A FUZZY LOGIC APPROACH FOR MODELING AND PREDICTION OF MECHANICAL PROPERTIES OF Al-5%Mg DOPED WITH NICKEL

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ABSTRACT

In this research, the average grain size and mechanical properties of aluminum-magnesium alloy doped with nickel were predicted using Fuzzy logic. The single input to the Fuzzy logic model was variation in percentage weight of nickel, while the multiple outputs were average grain size, ultimate tensile strength, yield strength, percentage elongation, hardness, and impact strength. In order for fuzzy model to accurately predict the mechanical properties of aluminum magnesium alloy, membership functions were established. In addition, a set of test case experiments were done so as to validate the fuzzy logic model. Fuzzy logic with a correlation coefficient (R) value of 0.99779 for average grain size, 0.99935 for ultimate tensile strength, 0.99733 for yield strength, 0.9906 for % elongation, 0.9996 for hardness and 0.9970 for impact strength were obtained. This result demonstrated agreement between the experimental values and Fuzzy model.

Keywords: Al-5% Mg alloy, Fuzzy Logic, Nickel, Average Grain Size, Mechanical Properties.

1.0 INTRODUCTION

Al–Mg alloys have been widely used in transportation industries such as airspace, automobile and railway due to good combination of properties, such as low density, medium strength, high fracture toughness, good corrosion resistance and excellent welding property [1]. In many situations, the performance of Al–Mg alloys in high-tech fields are required to be further improved. Al-Mg alloys are non-heat treatable but gain their strength from solid solution strengthening and pre-strain. Their performance can be increased by about 10-15% by means of cold-working, however a clear deterioration of their plastic properties [2-3]. Previous studies indicated that micro-alloying is an effective way to further strengthen the alloys. Alloying elements such as Y, Zr, Sc, Cu, Mn, V, La, Ce, Yb, Zr, Er, Sr have been added to Al-Mg alloys [2-13]. Previous studies have paid much attention to the effects of different micro-alloying elements on the mechanical properties of Al alloys [2-13]. Also, previous studies indicated that the addition of Ni to Al–Cu–Mg alloys [14], Al–Si–Cu–Mg alloys [15], Al–Zn–Mg–Cu alloys [16] and Al−Mg−Si−Cu−Zn alloy (17) which had a positive effect on the mechanical properties of the alloys]. However, the effects of nickel on the structure and properties of Al-Mg alloys have not been studied. Hence, this research aimed at investigating the role of nickel addition in improving the structure and mechanical properties of aluminum-magnesium alloy.

Precise prediction and modeling of the average grain size and mechanical properties of aluminum magnesium alloy are vital, since the conventional approach of attaining high mechanical properties at aluminum magnesium alloy various requires using a trial and error technique, which is very time-consuming. In recent times, due to significant advances in information and computer technology, soft computing techniques such as genetic algorithm (GA), artificial neural network (ANN), fuzzy logic, simulated annealing, adaptive neuro-fuzzy inference system (ANFIS), etc., are extensively used in modeling and prediction of mechanical properties of engineering materials[18,19,20].

Numerous researchers utilize fuzzy logic method due to its efficiency in predicting and modeling phenomena. Tarasov et al. [21] carried out extensive research on the use of Fuzzy logic for the prediction of the yield strength of A356 alloy. The authors reported that the experimental yield strength is in good agreement with predicted results obtained with Fuzzy logic model, and also the fuzzy logic predicted the yield strength at an average error of 3.53%. Marani et al. [22] employed Fuzzy logic approach for predicting surface roughness of machined Al-Si-Cu-Fe die casting alloy using different additives-turning. The results obtained posited that the actual surface roughness of the samples agrees with the results predicted by fuzzy logic model. The error rate of the predicted surface roughness was recorded at 5.4%. Zalnezhad et al. [23] predicted the surface hardness of TiN coating on AL7075-T6 with regard to changes in input process variables, nitrogen flow rate, direct current (DC) power and DC bias voltage using fuzzy logic method. Their results showed that there was an agreement between the fuzzy model and actual results with accuracy of 96.142 %. From the literature survey, it could be seen that fuzzy logic has not been applied at its full potential for modeling and prediction of mechanical properties of aluminum-magnesium alloys. The present research focuses on the mechanical characterization and fuzzy modeling of aluminum-magnesium alloy doped with nickel. The nickel at different percentage weight composition (0.1 - 1.0wt %) was assigned as the single input parameter while ultimate tensile strength, yield strength, % elongation, hardness and impact strength of the doped aluminum-magnesium was stated for multiple inputs, hence, a fuzzy model was established among the various parameters.

2.0 EXPERIMENTAL PROCEDURES:

2.1 Melting and casting of alloys

The alloys with a nominal composition of Al-5%Mg-xNi (x=0,0.1,0.2,0.3,0.4,0.4,0.5,0.6, 0.7,0.8, 0.9 and 1.0) were prepared by medium crucible furnace using pure Al, Mg, and Ni(all compositions stated in this work are in wt.% unless otherwise clarified). During alloy preparation, pure Al was placed inside a stainless steel crucible and melted at 710 ℃ in the crucible furnace, and then pure magnesium and nickel powder were pressed together into the molten aluminum, Mg was over added by 3 wt% for compensating the burning lost during melting. The melt was held at 710 ℃ for about 10 min to ensure the dopant dissolved absolutely.

2.2 Mechanical properties test

Aluminu-5% magnesium alloy samples were machined as per ASTM E8M-04 standards for mechanical properties test. The ultimate tensile strength was done with Instron universal tester with a crosshead speed of 50mm/min while the impact strength was carried out with Dension Charpy impact test machine (EXT96064/6705CE), with the rate of 5.24m/s. Brinell hardness machine with 2.5mm diameter ball indenter and with a minimum force of 62.5N was used to determine the hardness of the alloy.

2.3 Structural analysis

Guangzhou Liss optical microscope (L2003) type optical microscope (OM) and Phenom ProX type scanning electron microscope (SEM) was utilized to analyze the microstructures of the alloy. The average grain size was done with an image processing technique known as Image J software.

3.0 RESULTS AND DISCUSSION

The following results were obtained from the average grain size and mechanical testing of the samples as shown in Table 3.

Table3: Average grain size and mechanical properties test results.

Alloy	Average Grain Size (µm)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation%	Hardness (BHN)	Impact Strength (J)
Al-5%Mg	73.27	172.74	79.09	10.27	101.92	42.5
Al-5%Mg-0.1Ni	71.21	186.58	87.15	15.1	108.03	43.5
Al-5%Mg-0.2Ni	69.7	190.13	100.06	17.65	121.56	47
Al-5%Mg-0.3Ni	65.1	196.59	115.04	18.11	136.27	52
Al-5%Mg-0.4Ni	60.17	200.12	115.77	19.11	141.18	58.5
Al-5%Mg-0.5Ni	57.76	207.1	127.42	17.01	159.32	56
Al-5%Mg-0.6Ni	48.23	215.23	128.42	14.13	178.8	47.5
Al-5%Mg-0.7Ni	44.89	220.57	129.23	12.15	184.31	42
Al-5%Mg-0.8Ni	33.47	225.39	129.68	10.17	221.57	39.5
Al-5%Mg-0.9Ni	21.88	228.07	130.04	9.01	247.05	34
Al-5%Mg-1.0Ni	28.7	230.35	131.03	8.5	278.43	23.5

3.1 Mechanical properties analysis

From figure 1, 2 and 4, the ultimate tensile strength, yield strength and hardness of Al-5wt%Mg alloy increased from 172.74MPa to 230.35MPa, 79.09MPa to 131.03MPa and 101.92 BHN to 278.43BHN respectively at 0.1wt% nickel addition interval. The above trend represents 33.3%, 65.74% and 63.39% rate of performance, hence, reveal that the added alloying element systematically improved the matrix alloy. The reasons for the improvement in ultimate tensile strength are fine-scale uniformly distributed βAl3Mg2 intermetallic, reduced grain size and solid solution strengthening processes. The additive served as a growth-restriction element and reduced the grain size of Al-5%Mg alloy. Also, Al–Mg alloys are non-heat treatable aluminum alloys. These alloys are strengthened by Mg in solid solution. Magnesium is a primary alloying element and acts as an obstacle to the dislocation motion, the interaction of the solute atom-dislocation and/or the introduction of foreign atoms into a crystal lattice may result in a strengthening of the materials [24].

Fig 3 and 5 depict the percentage elongation and impact strength of Al-5%Mg doped with nickel. It was noticed that the percentage elongation and impact strength increased from 10.27% to 19.11% and from 42.5J to 58.5% by addition of 0.4% Nickel respectively before decreasing drastically with further increase in concentration of Nickel.

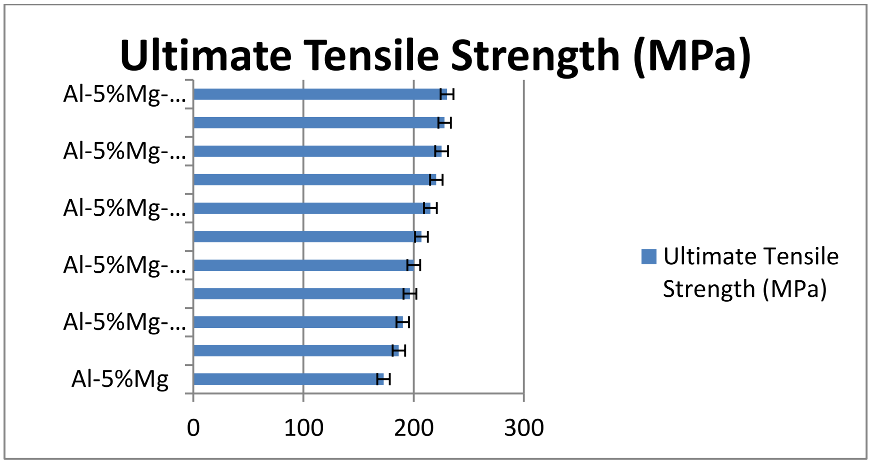

Figure 1: Effect of different Ni contents on the tensile strength of Al–5%Mg

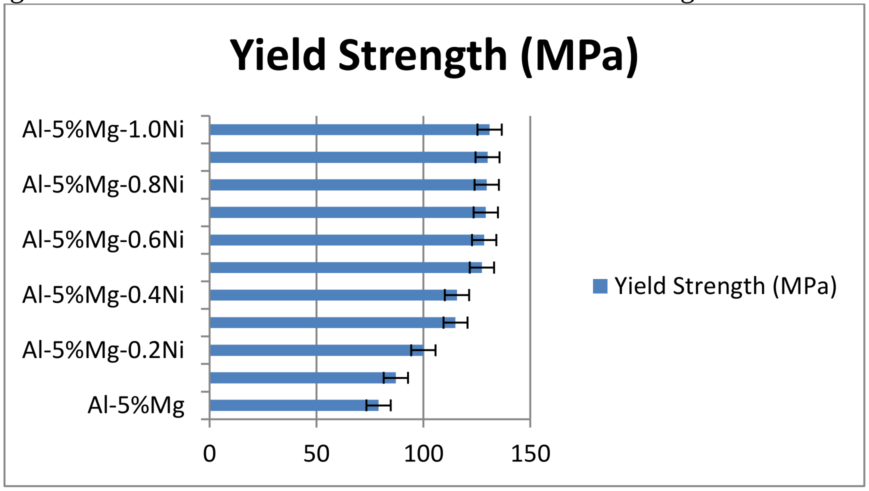

Figure 2: Effect of different Ni contents on the yield strength of Al–5%Mg

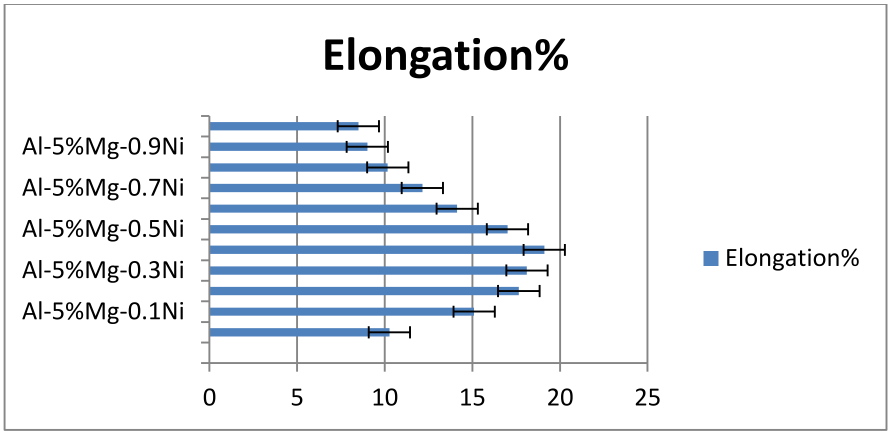

Figure 3: Effect of different Ni contents on the % elongation of Al–5%Mg

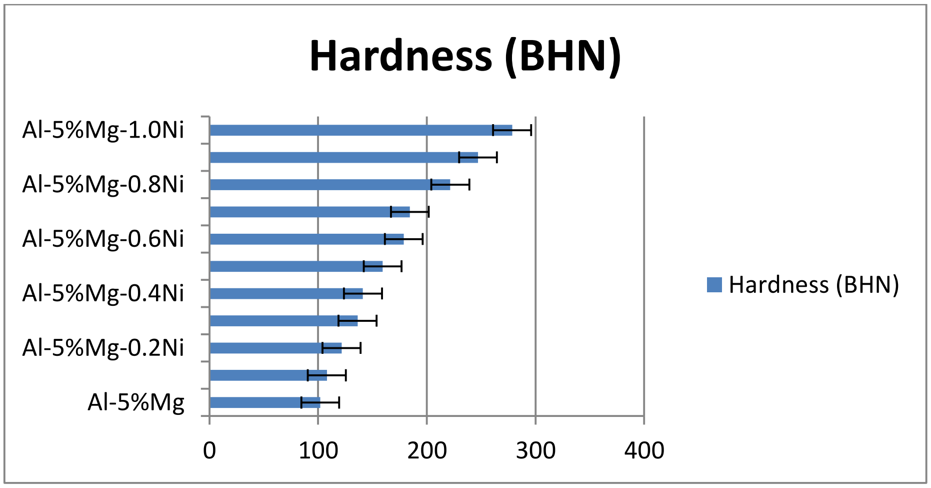

Figure 4: Effect of different Ni contents on the hardness of Al–5%Mg

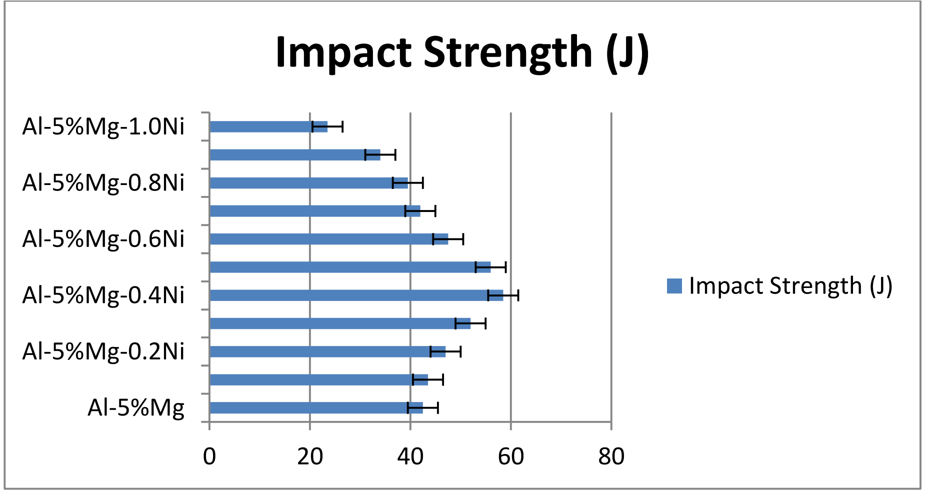

Figure 5: Effect of different Ni contents on the impact strength of Al–5%Mg

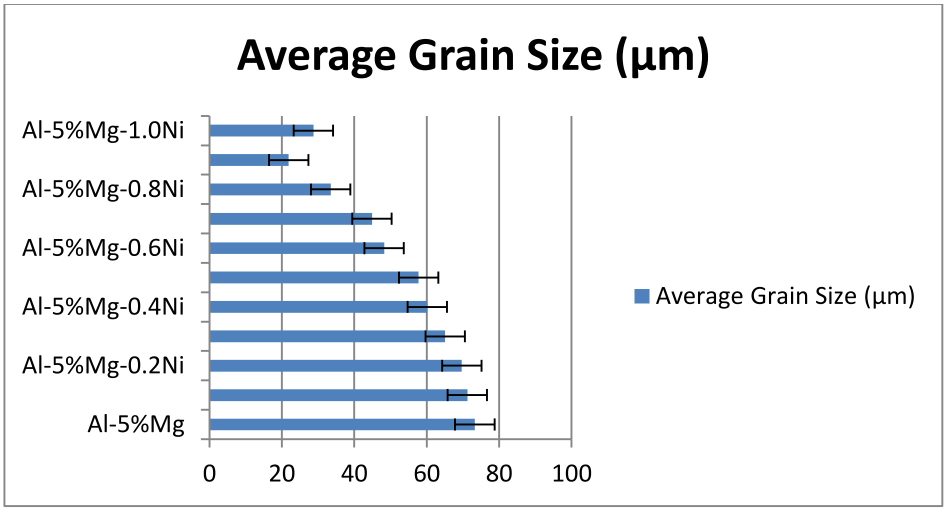

Figure 6: Effect of different Ni contents on the average grain size of Al–5%Mg

3.2 Structural Analysis

The micrographs of the alloy samples are shown in plate 1-11

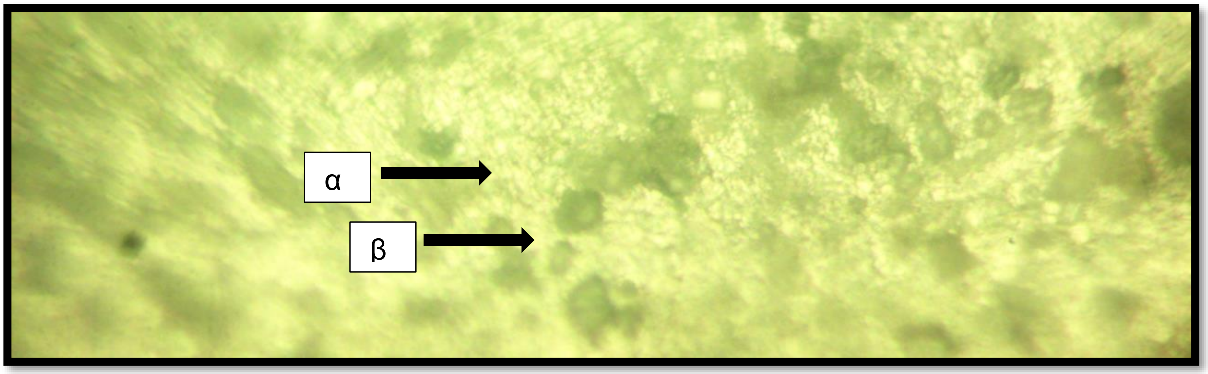

Plate 1: Micrograph of Al-5%wtMg (x400)

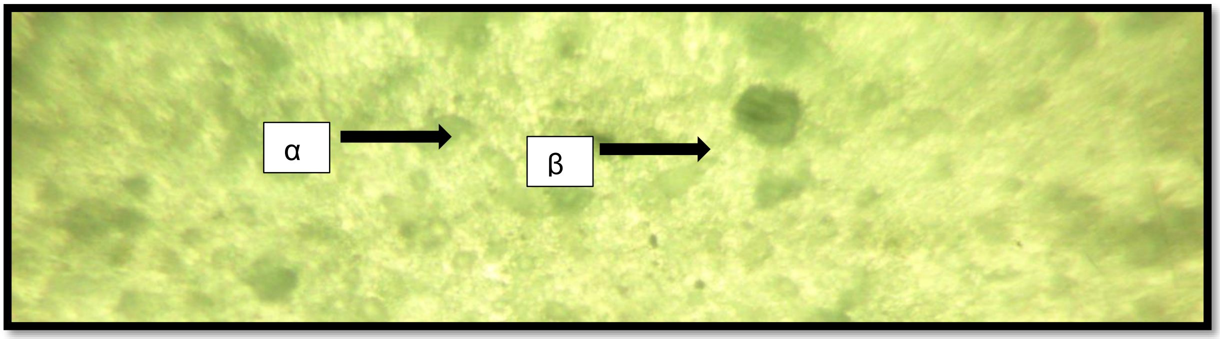

Plate 2: Micrograph of Al-5%wtMg-0.1wt% Ni (x400)

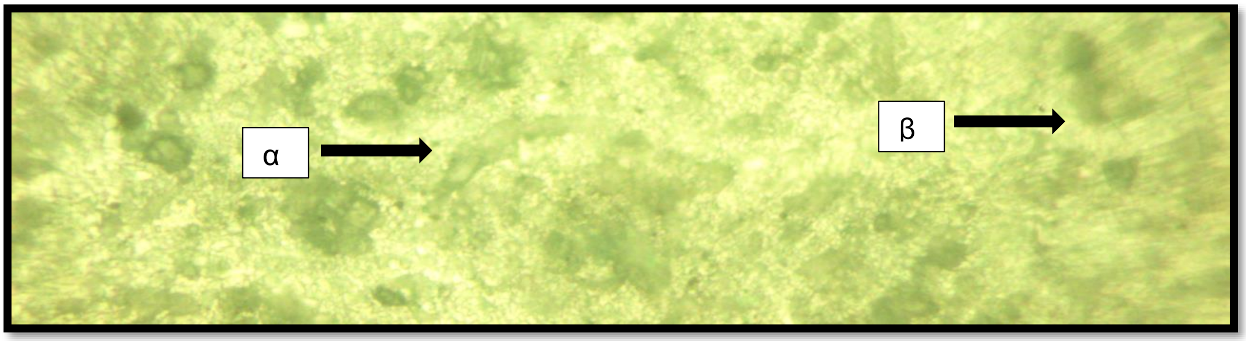

Plate 3: Micrograph of Al-5%wtMg-0.2wt% Ni (x400)

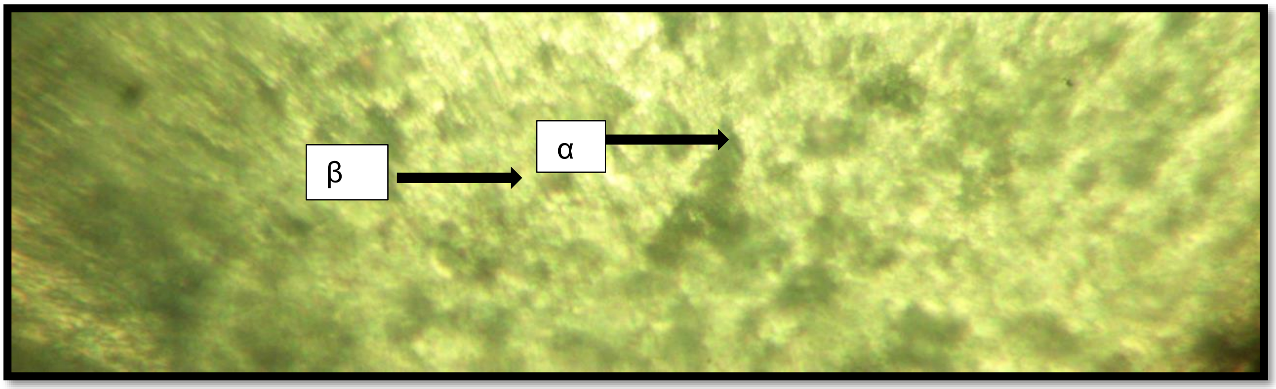

Plate 4.: Micrograph of Al-5%wtMg-0.3wt% Ni (x400)

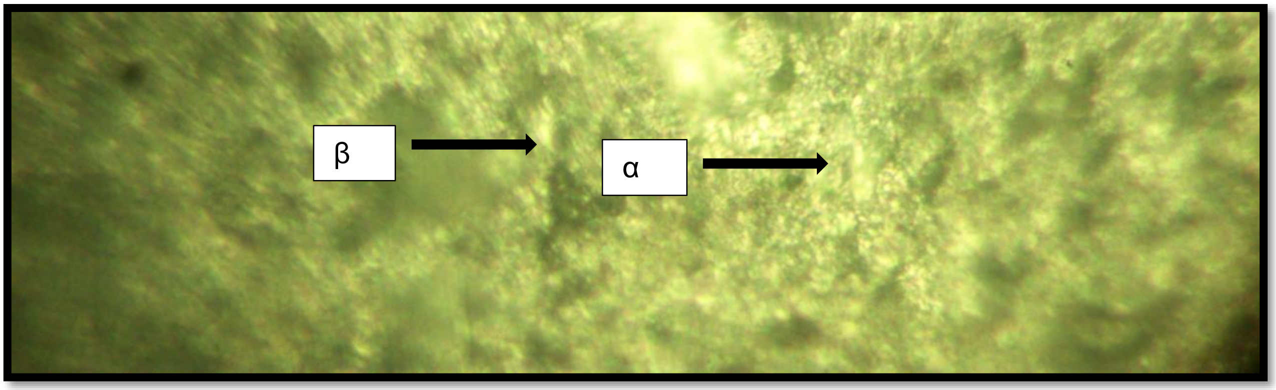

Plate 5: Micrograph of Al-5%wtMg-0.4wt% Ni (x400)

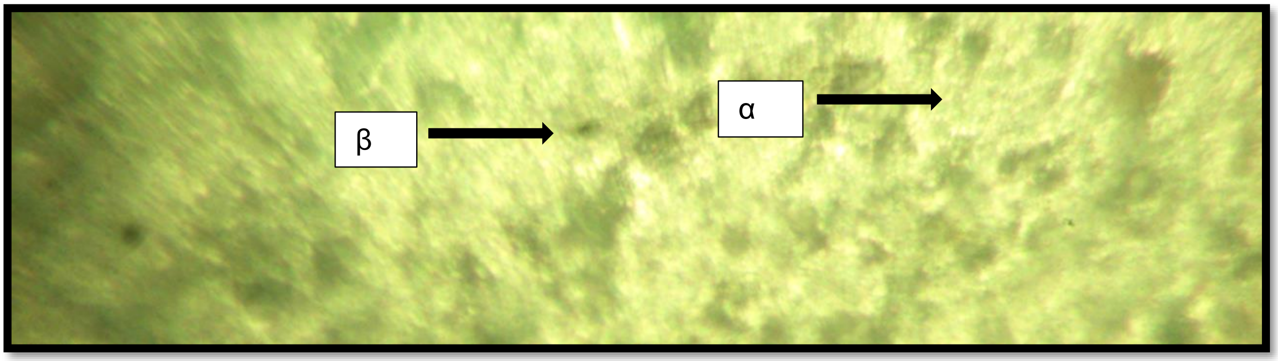

Plate 6: Micrograph of Al-5%wtMg-0.5wt% Ni (x400)

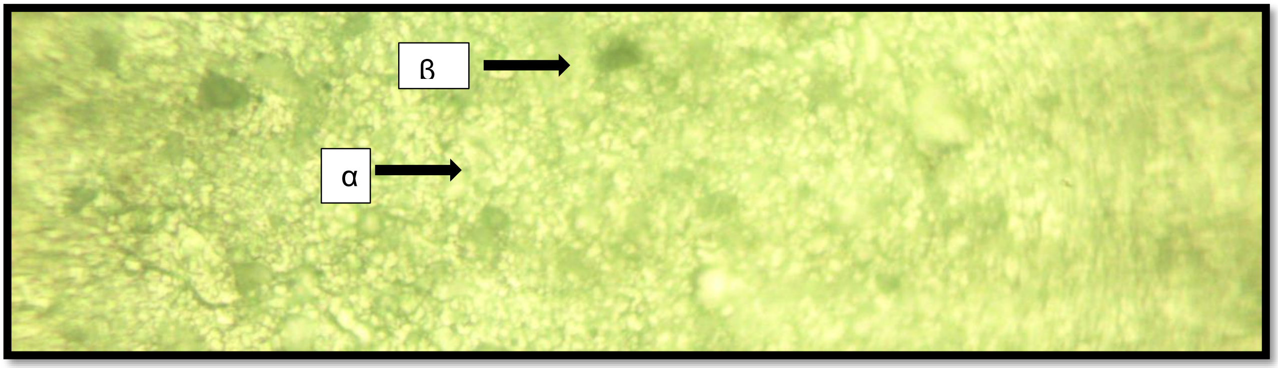

Plate 7:

Micrograph of Al-5%wtMg-0.6wt% Ni (x400)

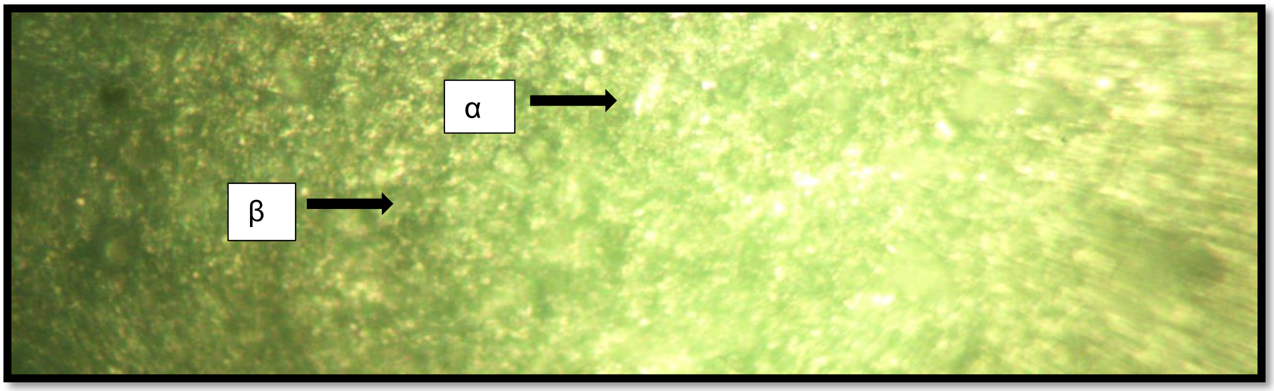

Plate 8:

Micrograph of Al-5%wtMg-0.7wt% Ni (x400)

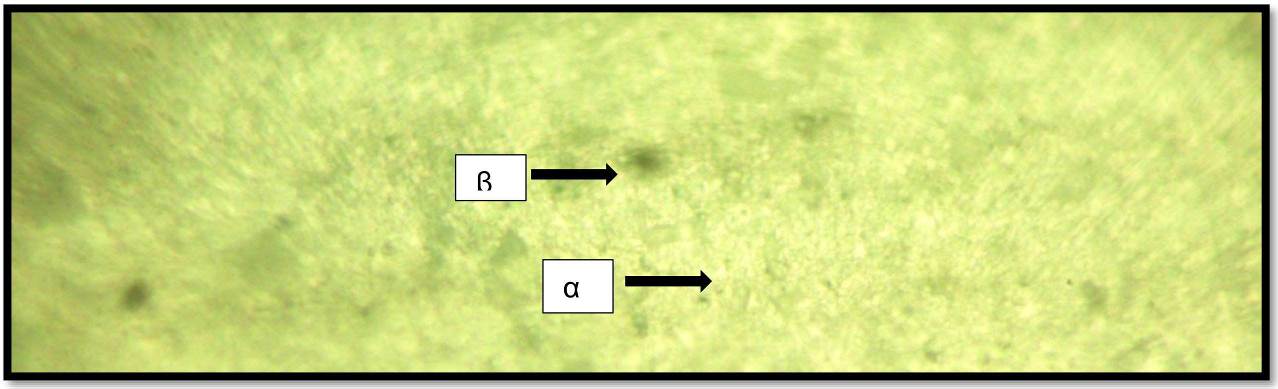

Plate 9:

Micrograph of Al-5%wtMg-0.8wt% Ni (x400)

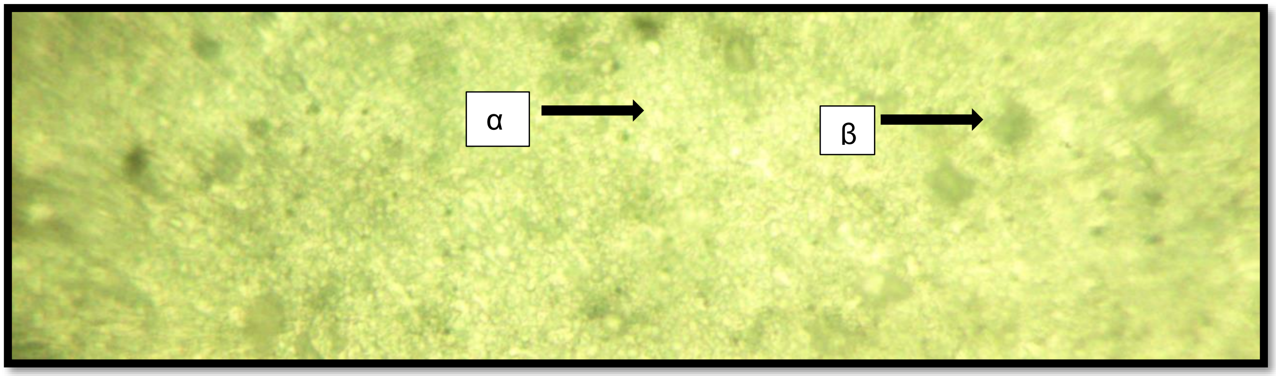

Plate 10:

Micrograph of Al-5%wtMg-0.9wt% Ni (x400)

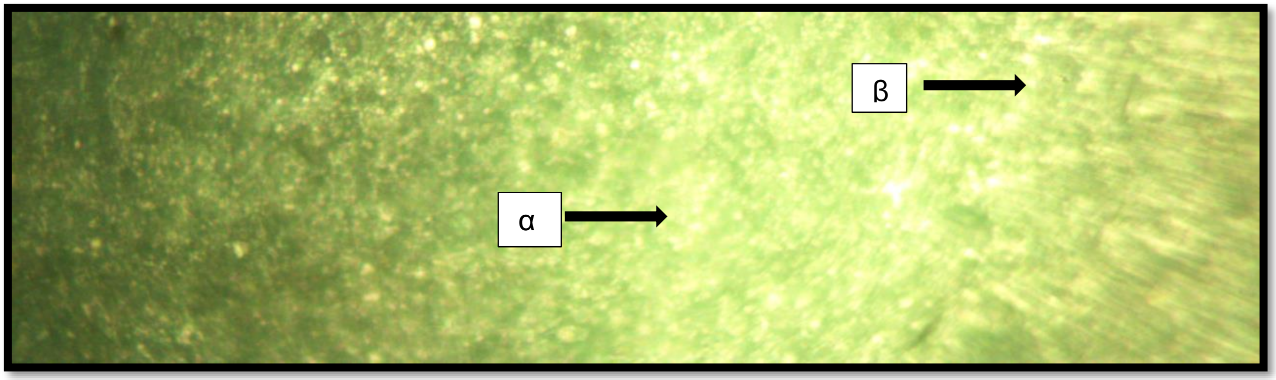

Plate 11: Micrograph of Al-5%wtMg-1.0wt% Ni (x400)

Plates: 1-11 represent the results of analysis of the microstructural evaluations of Al-5wt% Mg alloys doped with nickel. The observed microstructures contain two major phases the α-phase (single phase region: solution of magnesium in aluminum) and the region of βAl_3Mg_2 intermetallic compound (dual phase; precipitated magnesium from aluminum matrix) such as α-phase, βAl_2Mg_3 phase and particles of the element which it is doped with precipitated in *α*-phase. The light areas are the α-matrix, the dark regions are the βAl3Mg2 intermetallic phase. All these phases can be seen in the microstructure images of each sample. Their shape and size are different base on the different compositions of each element.

From figure 5, it can be seen that the addition nickel within the studied range of composition improved the average grain size of Al-5.0wt%Mg alloys. It can be seen that the rate of decrease in average grain size varied with increase in the concentration of the nickel, with increase in nickel addition, the average grain size decreased first from 73.2 µm to 21.879µm and reached the least value when the content of nickel was 0.9%wt, further increase in concentration, deteriorated the grain refining efficiency by producing coarse grains. Undoubtedly, the idea behind the decreased in the grain size was attributed to the grain refinement and modification of the globular morphology of $\beta\ Al_3Mg_2$ intermetallic compound. The addition of nickel increased the number of solidification sites for heterogeneous nucleation of the primary aluminum phase which led to increase in grain boundary area per unit volume and decrease in intra-particle distance [25].

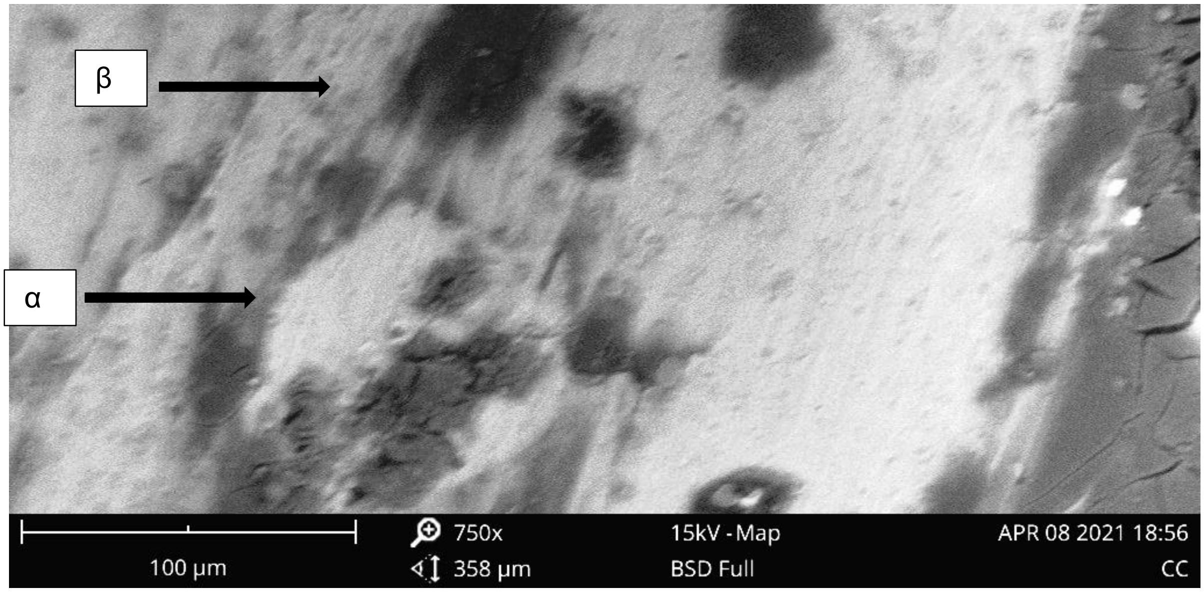

Plate 12 : SEM of Al-5%Mg alloy

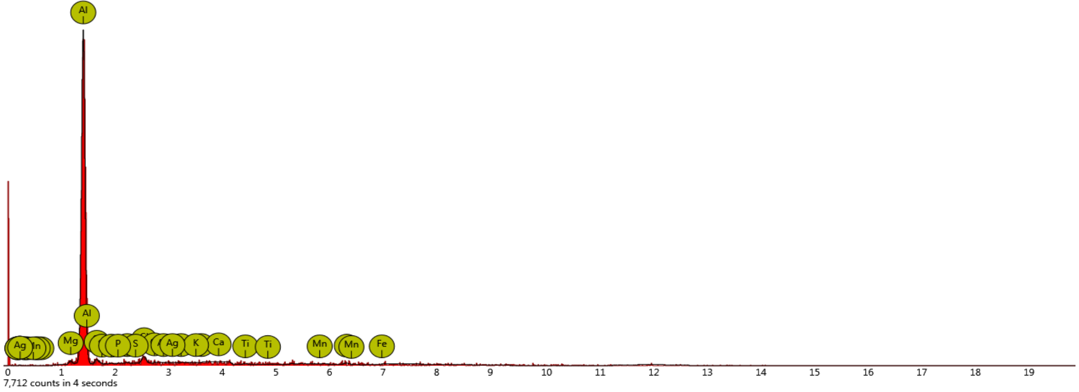

Figure 7 : EDS of Al-5%Mg alloy

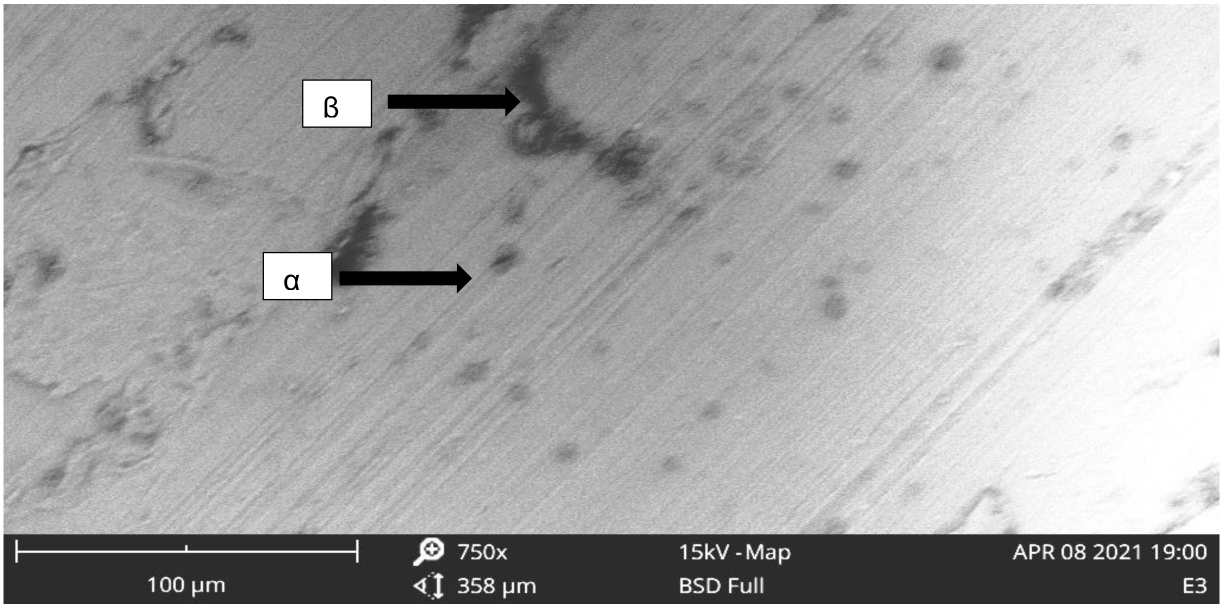

Plate 13: SEM of Al-5%Mg with 0.9% Ni

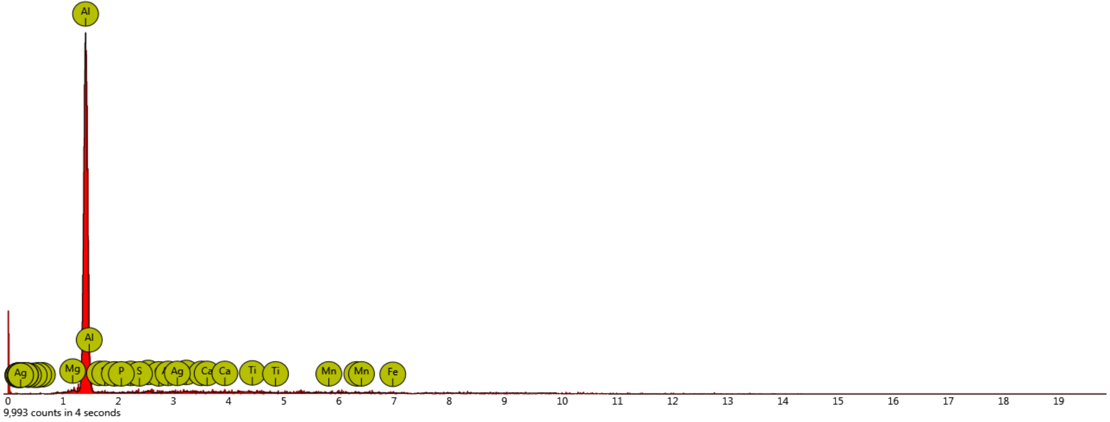

Figure 8: EDX of Al-5%Mg with 0.9% Ni

Plates 12-13 show scanning electron microscopes which revealed the phase present and figure 7-8 EDX showed the elements present and their peak. Two major phases were revealed under the optical microscopes the α- phase and β-phase (Al_3Mg_2) intermetallic, EDX depicts the elements present in the alloy such as Ag, P, Ca, Fe, Ti, Si, K and their peak. From the EDX and SEM results, it can be seen that as the concentration of Ni increased, the β intermetallic phase became suppressed and the α-phase increased in size.

4.0 FUZZY LOGIC MODELING OF MECHANICAL PROPERTIES

Fuzzy Logic System contains three components: fuzzification, rule base, and defuzzification. The fuzzifier maps crisp numbers into fuzzy sets, rule bases are collection of IF-THEN statements. It maps input fuzzy sets into output fuzzy sets. Defuzzification maps output fuzzy sets into crisp quantity.

Figure 9 shows the fuzzy inference system for micro-alloying of Al-5%Mg using Ni. As shown in Figure 9, micro-alloying with nickel represented the input variable to the fuzzy inference system, while the average grain size, tensile strength, yield strength, elongation, hardness and impact strength, hardness derived from defuzzification were the output variables. Figure 10, shows the membership function for the micro-alloying using nickel. The membership function contained ten (10) linguistic variables namely: mo1, mo2, mo3, mo4, mo5, mo6, mo7, mo8, mo9, mo10.

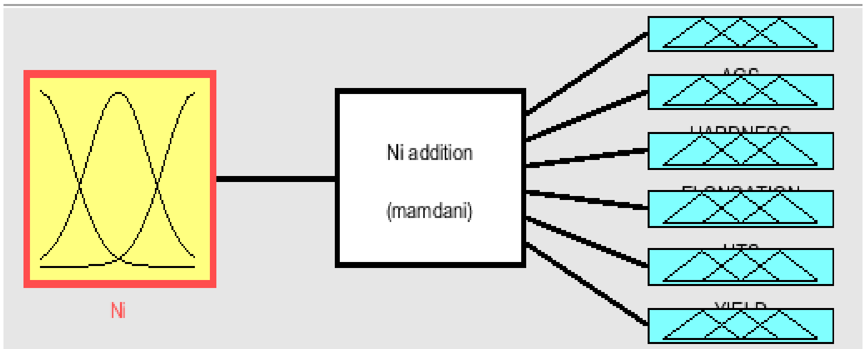

Fig 9: Fuzzy interference system of of Al 5%Mg doped with Ni

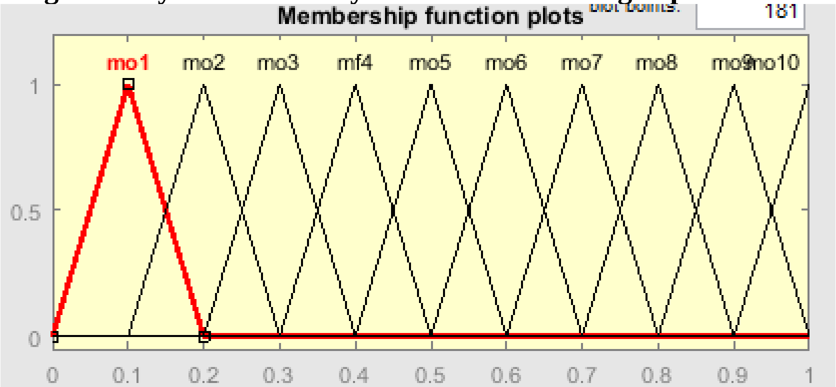

Fig 10: Membership functions for the micro additives using nickel

Six fuzzy logic models were used in the prediction of the modeling. Model I contained 17 linguistic variables for the output (average grain size) as shown in Figure 11, model 2 contained 35 linguistics for the output (hardness) as shown in figure 12, model 3 contained 18 linguistic variables for % elongation as shown in figure 13, model 4 contained 16 variables for UTS as shown in figure 14, model 5 contained 16 variables for yield strength as shown in figure 15, and model 6 contained 21 variables for impact strength (14).

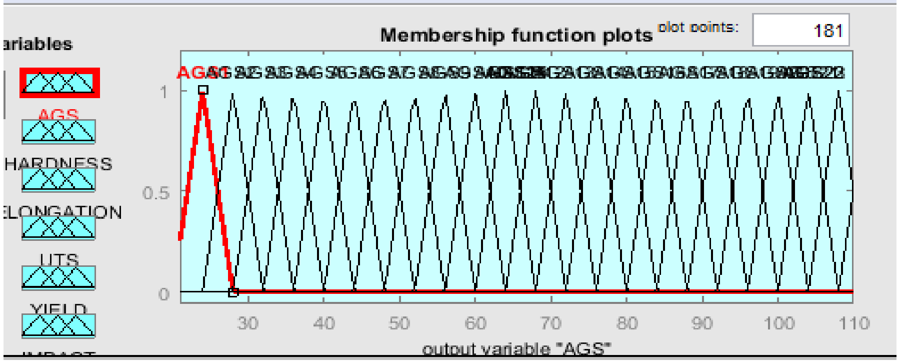

Fig 11: Membership function for Average grain size

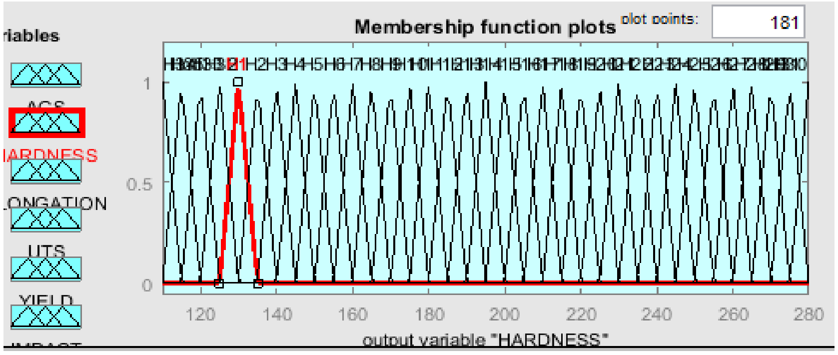

Fig 12: Membership function for hardness

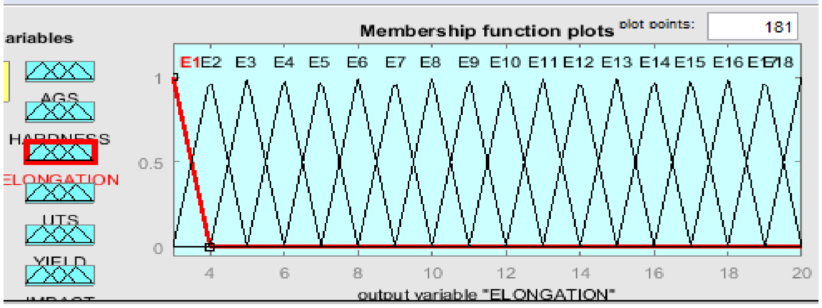

Fig 13: Membership function for Elongation

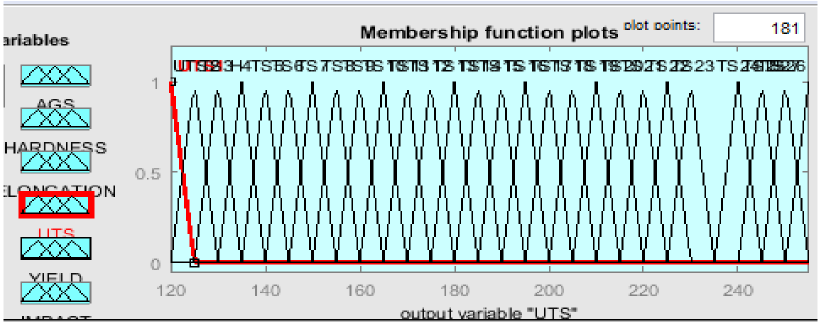

Fig 14: Membership function for UTS

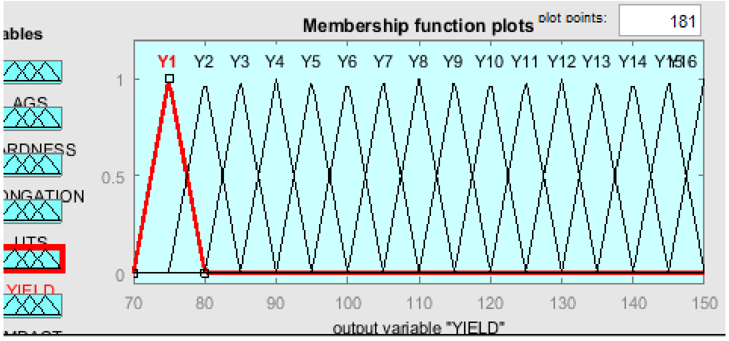

Fig 15: Membership functions for yield strength.

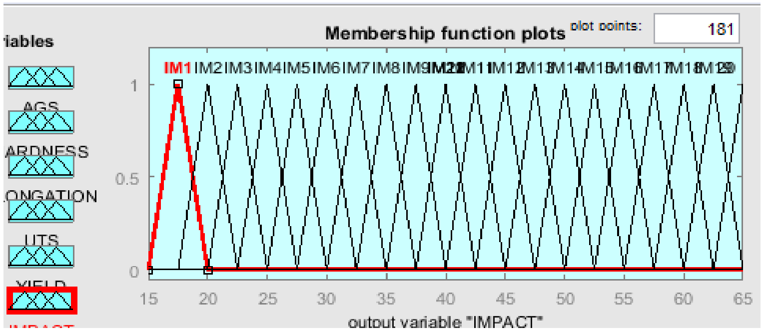

Fig 16: Membership functions for impact strength

The fuzzy logic model generated 10 different rules per model. The 10 rules were used by the Mamdani fuzzy inference system to predict the average grain size and mechanical properties (tensile strength, hardness, elongation, impact strength and yield strength) after defuzzification using the centroid method. The coefficient of correlation and regression line for the fuzzy predictions are shown in the figures below.

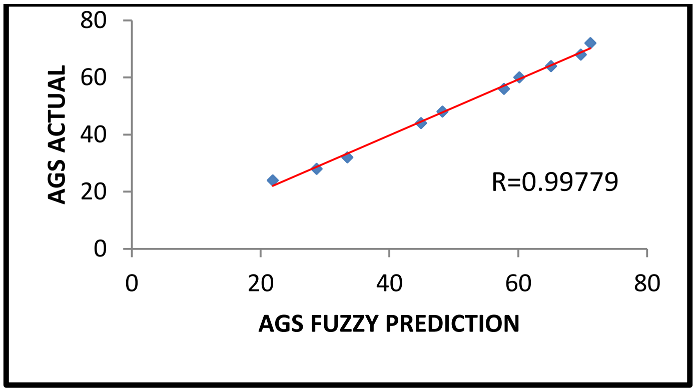

Fig 17: Actual average grain size and Fuzzy prediction

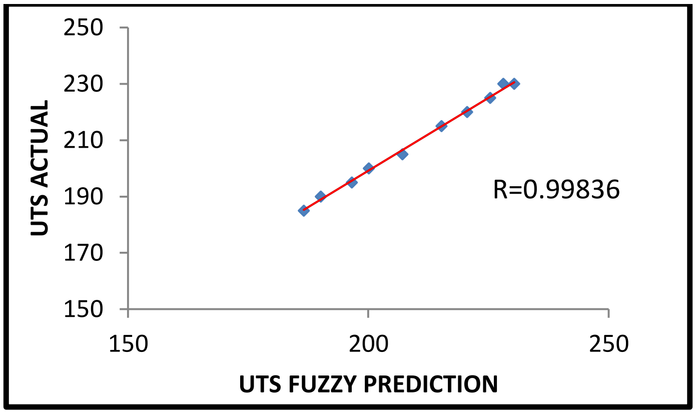

Fig 18: Actual ultimate tensile strength and Fuzzy prediction

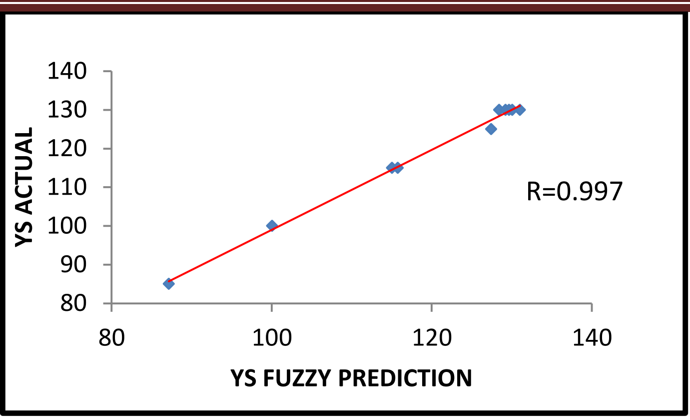

Fig 19: Actual yield strength and Fuzzy prediction

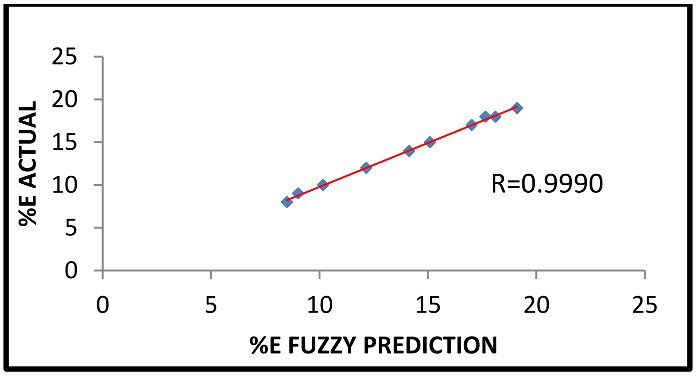

Fig 20: Actual % Elongation and Fuzzy prediction

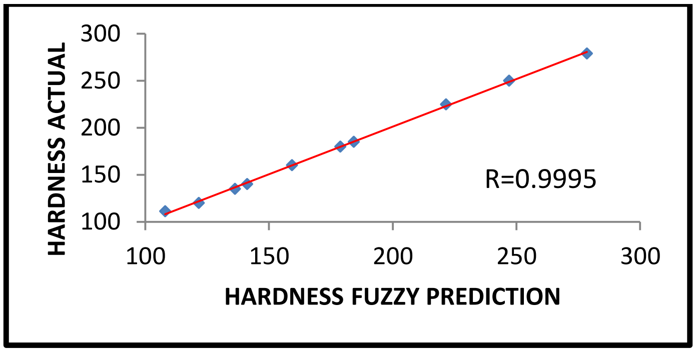

Fig 21: Actual hardness and Fuzzy prediction

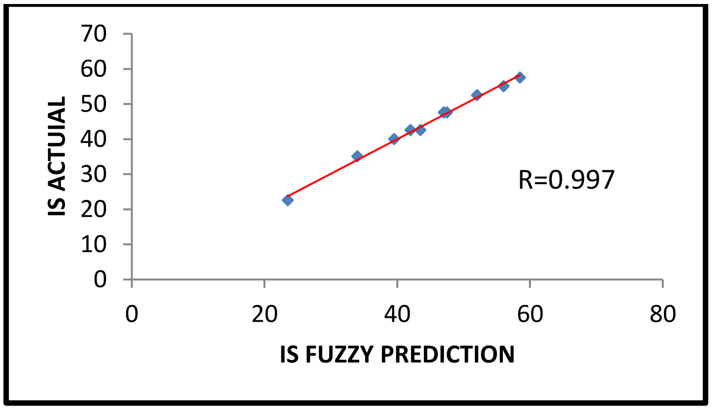

Fig 22: Actual impact strength and Fuzzy prediction

The graphs above (figure 17 to 22) show the regression lines for the mechanical properties and fuzzy predictions. As shown in the graphs, Fuzzy logic with a correlation coefficient (R) value of 0.99779 for average grain size, 0.99935 for ultimate tensile strength, 0.99733 for yield strength, 0.9906 for % elongation, 0.9996 for hardness and 0.9970 for impact strength were obtained. This result demonstrated agreement between the experimental values and Fuzzy model.

CONCLUSION

Modeling the mechanical properties of Aluminum-5%Magnesium doped with Ni using Fuzzy Logic approach .From this study, the following conclusions can be summarized as follows:

- Grain refinement and solid solution strengthening were responsible for the enhanced mechanical properties of the Al-5%Mg doped with Ni. The addition of Ni decreased both the average grain size and globular βAl_3Mg_2 intermetallic.
- Minor addition of Ni generally improved the hardness, ultimate tensile strength and yield strength of Al-5wt% alloy, mainly through microstructural refinement: a reduction of α-Al grain size and morphological changes in detrimental shape of intermetallic compounds. Also, the elongation and impact strength were increased from 10.27% to 19.1% and from 42.5J to 58.5J by addition of 0.4%Ni.
- Fuzzy model developed has capability to predict the average grain size for Al-5%Mg(0.1-1%)Ni with an accuracy of 99.8%, ultimate tensile strength with an accuracy of 99.8%, yield strength with an accuracy of 99.7%, percentage elongation with an accuracy of 99.9%, hardness with an accuracy of 99.9% and impact strength with an accuracy of 99.7%.

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