\mathbf{1}}{\boldsymbol{n}} = -RIn\boldsymbol{n}\Delta \boldsymbol{S}_{\boldsymbol{mix}} = RIn_{(n)} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\Delta \boldsymbol{S}_{\boldsymbol{conf}} = \boldsymbol{RIn}_{(\boldsymbol{n})} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where $\Delta \boldsymbol{S}_{\boldsymbol{conf}}$ is the molar concentration, K is the Boltzmann constant, w is the thermodynamic probability, R is the gas constant (8.134J/Kmole) and $\boldsymbol{n}$ is the number of elements in the composition [8].

High entropy alloys form stable solid solutions because of the crystal structure of the elements which is unaltered when different elements are included. Furthermore, they are stable when the chemical components remain in a single homogeneous phase. This happens when the elements in the composition are firmly packed together on the periodic table.

There is a relationship between the entropy of fusion and the phase transition metals used in the compositional design of high entropy alloys. At the point when the number of elements in a composition is increased, the framework will be progressively stable.

For instance, from (Eq. (5)),

$$\Delta \boldsymbol{S}_{\boldsymbol{conf}} = \boldsymbol{RIn}_{(\boldsymbol{n})}$$

When the number of elements in a system n=5, $\Delta S_{conf} = 1.61R$ where R is melting point value, when the number increases, the value of R increases. Thus, increasing the number of elements in a composition increases the mixing entropy which increases the stability of the alloy system.

Cantor *et al.* [11]demonstrated the number of alloys that have been studied including unitary, binary, ternary and High entropy alloy in a system with the total number of different possible alloys N as;

$$N = (\tfrac{100}{x})^{c-1} \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

With 60elements in the alloying range of the periodic table, at a material specification of 1, he gave the conservative number of possible alloys design as $\approx 10^{177}$.

2.1 Properties and Production Techniques of High Entropy Alloys

The property, microstructure and design of high entropy alloys are dependent on some core effects, the phase composition and technique of fabrication respectively[12].

2.1.1 Core effects

High Configurational Entropy

The High configurational entropy impact hinders the phase transformation influencing the thermodynamics of the system yet builds the formation of solid solutions. Despite having numerous meta-stable states, the equilibrium state has the most reduced free energy of mixing in solids from the second law of thermodynamics. This suggests that combining five or more components in equimolar or near equimolar concentrations may bolster two phases; the solid solution phase and the intermetallic phase. Intermetallic phase is a stoichiometric compound with super-lattices that give the high entropy alloy amalgams ominous properties while single-phase solid solution phases show a system with a total blend of elements forming simple (BCC, FCC, HCP) crystal structures over intermetallic compounds. The presence of a prolonged range order isolates the intermetallic phase for the solid solution phases. At elevated temperatures the higher the number of elements in a disordered state, the less the possibility of forming intermetallic phases.

This uses the Boltzmann equation;

$$(S=k\text{In}(N)) \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

To show the configurational entropy S, of an ideal solution with N, number of elements as it only regards configurational entropy each at an equimolar concentration and k is the Boltzmann constant however, this hypothesis presumes that the HEA studied constitute random sampling of all HEA systems which is not hypothetically valid.

Sluggish Diffusion

Sluggish diffusion involves the kinetics of the system; low diffusion rate, increases thermal stability, an increase in recrystallization temperature, slows down grain growth, slows down phase separation and improves creep resistance which might benefit the microstructure. The presence of nanocrystals in as-cast material and amorphous materials in sputter-deposited thin films and high recrystallization temperatures enlivened the sluggish diffusion theory. Cross-diffusion happens when the focus angle of one element prompts or changes the motion of another element. This occurs when one component changes the chemical attributes of other elements in the alloy system. Increasing the number of the composition of the elements in an alloy may make the diffusion become sluggish and reduce the temperature of the system.

Lattice Distortion

Lattice distortion manages the structure of the high entropy alloy system. A noteworthy contrast in the atomic radii; the movement of large and small atoms causes' lattice strain making the entire framework to have a distorted lattice. Lattice distortion prompts solid solution strengthening by restricting dislocation, the displacement occurring at each lattice spot relies on the atom dwelling at that spot.

Cocktail effect

Cocktail effect affects the properties of the system designed. It includes the compositional mixtures of elements where the consequence of the blend is both unpredictable and unexpected because of the distinctive properties the individual element provides. Adding an element to the mixture with properties realized will enhance the combination through the cocktail effect. High entropy alloys may exhibit properties dependent on the reaction between elements in the system. On the off chance that a high-temperature high entropy alloy is desired, elements with elevated temperature strength ought to be used.

2.1.2 Phase formation

In recent times, a few techniques for anticipating the phase(s) high entropy alloys will possess have emerged. The phases have been predicted most often, however not continually, using the calculation of phase diagram [13], the valence electron concentration or utilizing the thermodynamic and geometry effect.

According to Gibbs rule;

$$P=C+2-F \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where C is the number of elements in the system, F is the degree of freedom and P is the maximum number of phases at equilibrium. This standard proposes that high entropy alloys can exhibit multiple phases, nonetheless, High Entropy Alloys (HEAs) are usually a single phase or double phase system but rarely having multiple phases regardless of containing multiple elements. Solid solution High entropy alloys form FCC, BCC or HCP phases due to their mixing entropies. BCC structured HEAs have high yield strengths, low ductility, limited plasticity and are brittle while the FCC structured HEAs have a low yield strength, inferior cast ability, compositional segregation high plasticity and ductility [14]. The ductility of HEAs decreases as the yield stress and comprehensive strength increases and the blend of BCC and FCC phase produce mechanical properties with high strength and good ductility producing balanced alloys [15]. However, the combination of more BCC elements will show more BCC phases while combinations of elements with more FCC elements will show more FCC phases. Although entropy is not the only criteria for phase formation, both entropy and enthalpy must be considered. The crystal structures of elements used and the number of times the elements are used in an alloy system influences the phases found in that alloy system[16]. The hardness and yield strength of HEAs with FCC phases is smaller than the BCC phase; therefore, hardness increases due to the increase in the BCC phase. The BCC phase is more grounded than the FCC phase because of the structure and solution hardening and sometimes adding an element to the mixture can change the phase completely from BCC to FCC and vice versa[17].

2.1.3 Fabrication techniques

Preparation method of HEAs can be divided into three major routes Liquid mixing, solid mixing and gaseous mixing. The liquid mixing includes arc melting, electric resistance melting, inductive melting, Bridgman solidification and laser additive manufacturing [18]. In research, most HEAs were manufactured using Arc melting, which occurs in a vacuum sealed argon environment where the molten alloy is cast. The alloys to be fabricated are liquefied using a vacuum arc melter. The melter is fitted with a button- crucible. Melting is accomplished using a consumable tungsten electrode utilizing metal pellets as a charge striking the arc. A turbo-molecular and roughing pump is then used to pump the chamber to obtain a pressure of about $3x10^{-4}$ Torr[19]. Argon is filled in the chamber to reduce the pressure a little facilitating the plasma formation when the arc strikes. Then the melt pool is stirred by the plasma through the convention. Then the process is repeated several times to achieve homogeneity of the composition.

In any case, the challenges of heating the components together have the tendency to form a hypoeutectic that isolates itself from the rest of the elements due to slow cooling rates, the shape and sizes of bulk ingots are limited and fabrication of high entropy alloys also in bulk using this technique is relatively expensive. The solid mixing route involves mechanical alloying and subsequent consolidation process. Some studies have shown that mechanical alloying produces homogenous and stable nano-crystalline microstructure. While the gas mixing route includes molecular beam epitaxy, sputter deposition, pulse-laser deposition (PLD), vapour phase deposition and atomic layer deposition [20].

3 LASER ADDITIVE MANUFACTURING (LAM)

In recent times, the era of manufacturing technologies are automated, mechanized and computer integrated. Thus, Additive Manufacturing (AM) is a preferred alternative to conventional manufacturing technologies. AM enables industries to create products utilizing fewer parts and fabricate items that are less vulnerable to mileage pores and blowholes. It reduces new product cost by 70% and promoting time by 90% by utilizing the rapid prototyping and related assembling techniques [21]. Once the shape and dimensional resistance of a component or product are made as an automated 3-D image, a solid reproduction will be created in hours anywhere in the world. AM reduces life-cycle impacts and the heaviness of the final product. AM is versatile, flexible and customizable making it a preferred choice by most sectors of production. There is no need for storage as AM parts can be made and on demand from a computer-aided design file and along these lines, there is no compelling reason to change the production line to make one part. The AM parts are fabricated layer by layer reducing excesses [22] while human production errors are insignificant. More complex parts are produced in shorter time spans and it likewise guarantees higher product quality since parts created are without residual porosity. Thus, additive manufacturing can be solid, liquid or powder-based. The powder-based processes are better utilized in lieu of other processes because additive manufacturing of segments using a laser and powder together helps create complex structures assuring quality and strength to the finished parts. AM technologies of solid structures are realized by the successive deposition of layers of flowing powders, making the powder-base additive manufacturing methods practical and attractive.

Additive manufacturing via powder based melting is a technique utilized in most metal rapid frameworks which makes use of the continuous supply of metallic materials in powder shape and an energy source, dissolving the material while forming a melt pool which solidifies rapidly into metal layers. This rapid solidification or high cooling rate will produce fine microstructures making the final part fabricated have enhanced mechanical properties. Laser additive manufacturing via powder based melting process includes the Laser Engineering Net Shaping (LENS) [23] and Selective Laser Melting (SLM) [24]. The SLM uses a cold powder bed technique while LENS uses a blown powder method by a laser beam through nozzles for particle deposition. SLM and LENS liquefying technique is adaptable, achieves accuracy in geometry and there is a better tendency to form fine grains, non-equilibrium phases and new chemical compounds in both SLM and LENS technique which results in improved mechanical properties of the material with minimal/zero defects.

3.1 Manufacturing Processing of High Entropy Alloys using Laser Additive Manufacturing

The fabrication of high entropy alloy Al-Co-Cr-Cu-Fe-Ni using laser additive manufacturing will be discussed. It should be noted that this is the most studied high entropy alloy system with limited information on the fabrication of this system via LAM technique; however, this system is in great proportion an extension of the common superalloys used as aero-engine materials.

In view of this, the Powder characterization of the high entropy alloy Al-Co-Cr-Cu-Fe-Ni is achieved to check the morphology of the powders used.

3.1.1 Laser Engineering Net Shaping method (LENS™)

LENs substrates can be made out of stainless steels plate were subjected to a compressor used to apply pressure jet of air to blast an abrasive material, etching the surface of the plates in a process called sandblasting, the process is done in an enclosed cabinet designed to contain and recycle the abrasive grit at a high air pressure to make the blasting faster. A small nozzle size helps the blast make a fine and uniform pattern at a close blasting distance with a slighted blast angle to create the desired effect.

Afterwards, a continuous wave Nd: YAG laser processing system fitted with an off-axis nozzle with a dual hopper plasma spray powder feeder system is used to deposit the alloy system. The laser and powder stream move over the surface to create layers; two or more layers can be made to create a three- dimensional deposit. The LENS process then begins with a computer-aided design [25] file transferred to the laser optomec system which in turn slices the information on the file into layers of the desired height. The CAD file is converted into a stereolithography file and parameters such as the hatch space and layer rotation are set. This stereo-lithography file is then converted to a motor control file and the travel speed is set. The laser power is set and the federate is also set. Once all parameters are set, the process can begin automatically. The powders must be spherical in shape to flow smoothly through the hoppers while deposition takes place in an argon-filled chamber. The high entropy alloys fabricated is deposited on the substrate as the oxygen level of the chamber is constantly monitored.

3.1.2 Selective Laser Melting (SLM)

SLM is a powder bed fusion process [26]. It uses a laser beam which melts and then fuses the metal powders together as a thin layer of powder is deposited over the substrate plate then the laser beam fuses the powder particles selectively as dictated by the Computer Aided Design data. Process parameters must be taken into consideration in order to fabricate a defect-free-part [27, 28]. The process parameters are Laser power, laser scan speed, hatch distance, hatch overlaps, hatch style etc and these parameters all affect the mechanical properties and influences the microstructures of the parts [29, 30].

3.2 Influence of laser Additive Manufacturing Processing Parameters on High Entropy Alloys

3.2.1 Process parameters

Laser Power

Light Amplification by Stimulated Emission of radiation is simply a device that generates an intense beam of coherent monochromatic light by stimulated emissions of photons from excited atoms or molecules. Lasers can be classified as; gas lasers, diode lasers, liquid (dye) lasers, fibre lasers and solid state lasers. The rate of energy input with respect to time is called the laser power. The intensity of the laser beam increases with an increase in time, therefore, to know the influence of the laser power on high entropy alloys, different laser power needs to be observed.

For instance, the influence of laser power on high entropy alloy CrMnFeCoNi deposited via laser melting deposition was studied by Xiang et al. [31]. The authors observed that the laser power influences the densification behaviour of the alloy. They also observed that by changing the laser power, the proportion of equiaxed and columnar grains could be adjusted which affects the solidification and heat flux direction of the process.

Laser Scan Speed

Laser scan speed is the velocity of deposition carried out by the laser beam along the track created. It is the time rate at which the deposition is created when the laser beam is passed along the surface of the substrate is called the laser scan speed. Zhang et al. [32] observed that decreasing the scanning speed leads to a higher temperature of the melt pool. The laser scan speed offers the laser powers enough heating energy to melt the high entropy alloy powders and slower scan speed ensures a longer period to melt the powder layer completely. Therefore, the laser scan speed and the laser power will determine the energy density within the melt pool [33].

Laser Beam Diameter

The length at which the laser beam covers a focal distance in millimetres while creating a layer is called the beam size or beam diameter. The beam creates a melt pool as it moves along the track with an oval, thus, the major axis of the melt pool created is dependent on the scan speed. A decrease in the beam diameter increases the energy density which leads to a deeper depth at a constant powder feed rate.

Powder Feed Rate

During laser deposition, the high entropy alloy powders are carried through a feed tube by a carrier gas usually argon at a speed called the powder feed rate. The thickness of the layers is directly proportional to an increase in the powder feed rate. However, deposition of thick layers may result in a poor bond between layers as well as a high energy consumption which negatively increases the thermal stress and distortion of the high entropy alloy component.

Hatch Spacing

Hatch spacing refers to the distance and overlap between two consecutive scan vectors. An overlap is required between the successive hatch lines to avoid pores and the spacing is usually less than the beam diameter. Zhou et al. [34] studied the influence of hatch spacing on high entropy alloy $Al_{0.5}CoCrFeNi$ prepared by selective laser melting(SLM) and the authors reported that the hatch spacing influences the relative density of the alloy as the relative density increases with an increase in the energy density. Notably, the porosity decreases with an increase in the hatch spacing and vice versa.

Energy Density

This is also known as the powder density and it is the energy responsible for the melting of the powder on the substrate, therefore, the height of a single layer is dependent on the energy density. The energy density is directly proportional to the dilution; therefore, when the energy density is low, the dilution is low and no fusion bond can be formed amongst the high entropy alloy system.

$$E = \frac{P}{vD} (J/mm^2) \quad \text{..................} (9)$$

Where D is the laser beam diameter, P is the laser power and v is the scanning speed respectively

3.3 Laser Scan Strategies on the Morphology and Formation of High Entropy Alloys

The laser scan strategies are used to reduce residual thermal stresses and fill a single cross section that can be subdivided into smaller sectors with scan lines. The lines can follow patterns such as spiral, zigzag, parallel, chessboard or paintbrush. When the laser scan speed is reduced thermal gradients and solidification may lead to cracks, however, when the scan speed is increased, the power has to be increased, therefore, knowing the right scan strategy to use in fabricating high entropy alloys is important to achieve a homogeneous system.

The type of laser and the process parameters of a laser additive manufacturing technique are not included as the scan strategies. The scan strategies show a pattern that influences independent variables during the LAM process, therefore, the scan strategies must first be defined before another parameter optimization is achieved.

Scan strategies can be divided into the layer and vector scan strategies and these strategies not only control the properties of the material but also are an important factor used to control the grain location and texture of the high entropy alloy microstructure[35].

3.3.1 Helix vector scan strategy

Helix vector scan strategy is most suitable for producing complex parts and it reduces deformation caused by steep thermal gradients in the parts produced. A Voronoi diagram is used to build each layer and a tool path algorithm applies to the diagram and generates the recursive helix scan path for every layer[36].

3.3.2 Island Scan Strategy

This is a strategy that tries to remove thermal residual stresses and this is achieved by putting separating exposed areas in a track into smaller sections called islands and this is usually 5mmx5mm by default. The islands are then scanned in a random sequence with short scan tracks eliminating localized heating of the larger sections and subsequently reducing the thermal gradients and residual stresses[37].

3.3.3 Layer Scan Strategy

Layer scan strategies comprise an orthogonal scan strategy and inter-layer stagger strategy. An orthogonal scan strategy is used to reduce porosity and stresses building up along the scan track by changing the direction of the scan after each layer is built. This is achieved when consecutive layers are scanned orthogonally to each other. The inter-layer or knitting strategy is used to repair defects observed in previously scanned layers through overlapping. The defects are corrected by melting all the powder in the overlapping zone causing a strong bond between the layer[38].

3.3.4 Vector scan strategies

The vector scan strategy consists of the progressive and 'raster scan strategies. The 'raster scan strategy alternates the vector track after every scan. The laser scans from the beginning to the end of a vector before moving to the next vector beginning with the next vector at close range to the end of the previous vector. While the progressive scan strategy as the word progressive states is a scan strategy that does not stop but continues from one vector to another [39, 40].

3.4 Benefits and Limitations of Laser Additive High Entropy Alloys

Aero engines comprise different parts and those parts are composed of several materials; aluminium alloys, steels, titanium alloys, nickel superalloys, ceramics, composites and intermetallics to name a few, however, most of these materials have limiting properties. High entropy alloys fabricated using laser additive manufacturing through research and development show promising properties; elevated temperature strength, oxidation resistance, favourable compressive yield strength, advantages over other materials used in the jet engines despite its challenges[41].

The High entropy alloy system Al_x-Co-Cr-Cu-Fe-Ni fabricated at x=0.5 exhibits high strength at elevated temperatures. The aluminium content in the high entropy system influences the crystal structure of the alloy. At reduced aluminium content, a ductile FCC phase will be formed which is resistant to changes at high temperatures and the strengthening is as a result of the solid solution phases. The wear resistance of the alloy acts independently with respect to its hardness[42]. As opposed to some alloys that the resistance to wear is directly proportioned to its hardness, this alloy system has been reported to having a high wear resistance despite its reduced hardness and this is attributed to the surface hardening of the ductile FCC phase. At low Aluminium contents, delamination wear is observed while at high aluminium content, oxidation wear is observed.

Although this high entropy system shows variation in its corrosion properties from favourable to not favourable in both NaCl and H_2SO_4 solutions it has been reported to be susceptible to pitting corrosion in chloride environments, which is increased by anodizing in H_2SO_4. The aluminium and chromium content in the high entropy alloy system has shown to improve the oxidation properties of the alloy. Aluminium achieves this by creating a protective aluminium oxide (Al_2O_3) layer on the surface while chromium also creates a protective chromium oxide (Cr_2O_3) layer on the surface[43].

The fatigue resistance of the alloy has been reported to be favourable between 540 and 950MPa However, there is a need to improve the fatigue resistance of the alloy as recent studies have shown that $Al_{0.5}$CoCrCuFeNi high entropy alloy is sensitive to defects, such as micro-cracks, introduced using the conventional manufacturing techniques[44]. These manufacturing defects arise and contribute to a reduced fatigue life of the material and an increase in the cost of reproduction, therefore, the removal of these defects and an increase in the fatigue resistance of the material will cause improvements of the technology of production. SLM and LENS melting technique are versatile and achieve accuracy in geometry. SLM uses a powder bed and LENS uses a blown powder method by the laser beam. Formation of fine grains, non-equilibrium phases and new chemical compounds result in improved mechanical properties.

4 CONCLUSION

High Entropy Alloys (HEAs) possesses superior mechanical, thermal and oxidation properties exceeding that of pure metals. Attributed to the core effects; high mixing entropy, lattice distortion, slow diffusion and cocktail effect. HEAs have outstanding strength comparable to some metallic glasses and that of structural ceramics attributed to the simple solid solutions they form. Valence electron concentration, CALPHAD and using the thermodynamic and geometry effect are suggested means of discovering the phase(s) of HEAs.

High entropy alloys have shown good wear and corrosion resistance with their thermal conductivity lower than that of pure metals. The alloys have remarkable superconductivity and have been reported to be applicable in high temperature and low-density refractory for the aero engine components. However, defects have been reported to limit the fatigue resistance of high entropy alloys using arc melting; the most widely used technique of fabricating high entropy alloy until recently. Many techniques have been substituted over the conventional process of manufacturing high entropy alloys; mechanical alloying, sputter deposition, molecular beam epitaxy (MBE) pulse-laser deposition (PLD), atomic layer deposition (ALD) and vapour phase deposition. However, none of these techniques is versatile, flexible and customizable. None use a computer-aided design file eliminating the need to change the production line just to make one part. None of the techniques mentioned above is built layer by layer reducing excesses while human production errors are minimal. None have more complex parts produced in shorter time frames and which assures higher product quality because parts developed are without residual porosity than the laser additive manufacturing technique.

Therefore, there are limitless possibilities in using high entropy alloys fabricated using laser additive manufacturing for aero engine applications. Not only are high entropy alloys similar to nickel-based super alloys currently in use but also a cheaper alternative.

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