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Optimization of Artificial Ageing Time and Temperature on Evaluation of Hardness and Resistivity of Al-Si-Mg (Cu or/& Ni) Alloys

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***Abstract*—**The factors necessary to obtain an optimal heat treatment that influence the hardness and resistivity of Al-6Si-0.5Mg casting alloys with Cu or/and Ni additions were investigated. The alloys were homogenised (24hr at 500°C), solutionized (2hr at 540°C) and artificially ageing at various times and temperatures. The alloys were aged isochronally for 60 minutes at temperatures up to 400°C and isothermally at 150, 175, 200, 225, 250 & 300°C for different periods in the range 15 to 360 minutes. The hardness and electrical resistivity of the alloys were measured for various artificial ageing times and temperatures. From the isochronal ageing treatment, hardness found maximum ageing at 225°C. And from the isothermal ageing treatment, hardness found maximum for 60 minutes at 225°C. So the optimal heat treatment consists of 60 minutes ageing at 225°C.

***Keywords*—**Ageing, Al-Si-Mg alloy, hardness, resistivity.

I. INTRODUCTION

THE Al-Si cast alloys are widely used in the automotive industry due to their outstanding castability, good wear resistance and low thermal expansion, together with their low specific weight [1]-[3]. The castings are usually heat treated to obtain the desired combination of strength and ductility. The most common is the T6 heat treatment, which consist of a solution heat treatment, water quench, natural and artificial ageing. A solutionizing treatment in the range 400-560°C dissolve hardening agents in the Al matrix, homogenizes the casting, and modifies the morphology of the eutectic silicon. Castings are quenched from the solution treatment temperature to suppress the formation of intermetallic phases, retain alloying elements in solution to form a supersaturated solid solution and limit their diffusion to grain boundaries, undissolved particles or other defect locations [4].

Among the elements added to Al-Si-Mg alloys for increasing strength and grain-size control, copper has arrested considerable attention. Cu additions reduce the natural aging rate of Al-Mg-Si alloys but generally increase the kinetics of precipitation during artificial aging [5].

Heat treatment is generally carried out to obtain an optimum combination of strength and ductility in Al-Si-Cu-Mg alloys. The steps for the heat treatment consist of solution treatment, quenching and artificial aging [6]. The age-hardening mechanisms responsible for strengthening are based on the formation of intermetallic compounds during decomposition of a metastable supersaturated solid solution obtained by solution treatment and quenching (precipitation hardening). The mechanical properties of these alloys are significantly influenced by the presence of precipitates. W(AlxCu4Mg5Si4) and S(Al2CuMg) phases coexist with θ(Al2Cu) and Mg2Si phases in aged Al-Si-Cu-Mg alloys. θ′ phase preferentially precipitates on the dislocations introduced around eutectic Si particles in the Al-Si-Cu based alloys, while λ′(Al5Cu2Mg8Si5) phase homogenously precipitates in the α matrix, regardless the sites of dislocations, and therefore these precipitates significantly raise the age-hardening ability. Q (Al5Cu2Mg8Si6) phase exhibiting an effect on age-hardening may exist in aged Al-Si-Cu-Mg alloys [7], [8].

Additions of Ni lead to the formation of Al3Ni in the aluminum matrix through eutectic reaction during solidification. The major phases observed in the as-cast alloy are α-aluminum dendrite, primary Si particle, eutectic Si, Al7Cu4Ni, Al5Cu2Mg8Si6, Al15(Cr, Fe, Ni, Cu)4Si2 and Al2Cu. The Al2Cu phase dissolves completely after being solution treated for 2h at 500°C, while the eutectic Si, Al5Cu2Mg8Si6 and Al15(Cr, Fe, Ni, Cu)4Si2 phases are insoluble. In addition, the Al7Cu4Ni phase is substituted by the Al3CuNi phase. The α-aluminum dendrite network disappears when the solution temperature is increased to 530°C. Incipient melting of the Al2Cu-rich eutectic mixture occurs at 520°C, and melting of the Al5Cu2Mg8Si6 and Al3CuNi phases is observed at a solution temperature of 530°C. The void formation of the structure and deterioration of the mechanical properties are found in samples solution treated at 530°C [9].

The changes of the electrical resistivity during isothermal and isochronal aging of the alloys are significant. During age-hardening behaviors are confirmed due to the advantages of the experiment for the electrical resistivity such as the possible measurement of the initial stage of aging without interruption decrease of the electrical resistivity is caused by the decrease of number density with increase of the volume fraction of the precipitates [10], [11].

The main investigation of this paper is to study the optimization of artificial ageing time and temperature on evolution of hardness, resistivity and microstructure of Al-Si-Mg alloys with Cu or/and Ni Additions.

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II. Experimental Procedure

The alloys were prepared and the chemical compositions of the alloys are given in Table I. The experimental cast samples were first ground properly to remove the oxide layer from the surface. All the alloys were kept into furnace at the temperature of 500°C for 24 hours for homogenisation. The cast samples were solution treated at 540°C for 120 minutes and quenched in salt iced water solution. The coupons (15mm x 20mm x 8mm) were prepared from the homogenised plates. Samples were isochronally aged for 60 minutes at different temperature up to 400°C. And the others were isothermally aged at 150,175, 200, 225, 250 and 300°C for different ageing times ranging from 15 to 360 minutes.

Hardness of different alloys processed with different schedules and aged at different times and temperatures was measured in a Rockwell hardness testing machine with 60kg load [F scale and 1/16// steel ball indenter]. Averages of seven consistent readings were accepted as the representative hardness value of an alloy. The electrical conductivity of the thermal treated alloys was carried out with an Electric Conductivity Meter, type 979. 15mm x 20mm finished surface samples produced by grinding and polishing were prepared for these measurement. These measurements were performed using an eddy-current technique at 293 K. These readings were obtained as a percentage of the International Annealed Copper Standard (%IACS) and the resistivity was calculated from the %IACS.

III. Results and Discussion

The chemical compositions of the four alloys are shown in Table I.

TABLE I
CHEMICAL COMPOSITIONS OF THE EXPERIMENTAL ALLOYS

Alloy	Si	Mg	Cu	Ni	Ti	Sb	Al
Alloy-1	5.902	0.461	0.007	0.005	0.099	0.008	Bal
Alloy-2	5.801	0.497	1.980	0.003	0.094	0.005	Bal
Alloy-3	5.965	0.454	0.007	2.202	0.088	0.008	Bal
Alloy-4	5.760	0.501	1.968	2.001	0.081	0.005	Bal

A. Isochronal Ageing

Figs. 1 and 2 show the isochronal aging behavior of the alloys. For all the alloys, the peak aging conditions are attained at ~ 225°C. Although the hardness and resistivity of the base alloy (Alloy-1) is lower than the Cu or/and Ni bearing alloys all over the ageing conditions. The decrease in hardness and resistivity became more pronounced with increasing aging temperature beyond 250°C. The hardness and resistivity of alloy-4 is higher than all other alloys and all over the ageing conditions, the maximum hardness being attained at the peak-aged condition. However, Alloy-2 (2 wt% Cu) and Alloy-4 (2wt% Cu & 2wt% Ni) exhibit stronger resistance to softening in comparison with the other two alloys (Alloy-1& Alloy-3). The increase of hardness and resistivity in as quenched condition with addition of Cu or/and Ni content indicate that the solid-solution strengthening of the alloys. With the increasing of ageing temperature, the precipitation sizes are increase but the total number of precipitates decreases. As a result the resistivity decreases significantly with ageing temperatures.

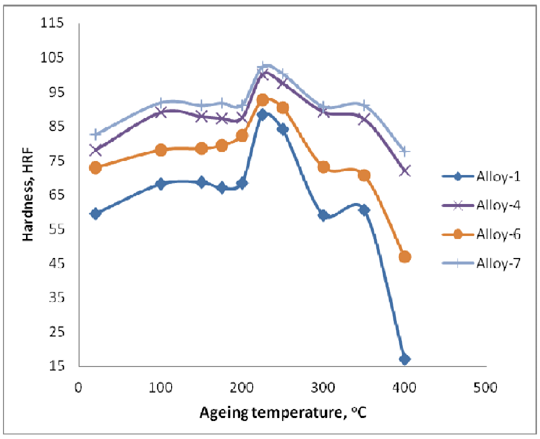

Fig. 1 Variation in hardness of the alloys as a function of ageing temperatures (Isochronally aged for 1 hour)

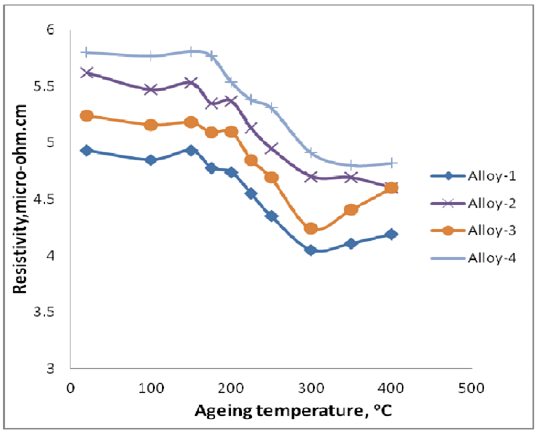

Fig. 2 Variation in resistivity of the alloys as a function of ageing temperatures (Isochronally aged for 1 hour)

B. Isothermal Ageing

Figs. 3-14 show the isothermal ageing behavior of the alloys for different times ranging up to 360 minutes. Hardness and resistivity change of the alloys due to ageing at 150, 175, 200, 225, 250 & 300°C depending on different ageing times. From the isothermal age hardening curves, mentioned at above temperatures the maximum hardness attained after ~60 minutes at ~225°C for all the alloys. The resistivity also decreases significantly after 60 minutes ageing at 225°C. Ageing beyond 225°C, the hardness and resistivity dropped significantly with ageing temperatures (Figs. 9 & 10). It is confirmed that the Cu or/and Ni added alloys show higher number density of Cluster (precipitates) than the Cu or/and Ni free alloys. It is clear that the electrical resistivity of the alloys decreased with increasing holding time of ageing. It can also be observed that the most significant decrees in the electrical resistivity occur at first 120 minutes of ageing. The electrical resistivity shows a step decrease and then an increase leading to peak or a plateau followed by a decrease until it reaches a nearly constant value of 6 hours.

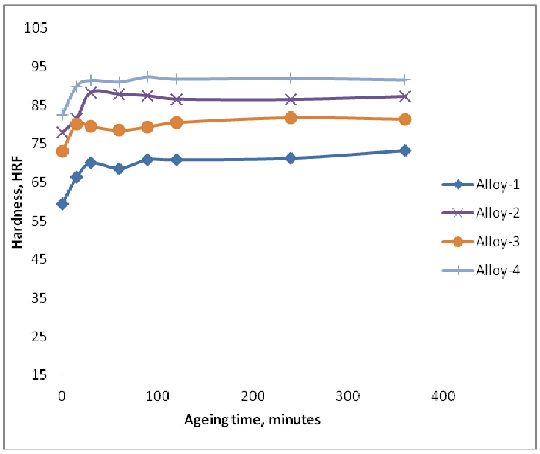

Fig. 3 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 150°C)

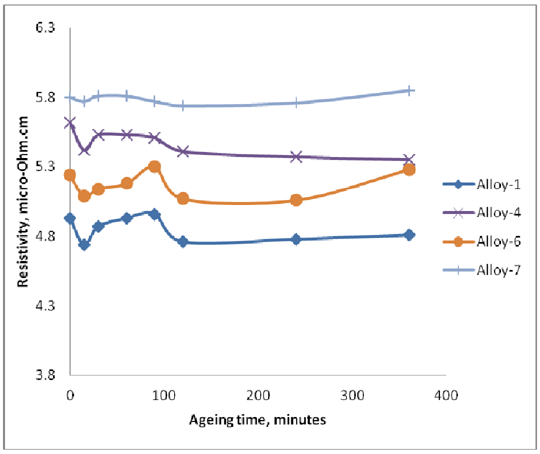

Fig. 4 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 150°C)

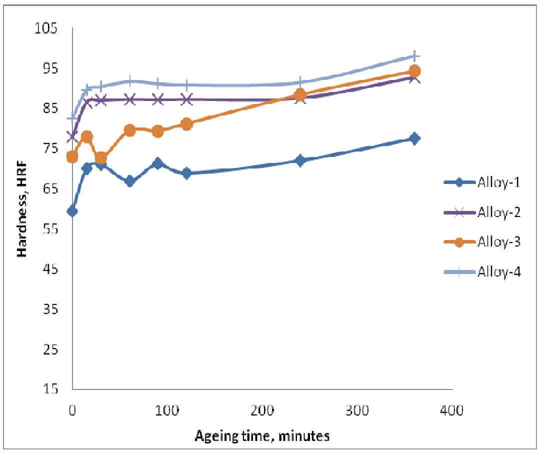

Fig. 5 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 175°C)

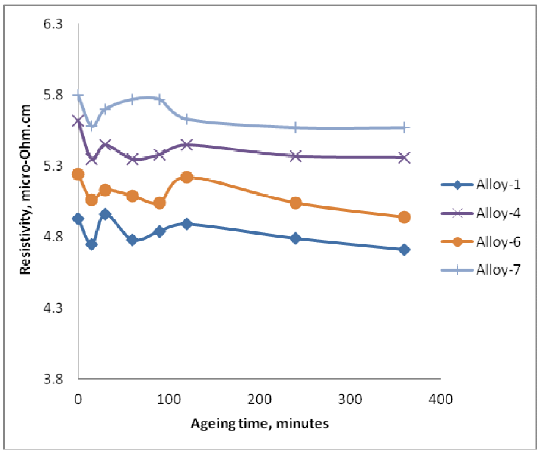

Fig. 6 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 175°C)

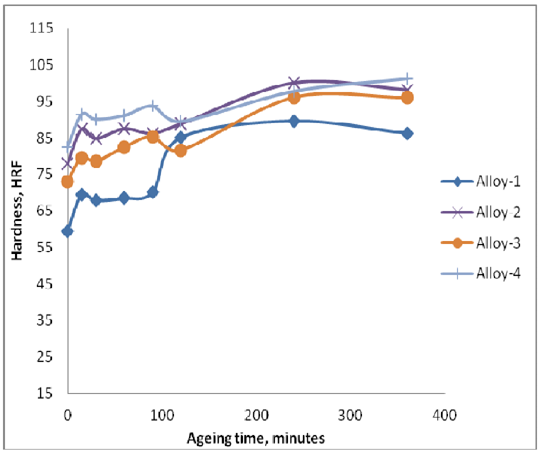

Fig. 7 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 200°C)

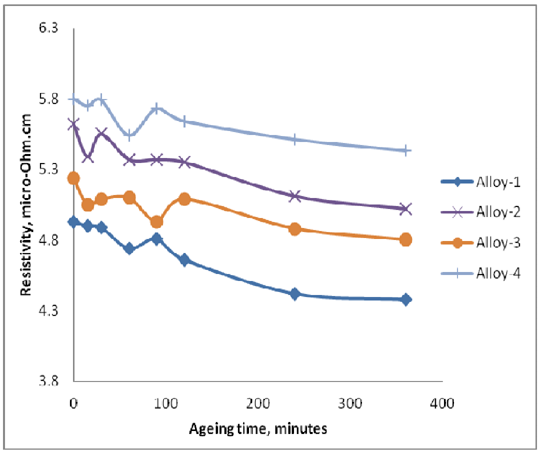

Fig. 8 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 200°C)

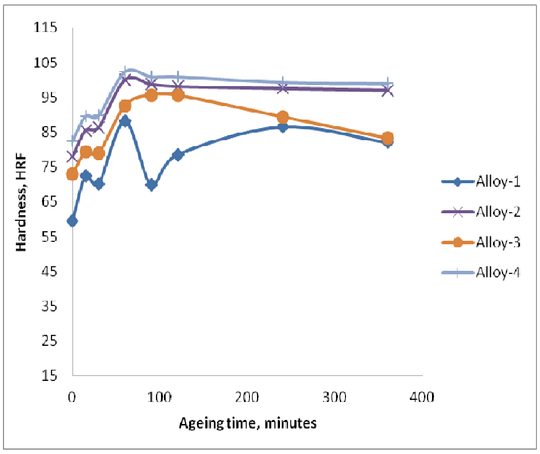

Fig. 9 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 225°C)

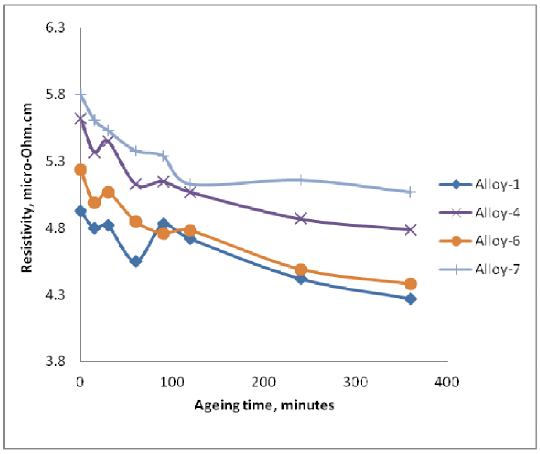

Fig. 10 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 225°C)

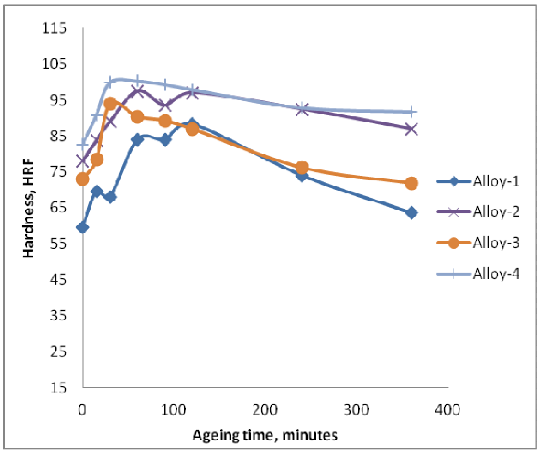

Fig. 11 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 250°C)

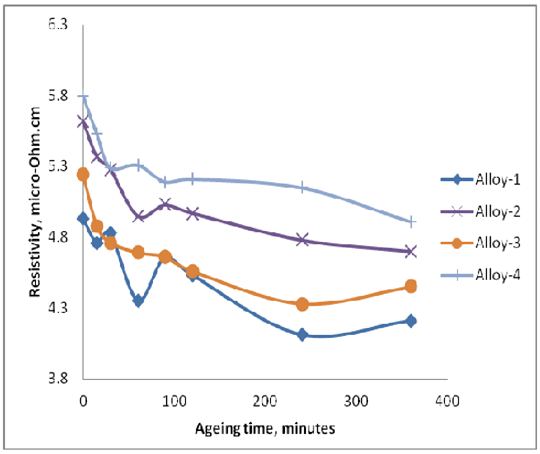

Fig. 12 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 250°C)

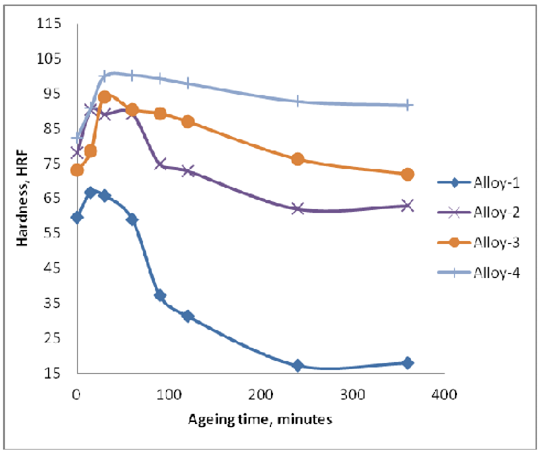

Fig. 13 Variation in hardness of the alloys as a function of ageing times (Isothermally aged at 300°C)

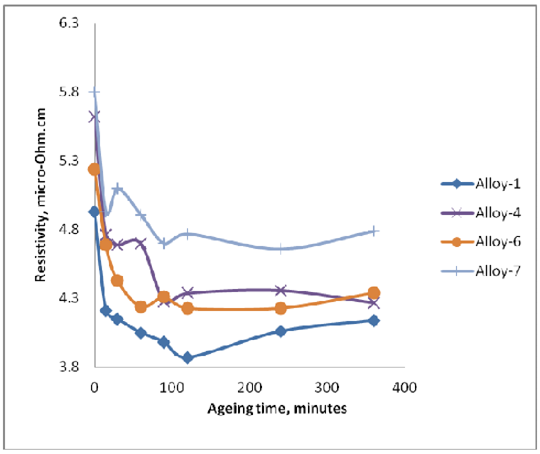

Fig. 14 Variation in resistivity of the alloys as a function of ageing times (Isothermally aged at 300°C)

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C. SEM and Optical Micrographs

The effect of ageing heat treatment on the microstructure of Alloy-1, 2, 3 and 4 at 225 °C for 60 minutes is shown in Figs. 15 through 18. All these micrographs show the α(Al) face centered cubic solid solution is the predominant phase in the microstructure of the alloys. The thermal modified Al-Si eutectics, partially modified Al-Al_3Ni eutectics and other eutectics are observed.

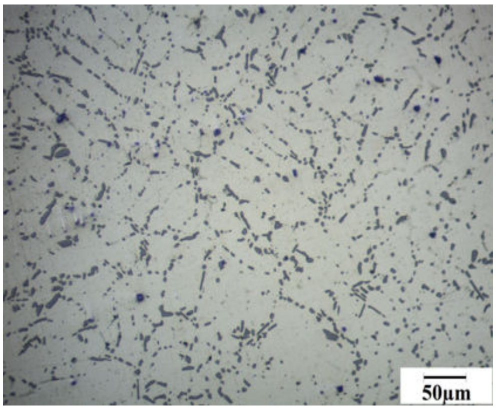

Fig. 15 Optical micrograph of the Alloy-1 ageing at 225^{o}C for 1 hour

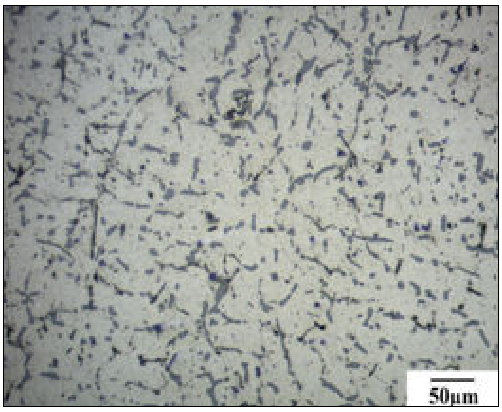

Fig. 16 Optical micrograph of the Alloy-2 ageing at 225^{o}C for 1 hour

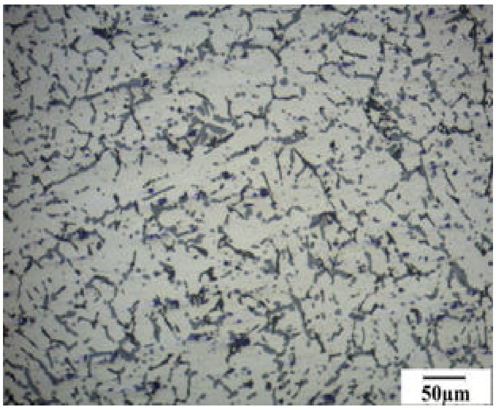

Fig. 17 Optical micrograph of the Alloy-3 ageing at 225^{o}C for 1 hour

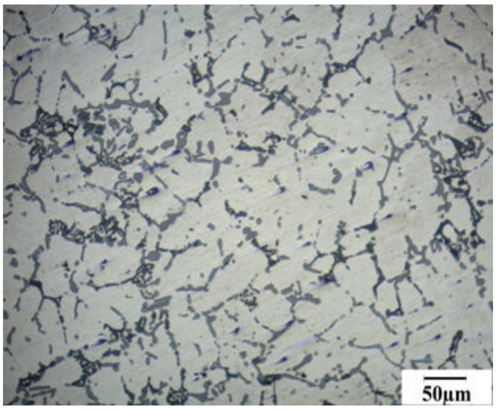

Fig. 18 Optical micrograph of the Alloy-4 ageing at 225^{o}C for 1 hour

The SEM micrographs in Figs. 19-22 (Alloy-1, Alloy-2, Alloy-3 and Alloy-4), show the typical microstructure of the Al-6Si-0.5Mg, Al-6Si-0.5Mg-2Cu, Al-6Si-0.5Mg-2Ni and Al-6Si-0.5Mg-2Cu-2Ni alloys. The SEM results ensure the intermetallic compounds present in the structure. The intermetallic phases are uniformly distributed in all samples. It is observed that the alloys contain the Al, Si, Mg, Cu and Ni containing intermetallic phases such as Al2Cu, Mg2Si and Al3Ni. The alloy-1 contains lower intermetallic phases than the other alloys. Alloy-2, 2wt% Cu addition into Al-6Si-0.5Mg alloy shows higher intermetallic phases than Alloy-1. Al-6Si-0.5Mg-2Cu-2Ni (Alloy-4) shows highest intermetallic phases due to Cu and Ni content.

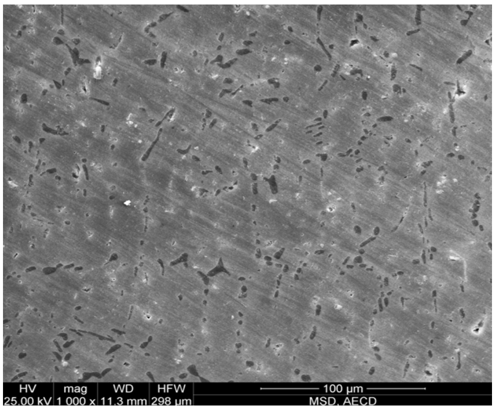

Fig. 19 SEM micrographs of the Alloy-1 ageing at 225^{o}C for 1 hour

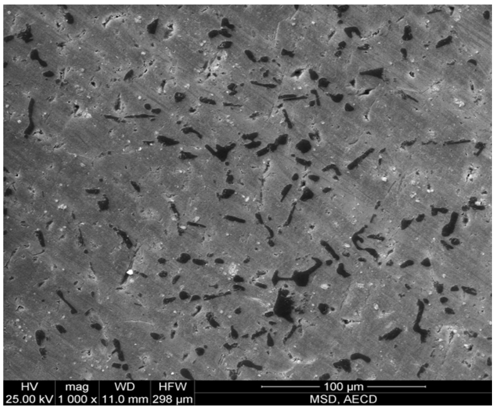

Fig. 20 SEM micrographs of the Alloy-1 ageing at 225^{o}C for 1 hour

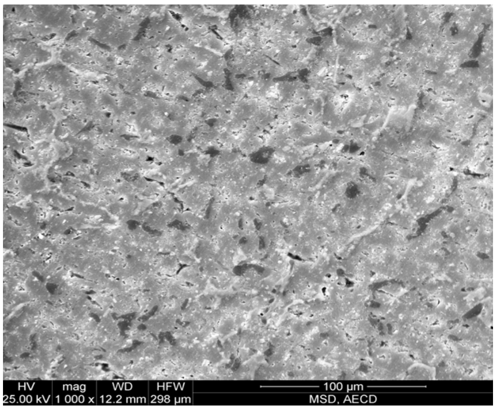

Fig. 21 SEM micrographs of the Alloy-3 ageing at 225^{o}C for 1 hour

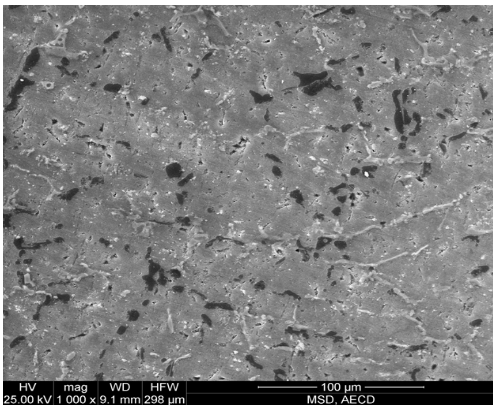

Fig. 22 SEM micrographs of the Alloy-4 ageing at 225^{o}C for 1 hour

IV. Conclusions

After solution treatment at 540^{o}C for 2 hours and quenching, the variance in the hardness and resistivity of Al-6Si-0.5Mg casting alloys with Cu or/and Ni content as a function of artificial ageing time and temperature are determined. The maximum hardness of Alloy-1(88.3HRF), Alloy-2(100.1HRF) and Alloy-4 (102.3HRF) is reached after 60 minutes ageing at ~225^{o}C but Alloy-3(90.5HRF) reached after 90 minutes. This is attributable to the increased volume fraction of precipitates, which contribute to the increased hardness of the aged alloys. During ageing, when coherent zones turn to semi-coherent intermediate precipitates and the volume fraction of precipitates increases, the hardness also increases but resistivity decreases.

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