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Assessment of the Heterogeneous High Entropy Alloys (HEAs) for Computer Numeric Control Milling Application

by

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Abstract

High Entropy Alloys (HEAs) have attracted more and more attention due to their potential beneficial mechanical, magnetic, and electro-chemical characteristics, such as high strength, high thermal stability and oxidation resistance. These promising properties offer many potential applications in various engineering fields. Sample of metallic materials were characterized using Optical Emission Spectroscopy (OES) for the experimental study. Then, one sample from the existing Aluminium (Al) material (160 × 60 × 40mm) and four samples of Magnesium (Mg) Zinc (Zn) Copper(Cu) - Iron(Fe) high entropy alloy (160 × 60 × 40 mm) were produced using the stir casting process. The potentiodynamic polarization method was used to study the Corrosion Rate (CR) of the samples in 3.65 wt.% NaCl solution. The study presents a series of results on alloys with high entropy from the Control Al high-Mg-Zn-Cu-Fe. The chemical composition of high entropy alloys used in the experimental program and the experimental alloys was done in successive five-samples. The obtained alloys were subjected to micro structural analyses, mechanical tests: Brinell hardness technique, ASTM A833 standard of hardness measurement and also dynamic impact tests using incendiary perforation projectiles. The results obtained in mechanical tests revealed high values of micro-hardness (over 600 HV0.1) as well as compressible strengths above 2000 MPa. Hence, in this work an attempt is being made to investigate and analyse the mechanical characteristics of these HEAs. The powdered samples were pelletized and sieved to 0.074mm.

Keywords: High entropy alloys (HEAs), machine tools, computer numeric control (CNC), corrosion and microstructure

Assessment of the Heterogeneous High Entropy Alloys (HEAs) for Computer Numeric Control Milling Application

High Entropy Alloys (HEAs) are alloys with five or more principal elements. Due to the distinct design concept, these alloys often exhibit unusual properties. Thus, there has been significant interest in these materials, leading to an emerging yet exciting new field (Ming & Jien 2014). Most conventional alloys are based on one principal element. Different kinds of alloying elements are added to the principal element to improve its properties, forming an alloy family based on the principal element. For example, steel is based on Fe, and aluminum alloys are based on Aluminium (Al). However, the number of elements in the periodic table are limited, thus the alloy families we can develop are also limited. These alloys are named 'HEAs' because their liquid or random solid solution states have significantly higher mixing entropies than those in conventional alloys. Because of the unique multi-principal element composition, HEAs can possess special properties. These include high strength/hardness, outstanding wear resistance, exceptional high-temperature strength, good structural stability, good corrosion and oxidation resistance (Huang, & Yeh, 2016). Some of these properties are not seen in conventional alloys, making HEAs attractive in many fields. The fact that it can be used at high temperatures broadens its spectrum of applications even further. Moreover, the fabrication of HEAs does not require special processing techniques or equipment, which indicates that the mass production of HEAs can be easily implemented with existing equipment and technologies (Ming & Jien 2014). The HEAs will enhance the performance of Computer Numeric Control Milling application because their improved mechanical properties. Computer Numerical Control (CNC) is one in which the function and motion of a machine tool are controlled by means of a prepared program containing coded alphanumeric data.CNC can control the motion of the piece of tool, the input parameter such as feed, depth of cut, speed and functions such as turning spindle on/off, turning coolant on /off. The design and construction of Computer Numerically Controlled (CNC) machines differ greatly from that of conventional machine tools. This difference arises from the requirements of higher performance levels. The CNC machines often employ the various elements that have been developed over the years. A Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) program. The part designer uses the CAD/CAM program to generate an output file called a part program. The part program, often written in "G Code," describes the machine steps required to make the desired part. You can also create a G Code program manually. A file transfer medium such as a USB flash drive, floppy disk, or network link, transfers the output of the CAD/CAM program to a Machine Controller. There are some of the important constituent parts and aspects of CNC machines to be considered in designing, for example Machine structure, Guide ways, Feed drives, Spindle bearings, measuring systems. Control of a machine tool by means of stored information through the computer is known as computer Numerical controlled. The information stored in the computer can be read by automatic means and converted into electrical signals, which operate the electrically controlled servo systems. Electrically controlled servo systems permit the slides of machine tool to be driven simultaneously and at the appropriate feeds and direction so that complex shapes can be cut, often with a single operation and without the need to reorient the work piece. Computer Numerically control can be applied to milling machines, lathe machines, grinding machines, boring machines, drilling machines. The main controller subsystem is able to interpret and communicate the limits of any job, and it can directly control movement of the attachable tool heads.

Computer Numeric Control (CNC) Machining

The Computer Numerical Control machining, or CNC machining, is an advanced manufacturing process that utilizes a computer to guide the motion of a cutting tool to remove material. This technology is used in a variety of machine tools including 3- and 5-axis mills, lathes, laser cutters, wire EDM, and others. CNC machining is extremely versatile, making it an option for a variety of applications and industries that use a wide range of materials to create essential products (Abderrahim & Whittaker (2020). This article explores the advantages, disadvantages, and special considerations for a range of CNC machinable materials. Milling machines use rotary cutters to cut a variety of manufacturing materials and rely on CNC commands to dictate the depth, direction and angle of the cut. The precision of a cut is far greater now using CNC technology than when these machines were operated by hand.

Custom-Built Types of CNC Machine

Customized types of CNC control systems were constructed specifically to interface with CNC programming. They are often newer, sleeker, more efficient and more expensive than their retrofitted counterparts. CNC routers, 3-D printers, metrology machines, laser and plasma cutters, and pick and place machines are common examples (Cheng, 2017). CNC router: Routers cut wood, plastic and sheet metal on an X, Y and Z axis and are primarily used for manufacturing larger scale products. While three-dimensional routing is the most common, some routers are four-, five- or six-axis, which is ideal for more complex products. A higher axis router not only increases efficiency, but reduces set-up times and produces fewer mistakes. 3-D printer: CNC technology has been essential in innovating the world of 3-D replication. In the case of a 3-D printer, an extruder is used to push hot plastic through a small hole slowly and methodically, layer by layer, until the copied part is complete. Metrology machines: Metrology is the science of measurement. Such machines use advanced 3-D software to inspect the parts of other machines for accuracy and precision. This increases overall production efficiency and reduces equipment failures (Cheng, 2017). Laser and plasma cutters: Laser beams and plasma torches are used for jobs that may prove insufficient for other cutting tools. Both are hot enough to burn through all types of stubborn materials, and are agile enough to create almost any shape or angle. Laser cutting is gradually phasing out plasma, however, due to its superior hole-cutting power. Pick and place machines: Also called surface mount technology, these machines are used to help assemble electronics like circuit boards, capacitors and resistors. They feature a number of small mechanical nozzles that lift up electronic components, move them to the specified location, and place them down.

CNC Drive Components

The drive components are the mechanical components that "drive" the CNC machine along its axis. The most common components associated with a drive system, are the motors, lead or ball screw, or rack and pinions. The whole idea of a drive system is to convert controlled rotary motion to controlled linear motion with the help of a CNC Controller. The idea of a CNC drive system is a fairly simple one. However, the actual mechanics evolved can be complicated. This is where many

"DIY CNC'ers" get lost when trying to choose the correct drive system for their CNC Setup. The drive system has a direct correlation to the machines capabilities. By understanding the CNC drive system, one has much better understanding of a CNC machine. Just by changing a few components he can control the machines cutting speed, cutting force, precisions, and accuracy. If one is buying a CNC machine, it is best to know what type of drive components are installed. This will give a sense of the machines' capabilities and life-span. This is especially true if buying a used machine.

The CNC Controller

The CNC controller is the brain of a CNC system. A controller completes the all important link between a computer system and the mechanical components of a CNC machine. The controller's primary task is to receive conditioned signals from a computer or indexer and interpret those signals into mechanical motion through motor output. There are several components that make up a controller and each component works in unison to produce the desired motor movement. The word "controller" is a generic term that may refer to one of several devices, but usually refers to the complete machine control system. This system may include the protection circuitry, stepper or servo motor drivers, power source, limit switch interfaces, power controls, and other peripherals. Owners, operators, designers, and builders of CNC devices should understand the tasks performed by these components and how they affect machine performance. Computer numerically controlled (CNC) machines are electromechanical instruments that input data from computer programmes to operate machine shop equipment. Computer Numerical Control is abbreviated as CNC.

Concept of High Entropy Alloys

Prior to today, alloys were created by combining a primary element with secondary alloying elements to enhance their mechanical, chemical, and/or structural properties. Yeh (2014), Cantor (2014), and Ranganathan (2003) released the first paper on the development of an alloy with several primary components. This study showed that multi-component alloys, often known as High Entropy Alloys (HEAs), had better attributes than those of traditional alloys.

Materials

As the mechanical characteristics of the samples of high entropy alloys are experimentally determined, and the sample is composed of aluminium (Al), magnesium (Mg), zinc (Zn), copper (Cu), and iron (Fe), The Aluminum (Al), Magnesium (Mg), Zinc (Zn), Copper (Cu), Iron (Fe), Chromium (Cr), Silicon (Si), and Nickel (Ni) were all purchased in billet form at Ikorodu, Lagos State, Ibadan, Oyo State, and Ota, Ogun State. The billet metals underwent cleaning and de-scaling. The chemical make-up of the metals was examined using optical emission spectroscopy, and the results showed that the metals were at least 99.9% pure. One of the desired qualities that guided the development of the high entropy alloys was their purity (Yang, 2015). The metals were cut using the automatic precision cutting machine and power hacksaw. These materials were charged in to the electrical furnace in Figure 3.1 in a crucible where they are melted at high temperature in figure 3.2 and the sample of the newly cast heterogeneous high entropy alloys (HEAs) is shown in figure 3.3.

Figure 1.

Figure 2.

Figure 3

Composition and Depositing Materials (control 99% Zn)

The materials that were purchased in Lagos State and Ogun State, Nigeria, are listed in Table 1. The metallic material's characterization found that it contains 79.80% zinc and 0.30 percent aluminium. The primary depositing material, zinc bar, was also purchased in Ogun State, Nigeria. After characterization, the zinc bars were found to be 99% pure.

The essential properties of the high entropy alloys developed have been studied using various suitable characterization equipment. Samples from the high entropy alloys developed were carefully prepared for various characterizations related to the service function of the materials. This section, therefore, focuses on the discussion of the findings from the characterization. However, it has been reported that "the interfacial bond strength between copper and aluminium is stronger than the copper itself" (Sing, Lam, Zhang, Liu & Chua, 2015; Butt, Mebrahtu & Shirvani, 2016). Moreso, copper enhances elongation and does not flow at terminations (Liao, Han, Zeng & Jin, 2015).

Table 1

Composition of the High Entropy Samples

Element	Al	Mg	Zn	Cu	Fe
Sample A	55	20	10	10	5
Sample B	55	10	20	5	10
Sample C	50	10	10	20	10
Sample D	55	10	5	10	20
Control (Al)		99% Aluminium			

Polarization data for the high entropy samples in the first phase

The polarization data provided in table 4.2 below gives information on the electrochemical behavior of the high entropy alloy samples in the first phase. The implications of these results can be discussed in terms of the corrosion potential (Ecorr), corrosion current densities (jcorr) and corrosion rates (CR) of the HEA samples and electrochemical properties of the alloys. The Ecorr value indicates the corrosion potential of the alloy, with more negative values indicating a higher tendency for corrosion. The results show that the Ecorr values for the high entropy alloy samples are generally less negative than the control (Al) sample, indicating that the alloys are more resistant to corrosion than pure aluminium. For example, Sample C has the lowest Ecorr value (-0.8988V), indicating that it has the best corrosion resistance among the samples. This suggests that the addition of Mg, Zn, Cu, and Fe to aluminium can improve its corrosion resistance.

The corrosion current densities (jcorr) value represents the corrosion rate of the alloys, with lower values indicating a slower corrosion rate. The results show that the jcorr values for the high entropy alloy samples are generally lower than the control (Al) sample, indicating that the alloys have a slower corrosion rate than pure aluminium. For example, Sample A has the lowest jcorr value of 2.504E-05 A/cm2, indicating that it has the slowest corrosion rate among the samples. This suggests that the addition of Mg, Zn, Cu, and Fe can also reduce the corrosion rate of aluminium. The Cr value represents the corrosion penetration depth of the alloy, with lower values indicating a lower corrosion rate. The results show that the Cr values for the high entropy alloy samples are generally lower than the control (Al) sample, indicating that the alloys have a lower corrosion rate than pure aluminium. For example, Sample D has the lowest Cr value of 0.2006 mm/year, indicating that it has the lowest corrosion penetration depth among the samples. This further supports the notion that the addition of Mg, Zn, Cu, and Fe can improve the corrosion resistance of aluminium. The Pr value represents the polarization resistance of the alloy, with higher values indicating a higher resistance to corrosion. The results show that the Pr values for the high entropy alloy samples are generally higher than the control (Al) sample, indicating that the alloys have a higher resistance to corrosion than pure aluminium. For example, Sample C has the highest Pr value of 99.56 Ω, indicating that it has the highest resistance to corrosion among the samples. This suggests that the addition of Mg, Zn, Cu, and Fe can also increase the resistance to corrosion of aluminium.

Finally, the $|ba|$ and $|bc|$ values represent the anodic and cathodic Tafel slopes, respectively, and provide information on the kinetics of the anodic and cathodic reactions during the corrosion process. The results show that the $|ba|$ and $|bc|$ values for the high entropy alloy samples are generally lower than the control (Al) sample, indicating that the alloys have a slower anodic and cathodic reaction kinetics than pure aluminium. This suggests that the addition of Mg, Zn, Cu, and Fe can slow down the corrosion process and reduce the rate of anodic and cathodic reactions. Overall, the polarization data supports the implications of the composition data in that the addition of Mg, Zn, Cu, and Fe to aluminium can improve its corrosion resistance and electrochemical properties. This information can be used to optimize the composition of high entropy alloys for specific applications, such as in the aerospace and automotive industries, where corrosion resistance is critical.

Table 2

Polarization Data for The High Entropy Samples

Sample	E_{corr} (V)	j_{corr} (A/cm^2)	Cr (mm/year)	Pr (Ω)	|ba| (V/dec)	|bc| (V/dec)
Control (Al)	-0.8905	2.620E-04	3.0722	13.53	0.01927	0.00715
Sample A	-0.7812	2.504E-05	0.3015	93.12	0.04157	0.02541
Sample B	-0.7851	1.620E-04	2.0829	15.85	0.01894	0.00128
Sample C	-0.8988	1.102E-05	0.2006	99.56	0.04686	0.01564
Sample D	-0.8287	2.522E-04	2.9649	14.78	0.01657	0.00342

Polarization curves for the high entropy samples

Polarization curves provide information on the electrochemical behavior of a material in a corrosive environment as shown in figures 4 and 5 respectively. They are obtained by measuring the current response of a material as a function of its applied potential, while it is exposed to a corrosive environment. The polarization curves for the high entropy alloy samples in the first phase can provide valuable information on their electrochemical properties and corrosion behavior. The polarization curves typically have two regions: the cathodic region and the anodic region. In the cathodic region, the reduction of oxygen takes place on the surface of the material. This reaction consumes electrons and reduces the potential of the material. In the anodic region, the oxidation of the material takes place, which generates electrons and increases the potential of the material. The point at which the current changes direction is known as the corrosion potential (Ecorr), which indicates the tendency of the material to corrode.

The polarization curves for the high entropy alloy samples in the first phase can be analyzed by comparing their corrosion potentials (Ecorr) and corrosion current densities (jcorr) with that of the control (Al) sample. The control sample (Al) serves as a reference point and helps to evaluate the effectiveness of the high entropy alloy compositions in enhancing the corrosion resistance of aluminium. As indicated in figure 4, the Ecorr values of the high entropy alloy samples are generally less negative than the control (Al) sample. This suggests that the alloys have a higher resistance to corrosion than pure aluminium. The jcorr values for the high entropy alloy samples are also generally lower than the control (Al) sample, indicating that the alloys have a slower corrosion rate than pure aluminium. The polarization curves can also provide information on the kinetics of the anodic and cathodic reactions during the corrosion process. The anodic and cathodic Tafel slopes, represented by |ba| and |bc| values in the table, provide information on the rate at which the anodic and cathodic reactions occur, respectively. The lower the Tafel slopes, the slower the reaction rate. The results indicate that the Tafel slopes for the high entropy alloy samples are generally lower than the control (Al) sample, suggesting that the alloys have slower anodic and cathodic reaction kinetics than pure aluminium.

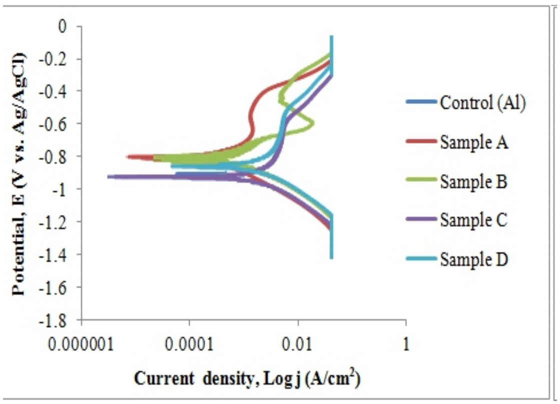

Figure 4: Polarization curve

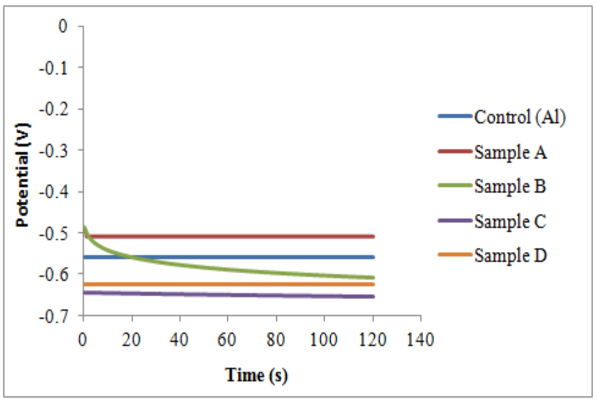

Figure 5 Open circuit potential (OCP)

Structural characterization of developed aluminum base high entropy alloy.

The structural characterization of control 100% of Aluminium (Al) is shown in figure 4.3, which consist of granular structure of the Aluminium material called Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscope (EDS)

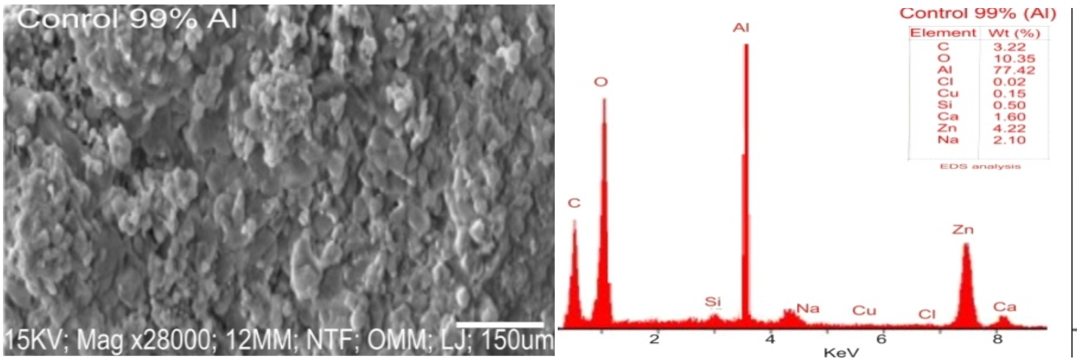

Figure 4.3: SEM/EDS of the control Aluminium (Al) of the first phase

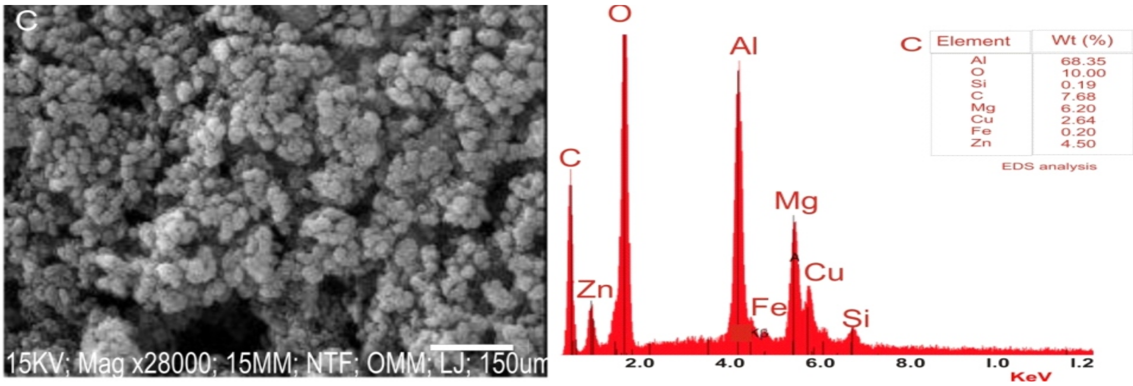

Figure : SEM/EDS of the first phase high entropy alloy of sample C

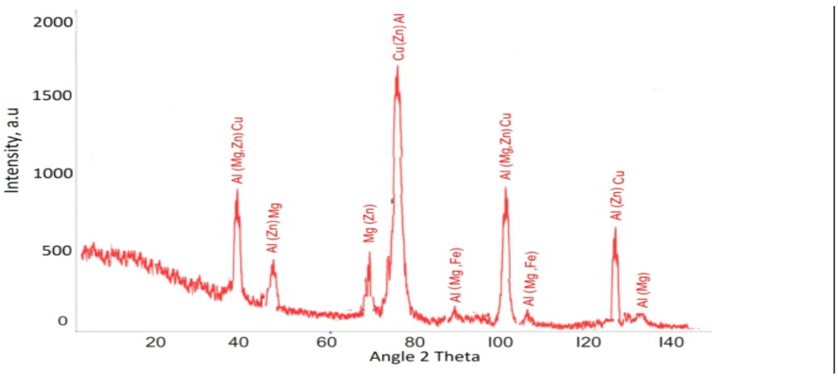

Figure: XRD profiles of high entropy alloy of sample C

Brinell Hardness of the HEAs samples

Figure 8 displays the Brinell hardness of five distinct first-phase samples. As compared to the other samples, the control (Al) sample had the lowest Brinell hardness, measuring 98.45Kgf/mm2. In comparison to the control (Al) sample, sample A was found to have unusually high Brinell hardness. The biggest rise in hardness during this first phase was seen in sample C, which had a Brinell hardness of 162.45Kgf/mm2. The hardness exhibited by samples B and D are with values of 124.74Kgf/mm^2 and 120.56Kgf/mm^2 respectively. The sample C exhibited notably the highest hardness value compared to the other samples. This shows that the coatings adhered firmly to the base material (Ayoola *et al.*, 2019; Kodama*et al.*, 2021).

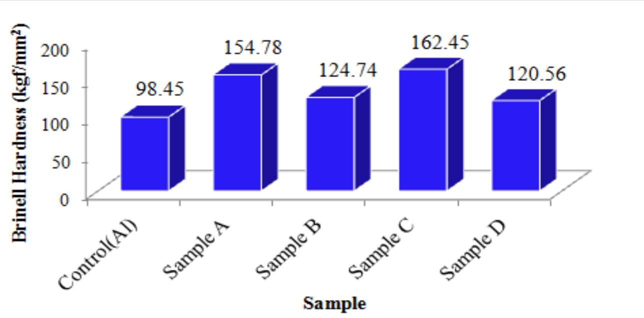

Figure 4.4: Brinell hardness chart

Conclusions

This research was carried out with the aim of creating and comparing high entropy alloys that will be most suitable for CNC Milling operation and application through the experimental study of heterogeneous high entropy alloys (HEAs). The experimental research was carried out to developing and comparing the corrosion, resistance, mechanical, thermal and microstructural performance of high entropy alloys of control Al highMg-ZnCu-Fe.

Recommendations

i) The developed Al-Mg-Zn-Cu-Fe high entropy alloy is hereby recommended to the manufactures, users of CNC machines and policy makers as an outstanding material for CNC milling operation and application.

ii) Other techniques of producing high entropy alloys (HEAs) can be used, and the results can be compared to the existing results from this method to determine the variation results.

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