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Development and Determination of the Age Hardening Characteristics of Al-2.00Mg-2.66Si Wrought Alloy

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ABSTRACT. The study, was carried out by developing the alloy using the foundry route of melting, alloying, and casting. The produced test samples were machined to produce test specimens which were subjected to precipitation hardening treatment. The test specimens were for impact and hardness test to inference the response of the developed alloy to age hardening treatment. The ageing temperature was 190°C, and the ageing time was from 1 -5 hrs. The control specimen was not age hardened and when compared with the age hardened specimens, the tested mechanical properties of the age hardened specimens were better than the control specimen. The hardness was seen to increase, with ageing time peaking at 3hrs of ageing to a value of 38.34 HRB, dropped and rose after 4hrs of ageing and continued to increase, thereby prompting curiosity. The toughness had a steady increase as the ageing time was increased, which clearly showed that the developed alloy responded to age hardening treatment.

Introduction. A lot of aluminium-based alloys have been developed and characterized as can be seen in B.S. Aerospace Series, section L (aluminium and light alloys). Specification of the aluminium-based alloys is clearly stated unfortunately the specification for this research work could not be sighted however, close compositions were seen. According to the wrought aluminum alloy designation system, alloys of these series (Al-Si-Mg) are designated 6xxx. Aluminum – Magnesium – Silicon alloys are heat treatable [2, 5, 11]. Solution treatment followed by either artificial or natural ageing allows considerable increase in yield-strength (3-5 times). Ductility of the alloy decreases as a result of the heat treatment. Hardening of the alloys from this group is achieved due to precipitation of the phase Mg-Si occurring during ageing [5]. The phase has a fixed ratio between the elements content (valence compound), therefore amount of magnesium and silicon in 6xxx alloys is balance according to this ratio or with an excess of silicon. Alloys of this series possess high mechanical strength combined with good formability and corrosion resistance. Excess of silicon enhances effect of precipitation of the alloys but decreases their ductility because of segregation of silicon in the regions of grain boundaries. This adverse effect of silicon may be diminished by addition of chromium and manganese depressing recrystallization during solution treatment. Temperature of artificial ageing of 6xxx alloys is 320 – 360°F (160 – 182°C). Aluminum – Magnesium - Silicon alloys (6xxx series) are used in aircraft and automotive applications, in architectural applications and as structural materials [2].

Aluminium alloys used in both cast and wrought forms may be precipitation hardened if of suitable composition. Age-hardening as it was then called, was infact discovered in some aluminium-based alloys at the beginning of the century and subsequently developed for use in military aircraft during the First World War. The extent of the formation of coherent precipitates at ordinary temperatures is limited so that strength attains a fairly low maximum value in a few days and this process used to be called ‘age-hardening’. At higher temperatures the formation of coherent precipitates proceeds further and so the strength continues to increase. However, a point is reached where the thermal activation is such that tiny non-coherent particles of θ begin to form in accordance with phase equilibrium. Other wrought aluminium alloys which can be precipitation hardened are those

containing small amounts of magnesium and silicon. These form the compound Mg₂Si the solubility of which, like that of CuAl₂, increases considerably with temperature [11].

Pure aluminium is relatively soft and weak, it has a tensile strength of no more than 90N/ mm² in the annealed condition-and for most engineering purposes is used in the alloyed form. The strengths of many aluminium-base alloys can be further increased by precipitation hardening to produce a strength / mass ratio of the same order as for high-tensile steels. The greater relative volume of aluminium alloy involved for a specific force-bearing capacity means that greater flexibility in design is possible. The objective of this research is to develop another aluminium alloy from the 6xxx series (Al-Mg-Si) and determine its ageing characteristics in terms of effects on its hardness and toughness properties. It's already established that there is a relationship between hardness and tensile strength for most metallic materials although it may not be a direct proportional relationship [1, 11]. In like manner there is a relationship between tensile strength and toughness of a material, this can be observed in stress-strain curve where the area under the curve is proportional to the energy required to fail the metal. This energy is equal to the energy required to fail the same material under toughness or impact test. By implication the toughness of a material can be inferred from the area under the curve of its stress-strain plot [5].

Materials and Method.

Materials. The materials used for this project included the following: aluminium cables which were procured from an electrical company in Uyo, pure silicon and magnesium were acquired from Zaria and other materials like, salt (NaCl), sand, clay and water were locally sourced in the University of Uyo and Uyo town.

Equipment. The equipment used during the research included; melting furnace, round metal mould, impact tester, Hardness tester, centre lathe, hack saw, Bench vice, crucible pot, electric furnace with 1200°C peak capacity, furnace pan and tong, vernier caliper, electronic measuring scale, and stop watch.

Method. Aluminum cables known to possess 99.8% purity, silicon powder, industrial salt (NaCl), and magnesium were used to produce Al-2.00Mg-2.66Si wrought alloy. The Foundry route was used for the production. Metal moulds, charge preparation and calculation were all carried out before melting in the crucible furnace where it was possible to stir the melt for homogeneity. The melt was poured to produce four test samples of 20.6 mm dia x 302 mm. These were used to produce test specimens for solutionising and ageing treatments before they were subjected to hardness and toughness tests. Details of the work procedure is as presented below:

Charge Calculations. Total quantity of the developed alloy required for characterisation = 1.4kg (1400g).

But percentage of the alloying element required for the production of the wrought alloy was calculated as follows:

$$\text{The percentage of silicon} = \frac{37.2}{1400} \times 100 = 2.66\%$$

$$\text{The percentage of Mg used} = \frac{28}{1400} \times 100 = 2.0\%$$

The total weight of the cast samples was 1400g and the amount of Si and Mg, used were 37.2g and 28g respectively.

Therefore 37.2+28.0 = 65.2g

Subtracting 65.2g from total cast material the balance will be 1334.8 g i.e (1400-65.2)

Total amount in grammes of Al used = 1334.8g.

Preparation of the mould:

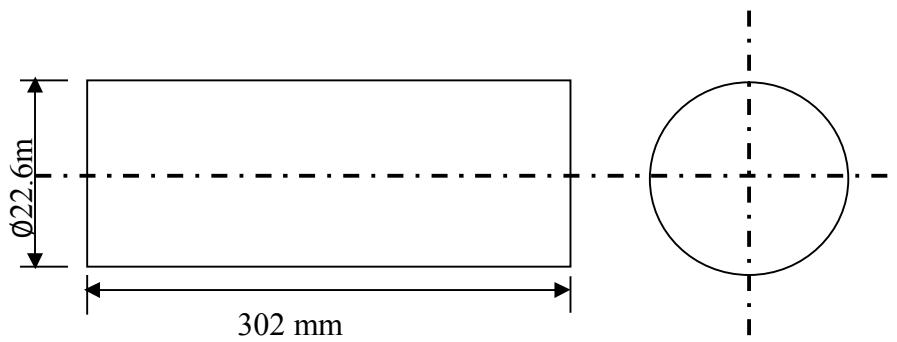


Fig. 1. Side view and bottom view of the steel pipe used in the construction of the metal moulds.

Fig. 1 shows a 302 mm length x 22.6 mm diameter pipe before the pipe was divided into half. Round and flat file was used to remove built up and sharp edges from the surface of the cut to maintain a smooth surface. This pipe was divided in this manner so as to enable the easy removal of the solidified alloy after pouring. Flat sheet metal was welded to each half of the pipe using electric welding. The two halves were brought together again to make one piece, binding wire was used to hold it together and clay was used to seal the opening at the joint. The moulds prepared in this way were dried and ready for use.

Melting and Casting.

The charge as calculated above was transferred to the crucible furnace, where the aluminium was first charged and allowed to melt before the addition of the magnesium and silicon alloying elements. Industrial salt (NaCl) was sprinkled to the melt and vigorously stirred to obtain a homogeneous melt before pouring into the already prepared moulds. The castings were allowed to cool before they were removed from the moulds.

Specimen Preparation.

The sample test bars were as shown in Plate 1, they were machined to produce standard test specimens for hardness test and toughness test. The hardness test specimens were 20mm x20mm while the toughness test specimens were prepared according to ISO Standard for V-Charpy impact test. Plate II shows the prepared specimens.



Plate I. Sample test bars of Al-2.00Mg-2.66Si Alloy.



Plate II. Impact and hardness test specimens before being subjected to ageing process.

Ageing Treatment. The test specimens shown in Plate II were subjected to ageing treatment with the exception of the control specimens. The specimens for ageing treatment were first solutionised at 500°C using the furnace shown in plate III. The test specimens were then quenched in warm water. The quenched specimens were removed and dried before precipitation treatment at 190°C in the same furnace shown in plate III. The ageing time of the test specimens ranged from 1 hr to 5 hrs in steps of 1hr. After the ageing treatment the test specimens were ready for mechanical properties testing.



Plate III. The furnace used for precipitation treatment.



Plate IV. Removal of specimen after each hour of ageing time.

Hardness Testing Procedure. In this experiment test pieces were in round shape as shown in the plate IV below:



Plate V. Hardness specimen before undergoing hardness test.

The test pieces were placed on the table of the testing machine, the wheel was rolled to bring into contact the test piece and the indenter under a minor load of 9.8 kg, which took up the “slack” in the system while the dial indicator was set to zero. The major load was then applied; the indicator made about 2 revolutions before becoming steady, and the hardness value was directly read on the indicator. The machine used had an indenter steel ball (1.6 mm) and Rockwell Hardness B-Scale with minor load 98N (9.8kgf) and major load 980N (100kgf) were selected. The hardness machine identity was Karl Frank 6MBH, WEINHEM BIRKENAH, type – 38506 and werk-Nr-21289.

Impact Testing Procedure. A Notch-bar test piece of standard geometry was mounted horizontally on the anvil of the machine which was struck by a fast moving weighted pendulum with a velocity of 5.24 m/s, while the energy absorbed in breaking the specimen was measured in joules and read directly from a dial indicator. It measured the relative toughness of the material, which indicated the material capacity to absorb energy and deform plastically before fracture. The machine capacity was 300J scale-Charpy with test temperature being room temperature; velocity of pendulum was 5.24 m/s, and the equipment was made by Avery-Denison, England.

Results and Discussion.

Results. The results of the research are displayed in Tables 1-3 below. The variation of the hardness and toughness of the material with ageing time is also shown in figs. 2-3.

Table 1. Result of the hardness test.

Ageing Time	Average Hardness Value
0 hr (unaged)	36.50
1 hr (aged)	36.00
2 hrs (aged)	35.95
3 hrs (aged)	38.34
4 hrs (aged)	34.00
5 hrs (aged)	39.33

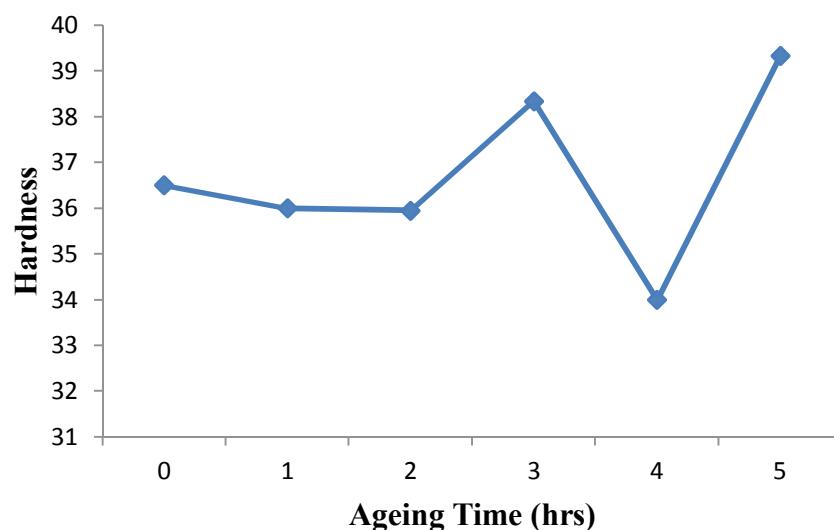


Fig. 2. Hardness variation of the developed Al-2Mg-2.66Si alloy with ageing time.

Table 2. Result of impact test.

Ageing Time	Energy absorbed (J)	Type of specimen
1hr	8j note: blow hole noticed in the sample	Standard v- note (square shape)
2 hrs	28j	Standard v- note (square shape)
3 hrs	21j	Standard v- note (square shape)
4 hrs	28j	Standard v- note (square shape)
5 hrs	38j	Standard v- note (square shape)
Control (Unaged specimen)	9.5j	Standard v- note (square shape)

Table 3. Ageing time versus toughness.

Ageing Time	Toughness
0 hr (unaged)	9.5j
1 hr (aged)	8j
2 hrs (aged)	20j
3 hrs (aged)	21j
4 hrs (aged)	28j
5 hrs (aged)	38j

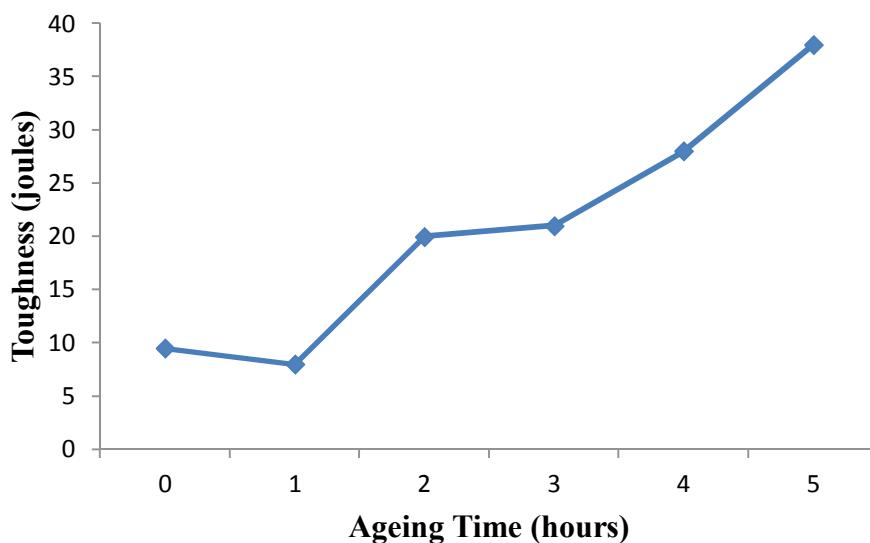


Fig. 3. Toughness variation of the developed Al-2Mg-2.66Si alloy with ageing time.

Discussion. The objective of this research is to develop a wrought aluminium alloy of the composition Al-2Mg-2.66Si and to determine whether it has ageing characteristics. This objective has been implemented and the burden of proof lies with the results generated from the mechanical

tests carried out on the developed alloy. The results are interesting as discussed below and should elicit more research work on the alloy from the materials science and engineering research world.

Analysis of Hardness Test Result. Table 1 shows the result of the hardness test and Fig.2 shows a graphical representation of the variation of hardness and the ageing time at constant temperature (190 °C). The hardness value of the unaged specimen was 36.50HRB this value dropped gradually to 35.95HRB at 2hrs of ageing. This softening is normal because of the precipitates being formed and rearrangement of atoms. Immediately after 2 hrs of ageing the hardness started increasing and peaked at 38.34HRB this pattern fits in with previous works which showed the curve peaking at 3hrs and then the hardness dropping with further ageing. The hardness in this case actually dropped to 34.00HRB at 4hrs of ageing but suddenly started rising and rose to 39.33 at 5hrs of ageing. It is possible that the hardness will continue to increase beyond the 5hrs of ageing. Unfortunately the work terminated at 5hrs it is suggested that further research work should be carriedout which should go beyond the 5hrs used in this work to actually establish the ageing time relationship with the hardness of the developed alloy. The line trend of hardness-ageing time relationship is very interesting and could mean that at longer ageing time; higher hardness values may be obtained. Essien and Udo [2] have observed that the behaviour of the hardness-ageing time curve to rise, fall and start rising again is not uncommon with ageing, it is possible for the hardness to decrease, and is normally linked to the nature of precipitate that has been formed at a particular time. The formation of Mg₂Si precipitates is normally associated with the alloy system under consideration. Coherent and non-coherent precipitates will exhibit different hardness values. Non-coherent precipitates are normally associated with discontinuities at the interface with the matrix [9]. Their formation therefore normally results in decrease of hardness of the material. Ihom, et al. [7] agreed with the above explanation but further added that the ageing process is a diffusion controlled process and is controlled by this equation.

$$D = D_0 e^{Q/RT} \quad (1)$$

Where D is the diffusion rate;

D_0 is the diffusion co-efficient;

Q is the activation energy required to move an atom;

R is the gas constant and T is the temperature in Kelvin.

At higher temperatures, the movement of solutes is faster because the activation energy required is met quickly. Also time is required for the atoms to diffuse to new position X ; that is why the distance travelled by the atoms is a function of diffusion coefficient and resident time of the aged alloy ($X = \sqrt{D_0 t}$). According to the equation the extent of interdiffusion X increases with the square root of time t . Therefore if a longer ageing time is applied it may lead to over-ageing, which means the hardness cannot continue to increase indefinitely but must reduce after some time [7, 9, 10].

Impact Test. The essence of the impact test was to determine the effect of age hardening on the developed alloy as would manifest in the toughness of the material with increased energy absorption of the specimens before failure (fracture). The result and the pattern as the ageing time is increased is shown in Tables 2-3. Fig. 3 shows the toughness variation of the developed Al-2Mg-2.66Si alloy with ageing time. The graph clearly shows that as the ageing time was increasing the material toughness was also increasing. There was a drop in toughness value at 1hr of ageing and the reason was as explained in Table 2. There was a blowhole in the test specimen which reduced the true value of the toughness of the material, because of the presence of the blowhole underneath the specimen the energy absorbed before fracture was drastically reduced. The other specimens were defect free and so gave more realistic results. The toughness kept increasing with ageing time, however, previous works have shown that there comes a time when over ageing occurs and

thereafter both the hardness and toughness reduces [5, 8]. It therefore means that toughness cannot continue to increase indefinitely with ageing time. The developed alloy from the toughness-ageing time curve has clearly demonstrated that it has responded to precipitation hardening treatment, and it is therefore an age hardening alloy. longer ageing periods may be employed to see the extent of improvement of this property. There is a correlation between toughness of a material and its tensile strength that is why the area under a stress-strain curve can be used to infer the toughness of a material. When the area is small it means the toughness of the material is low the energy absorbed by the material before failure is low, if however, the area under the curve is large it means the material is a tough material and must absorb a substantial amount of energy before failure [5, 8]. From the preceding it therefore means that the tensile strength of the developed material was improved alongside with the toughness of the material as the material was aged at different time intervals.

Summary. The research work titled “Development and Determination of the Age Hardening Characteristics of Al-2Mg-2.66Si Wrought Alloy” has been extensively considered and the following conclusions drawn from the work:

- i) the work developed an alloy of the composition Al-2Mg-2.66Si a wrought alloy that was precipitation hardened at various intervals
- ii) the hardness test results of the age hardened alloy at various periods revealed that the developed alloy responded to age hardening
- iii) the impact results of the age hardened alloy specimens clearly showed that the developed alloy responded to age hardening, as the ageing time was increasing the toughness of the developed alloy was also increasing, and
- iv) the developed alloy exhibited an interesting characteristics as the tested mechanical properties kept increasing with increase in ageing time necessitating the suggestion that further work should be carried out on the developed alloy with ageing treatment covering twelve hours.

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