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Fabrication and Characterization of AlCrFeCuNi High Entropy Alloy doped with (Yx) via Arc Melting Technology for Engineering Application

P Mpofu[1], N Malatji[1], M.B Shongwe[1], P.M Lekoadi[2], M Tlotleng[2,3] and L.R Kanyane[1]

[1]Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, P.M.B. X680, Pretoria, South Africa

[2]Laser Materials Processing Group, National Laser Center CSIR, Pretoria 0001, South Africa

[3]School of Physical and Chemical Sciences, North-West University, Mahikeng Campus, Corner of Albert Luthuli and University Drive, Mmabatho, 2745. South Africa.

Authors contacts: mpofupraise9@gmail.com, Tel: +27 605868097,Malatjin@tut.ac.za, Tel: +27 123824363, lrkanyane@gmail.com, Tel: +27 123824663

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Abstract. AlCrFeCuNi high entropy alloy (HEA) was fabricated using an arc-melting and casting process. Furthermore the alloy's characteristics were adjusted through the addition of Yttrium (Y) alloying additives at 1wt%, 3wt%, and 5wt%. The effect of Y at varied atomic ratios on the microstructural evolution and Nano-mechanical behavior of the synthesized HEAs was investigated. The HEA being studied proved to possess superior mechanical properties as compared to Ti64, Ni-based alloys and stainless-steel materials. The hardness and Young's modulus were the HEAs' mechanical properties investigated. The results show that Y incorporation in the AlCrFeCuNi HEA matrix resulted in the increase in microhardness. This was because the presence of Y caused grain refinement and increases the probability of precipitates or second phases forming inside the alloy. It was also observed that the elastic modulus increased with the addition of Y. This was because elastic modulus, which is a measure of a material's stiffness, also tends to increase with grain refinement.

Introduction

Owing to their unique characteristics, HEAs are currently generating a lot of research interest in materials science and engineering [1, 2]. Contrary to ordinary alloys, which typically include one or two principle elements, HEAs contain numerous primary elements, with a far greater variety of HEA compositions than conventional alloys [1, 3, 4]. Many studies have been conducted to investigatethe chemical and physical characteristics of HEAs for prospective uses. There have been numerous attempts to enhance the mechanical characteristics of HEAs. The addition of metallic components to alloys is an effective way of improving HEA characteristics [5].

To increase mechanical qualities, the rare earth metal Yttrium, which has a hexagonal closed-packed (HCP) structure, is frequently added to standard alloys for the purification of alloy solutions [6]. Yttrium can influence the microstructural evolution of HEAs by promoting grain refinement, enhancing solid solution strengthening, and influencing precipitation behaviors. Its presence can lead to the formation of various phases, such as Y-rich intermetallic or oxide particles, which can affect the mechanical properties, corrosion resistance, and thermal stability of the alloy [7]. The presence of Y can lead to improved mechanical properties such as increased hardness, strength,and ductility at the nanoscale. Y can influence dislocation motion, grain boundary strength, and precipitation kinetics, resulting in enhanced deformation mechanisms and improved resistance to plastic deformation. Additionally, the interaction between Y and other alloying elements can lead tothe formation of Nano-sized precipitates or strengthening phases, further enhancing the alloy's mechanical performance at the nanoscale [8].

Several authors have studied how Y additions to different HEAs affect their mechanical properties. Long et al [7], discovered that the inclusion of Y in FeCoNiAlCrB HEA increased fracture toughness by 50% while only reducing Vickers hardness by 10%. Vickers hardness and yield strength of CoCrFeNi HEA rose as Y content increased, but fracture strength and plastic strain decreased [8]. According to Hong et al. [9], the microhardness, yield strength, and tensile strength of CoCrNi MEA increased significantly with increasing Y percentage in the alloy. Garah et al [10], observed that when the Y amount grew, TiTaZrHfW HEA got harder, from 9.7 GPa to 5 GPa. A similar trend was seen for Young's modulus, which varies from 111.6 to 82 GPa. In CoCrFeNi HEA, Y additions were found by Polat et al, [11] to slow down grain formation and lower average grain size. The mechanical properties of the films were, however, impacted by the discovery of Garah et al, [10] that the grain size of the Nano-grains increased with the rise in Y content. With a rise in Y concentration, the grain size decreases [12]. This phenomenon can be attributed to the fact that both the Y element in the solid solution matrix and thepresence of precipitates can give resistance to grain boundary migration, causing grain growth to be suppressed.

Among the most the studied HEAs is the AlCrFeCuNi system, it has demonstrated remarkable physical and mechanical characteristics, causing it to be an appealing contender for a variety of applications. However the specific properties of AlCrFeCuNi HEA may not always meet the requirements of certain applications. The exploration of new compositions and doping elements aims to further enhance these properties for specific engineering applications. According to previous research, the presence of Y in HEAs can lead to improved mechanical properties such as increased hardness, strength,and ductility at the nanoscale. However no research was done to investigate the effect of Y in AlCrFeCuNi HEA. Hence in this study, AlCrFeCuNi HEA has been modified with Y to improve the alloy's microstructure, Nano mechanical behavior, and tribological performance.

Methodology

Aluminum (Al), Nickel (Ni), Iron (Fe), Chromium (Cr), Copper (Cu) and Yttrium (Y) metal powders of high grade were utilized in a successful attempt at creating an equiatomic AlCrFeCuNiY HEA. A tubular mixer was employed to ensure that there was uniform distribution of the HEA, the powders were combined and kept in the mixer for 8 hours.A tablet machine was used to compact the mixed powders into blocks which were arc-melted in a furnace. To ensure inertness during melting, high-purity argon gas was used while crucibles of copper were flipped over in the furnace to attain chemical uniformity. Ingots cast of 20mm in diameter and 10mm in height were sectioned. Annealing was carried out at temperatures of 400,600 and 800ºC for 2 hours in air. Scanning electron microscopy (SEM) along with energy dispersive spectrometry (EDS) was used to study the microstructural formation of the HEAs. Anton-Paar TTX-NHT^3 Nano-indentation tester was used to measure the Nano-indentation behavior of the fabricated alloys. The equipment has a Berkovich indenting tip with a radius of 20nm. During indentation, a matrix array of 4 by 4 (totaling 16 indents) was recorded. 200 mN loading force was used and the holding and unloading time was for 20 seconds The equipment was used to determine material properties such as indentation hardness and Young’s modulus.

Results and Discussion

Figure 1 shows the SEM and EDS micrographs for the control HEA sample. The presence of all of the HEA elements is confirmed by the EDS images. Three distinct phases can be observed on the alloy sample image. Irregular dark grey particles encircled by light grey phases with needle-like smaller particles distributed throughout the region. SEM micrographs of AlCrFeCuNi HEA with different Y percentages are shown in Figure 2. The microstructure of all three samples reveals three distinct phases, denoted on the microscope as white, grey, and black. The grain refinement in the sample containing 1 wt% Y was seen to coarsen as the concentration of Y increased in the samples containing 3 and 5 wt% Y. In the microstructure, a light grey phase predominated with an uneven dark grey phase around it. The black dotted region was greater in the 1 wt. % sample, but it was shown to decrease in the 3 and 5 wt. % samples.

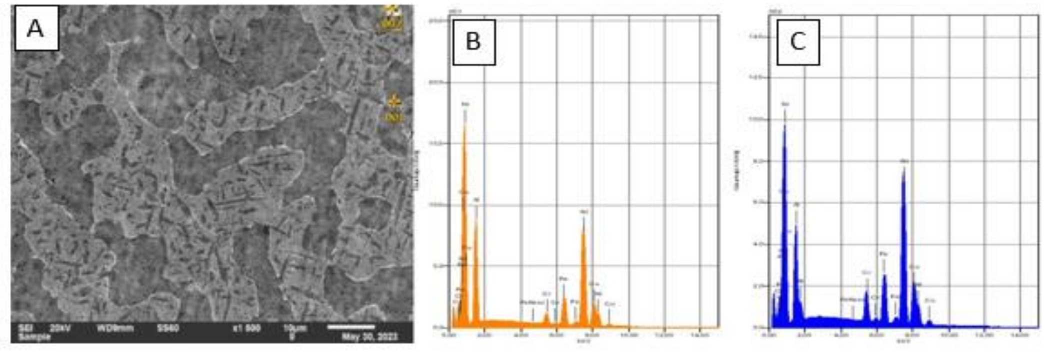

Figure 1: a) SEM micrograph of the control HEA, b) EDS peaks of region 1 and c) EDS peaks of region 2.

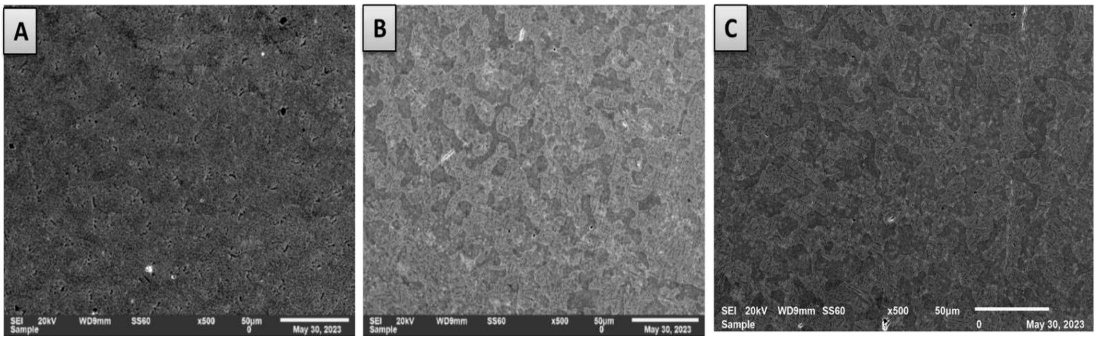

Figure 2: SEM of a) 1wt%Y b) 3wt%Y and c) 5wt% Y.

Figure 3 depicts a plot of microhardness for AlCrFeCuNi HEA and modified alloy samples containing 1 wt.%, 3 wt.%, and 5 wt.% Y. The addition of 1 wt. % Y showed an increase in the microhardness of the AlCrFeCuNi HEA from 550HV to 721HV. This may be due to the grain refinement observed in Figure 2a. As the grain size decreases, the number of grain boundaries and their corresponding obstacles to dislocation motion increase. This results in higher resistance to plastic deformation, leading to an increase in microhardness. The smaller grain size effectively hinders the movement of dislocations, making it more difficult for them to propagate through the material [13, 14]. At lower Y concentrations, Y atoms can enter the crystal lattice of the alloy, creating lattice strain and hindering dislocation movement, leading to an increase in microhardness. This is a common mechanism of strengthening through solid solution alloying.

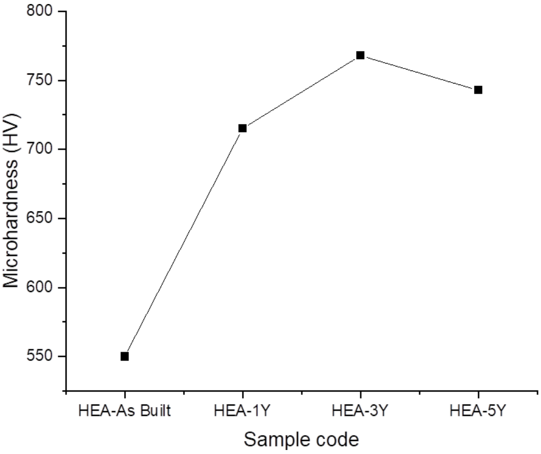

Figure 3: Microhardness Results of HEAs

As the amount of Y increases to 3 wt. %, the microhardness increases furthermore. This might be because the presence of Y increases the probability of precipitates or second phases forming inside the alloy. Depending on their size, distribution, and composition, these precipitates can be beneficial or detrimental to mechanical characteristics. The formation of precipitates in the case of 3wt.% Y may have led to extra hardening, resulting in enhanced hardness. However, beyond 3 wt. % Y, the microhardness begins to decrease potentially due to increased lattice distortion and dislocation interactions. Also, at 5 wt.% Y, the formation of certain detrimental phases could lead toa reduction in microhardness. Higher Y concentrations could influence grain boundary behavior. Ysegregation at grain boundaries might lead to embrittlement or other microstructural changes that affect the deformation mechanisms and thus the microhardness of the alloy [15].

At 5 wt.% Y, it's possible that Y's solubility in the host alloy was surpassed, resulting in the creationof distinct Y-rich phases or clusters. Reduced hardness might result from these phases having differing mechanical characteristics from the surrounding matrix. Such phase separation can reduce the overall hardness of solid solutions by preventing them from hardening and even by introducing weak spots. Higher Y concentrations may cause changes in the alloy's microstructure, including adjustments to grain size, grain boundaries, or the creation of new phases. The mechanical behavior of the alloy, particularly hardness, can be affected by these microstructural variations. The hardness probably decreased because of the microstructural alterations brought on by 5 wt.% Y. Y can also change the dislocations' mobility and the way a material responds to plastic deformation. At 5 wt.% Y, the atomic configuration, and interactions of the Y atoms with the dislocations may result in a decrease in the mobility of the dislocations, which will alter how the material responds to applied stress and result in a loss of hardness.

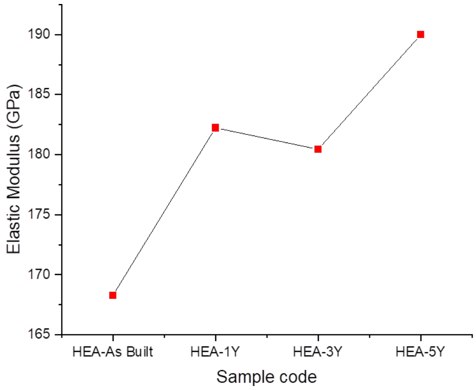

Figure 4: Elastic Modulus Results of HEA

It was observed that the elastic modulus increased with the addition of Y as presented in Figure 4. The elastic modulus, which is a measure of a material's stiffness, also tends to increase with grain refinement [8]. Smaller grains introduce more grain boundaries and interfaces, which restrict the movement of atoms under stress. This confinement of atomic motion contributes to a stiffer response of the material, leading to an increase in the elastic modulus. The addition of Y to the alloycan influence the arrangement of atoms and lattice parameters. In small amounts (1 wt.% Y), Y maycontribute to solid solution strengthening and lead to a more ordered atomic arrangement, resulting in a higher elastic modulus [12]. However, as the Y content increases, the alloy's lattice structure might become distorted or disordered due to the difference in atomic sizes between Y and the other elements. This could be the cause of the decrease in elastic modulus at 3 wt.% Y. The elastic modulus further increased at 5 wt.% Y. This may be attributed to the alloy’s ability to undergo a phase change that results in a higher elastic modulus, [10]. At 5 wt.% Y, different microstructural features might develop that enhance the stiffness of the alloy.

Summary

The AlCrFeCuNi HEA was doped with different w% of Y in order to improve its mechanical properties. It was observed that microhardness increased with the addition of 1 wt.% Y. The microhardness increases even higher when Y content rises to 3 wt.%. Beyond 3 wt.% Y, however, the microhardness starts to decline, possibly because of enhanced lattice distortion and dislocation interactions. It was discovered that adding 1 wt.% Y caused the elastic modulus to rise. The elastic modulus decreased at 3 wt.% Y and then rose again at 5 wt.% Y. In conclusion, it is likely that a combination of grain refinement, formation of different phases and interactions between Y and other elements in the alloy caused the observed variation in elastic modulus with varied Y concentration in the AlCrFeCuNi-(Yx) HEA.

Conflict of interest

There authors declare no conflicts of interest.

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