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Production and microstructural analysis of as-cast and heat treated aluminium alloy, (Al-20%wtMg)

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ABSTRACT

As technology advances, the need for lightweight materials for equipments, aircrafts, vehicles and space stations, has become imperative. In view of this, Microstructural analysis of aluminium alloys becomes very essential in establishment of their physical properties. 16 samples were cast and heat treated at 450^{o}C for 1 hr, after which the samples were annealed, and quenched in water and used engine oil. Tensile, fatigue and hardness tests were carried out on the samples (Using ASTMB557, E466 and E10 respectively). Microstructural analysis was effected using metallurgical microscope with magnification of 400x and digital camera attachment. The samples were characterized by hardness of 59.8, 60.5, 69.1 and 79.6 BHN for as-cast, annealed, used engine oil quenched and water quenched samples respectively. The results show that the hardness increased with increasing quench severity. When the samples were subjected to 3.924, 7.848 and 11.772 Nm, the yield at varying stresses, and number of cycles for each of the samples, the ultimate tensile strength observed were 115.159, 77.057, 70.772 and 61.164 MN/m^2 which increased with decreasing quench severity of quench media. The microstructure showed the presence of pores and magnesium grains validating the fact that aluminium and magnesium generate pores during casting.

Key words: Microstructural analysis, Tensile strength, Hardness, Fatigue, Annealing, Quenching.

INTRODUCTION

Modern day engineering materials are required to be light weight and corrosion resistant, coupled with high strength and hardness. Since no material in nature possesses all these properties, alloys and composites have been developed (Agbanigoand Alawode, 2008). Aluminum alloys have been the material of choice for aircraft construction since1930s and hence, aerospace industry relies heavily on 2xxx and 7xxx alloys (Tan and Ögel,2007). These alloys are used in commercial aircraft structures such as fuselage and lower wing surface due to their good damage tolerance, resistance to fatigue crack propagation and fracture toughness(Kamp et al., 2007; Khanand Starink,2008). Another advantage, which is equally important from an environmental point of view, is the fact that aluminum components may be recycled at relatively low energy costs (Moustafa, Samuel and Doty,2003). This has lead to the cost effectiveness of the production and application of aluminum alloys is being constantly improved, e.g., at present an average European automobile contains about 90% of recycled aluminum alloys out of the total share of aluminum alloys in an automobile (Högerl, 1996; Panušková,Tillová and Chalupová, 2008). However, the cost of recycling aluminium alloys can be very expensive, considering the stages, materials additives and machinery that would be involved. The addition of alloying elements such as Mg and Cu make these alloys heat treatableand further improving their mechanical properties and allowing their use in new, more demanding applications such asengines and cylinder heads (Panušková,Tillová and Chalupová, 2008). The presence of magnesium improves strain, hardenability and enhances the material strength by solid solution (Alfonso et al., 2006).

Aluminum–Magnesium alloys have excellent resistance to corrosion in seawater. This is the main reason for their widespread use in the naval industry. In most naval applications, these alloys are exposed to severe hydrodynamic conditions (Jafarzadeh, Shahrabi and Oskouei, 2009; Brown, 1999). To date, only a few studies have been reported in the open literature on the use of A1-Mg alloys in composite solid rocket propellants. One study reported that the use of Mg-A1 alloy resulted in the complete consumption of the metal in the reaction (Deevi, Deeviand Verneker, 1996). Although the Al-Mg alloy sheets have many advantages comparedto conventional materials, their formability is lower than that of steel sheets. Moreover, on the surface of sheets the stretcher-strain (st-st) marks frequently appear during the metal-forming processes. Obviously, such st-st marks are not required, since they decrease the quality of final products such as outer panels of cars. Moreover, the marks may sometimes lead to strain localization and fracture (Nakaand Yoshida, 1996; Nakaand Yoshida, 1998; Naka et al., 2003).

Heat treatment involves solution and aging heat treatments during which a series of changes in microstructure occur which then lead to the improvement of strength. These changes in microstructure include the dissolution of precipitates, homogenization of the cast structure, such as minimization of alloying element segregation, spheroidization and coarsening of eutectic silicon, and precipitation of finer hardening phases (Panušková,Tillová and Chalupová, 2008; Kišand Skoèovský,2005; Majerová, Konečnáand Nicoletto,2006).Liquid aluminium is prone to hydrogen absorption and oxidation, gas porosity and oxide incursion are inevitably found in aluminium casting. If casting is not properly done, shrinkage porosity occurs. Quantitative methods of predicting the relationship between mechanical properties and defects has been developed. Although it is still not possible to fully account for effect of pore shape and defect type on the mechanical properties, but the fact is that there is deterioration in mechanical properties with increasing porosity. Cast aluminium alloys are often considered to be unreliable in view of their mechanical properties due to the presence of variety of casting defects. Consequently design stress in casting are usually very low compared with those allowed in forging (Nyahumwa, 2005).

MATERIALS AND METHODS

Preparation of samples using casting

The samples in their pure form were obtained as aluminium and magnesium. From the percentages given above, various weights of alloying elements were calculated by taking into consideration the specific gravity of the base metal, aluminium-2.7g/cm^3. Since the samples to be cast are in cylindrical shape, the formula for the volume of a cylinder $\pi r^2 h$ was used for the calculation.

Experimental Calculation

The samples to be cast in cylindrical form, therefore the volume of the cylinder = $\pi r^2 h$

h - height of the rod = 200mm, r - radius of the rod = 12/2 mm = 6mm, m - mass, ρ - density, V – volume, density of aluminium = 2.7g/cm^3, 80% aluminium, 20% magnesium

$$V = \pi r^2 \mathrm{h} = \frac{22}{7} \times 0.6^2 \times 20 = 22.63\mathrm{cm}^3$$

$$m = \rho \, x \, V = 2.7 \, x \, 22.63 = 61.1g$$

Mass of aluminium

$$m \, Al = {}^{80}/_{100} \, x \, 61.1 = 48.88g$$

Mass of magnesium

$$m \, Mg = {}^{20}/_{100} \, x \, 61.1 = 12.22g$$

The cylindrical rods of dimensions 200mm long, 12mm diameter was used as pattern for moulding. The horizontal moulding was done in the cope and drag-moulding box while the melting of the samples was done in a pit furnace using small size of melting pot.

The metals were charged into the pot, after becoming molten was thoroughly stirred before being pored into the mould. The mould had two runners and the upper side was vented so as to allow gas to escape in order to avoid trapped air that may result from in gas bubbles. The pouring was done at constant rate to avoid shut run. After the casting the samples were knocked out of the sand and the gating system were cut off using hacksaw.

Heat treatment

Heat treatment of the castings was carried out in a furnace. This was done by heating the samples to 450◦C and holding temperature constant for 1 h. some of the samples were quenched in Water and used engine oil (LubconADRENALIN 20W/50 –PremiumQuality Multigrade Engine Oil) at a room temperature and the remaining samples were left in the furnace to cool with the furnace for annealing. The different types of quenching media were selected arbitrarily to investigate the effect of heating on hardness, microstructure, fatigue and tensile properties.

Tensile test

The samples used for tensile tests were machined into various test piece sizes with the aid of lathe machine. The test piece was machined to comply with ASTM B557 (standard test methods for tension testing wrought and cast aluminum- and magnesium-alloy products). The test pieces were subjected to constant extension rate tensile test (CERT). The samples were clamped to the tensometre and a load of 100kg was used to apply stress in a tensile manner. As the stress is being increased, the test piece showed an increase in length and the pointer to the machine automatically indicates the value of the stress applied. When the elastic limit is reached, the pointer on the dial flickers, as soon as the yield point is exceeded there is an indication of increased stress.

Microstructure

The microstructure changes was observed by passing the specimen through a series of preparatory process in which the specimens were cut with a hack saw on the work bench held with a vice to small size. Immediately after cutting, the specimen is grinded using emery paper / cloth. The emery cloths used was from the coarsest to the finest in order to achieve a very smooth surface.

The specimen was then polished to remove parallel grooves that were scratched into the specimen during the final grinding. This was done using polishing powder and it is to achieve mirror finish. On completing this, the specimen is then inserted into an etchant (NaOH) for a few seconds and then dipped into water to stop the reagent from reacting with the specimens. This process is called etching. After etching, the specimen is ready and viewed under a metallurgical microscope to a magnification of 400x. The picture is then taken with a digital camera (DCM 35) attached to the microscope for all the samples.

Fatigue Test

The samples for fatigue test were machined on the lathe to conform to ASTM standard E 466 (standard practice for cutting constant amplitude fatigue test for metallic material) (Agbanigo and Alawode, 2008).This was done by applying reverse loads (of equal magnitude but different signs with / without any static load) on the Avery Denison 7305 fatigue testing machine. For the pure bending test which we are considering, the loads were imposed at one end of the specimen by an oscillating spindle driven by means of connecting rod, crank and eccentrics. The loads were applied in form of bending moment, the eccentric was mounted on the shaft of the electric motor and can be adjusted to give the required range of bending angles. It is graduated by half degree intervals in order to indicate the angle of oscillation imposed on the specimen. The revolution counter fitted to the motor record the number of cycles to failure. When the specimen breaks, cut out switches attached to the machine stops it automatically. This procedure was repeated on all the specimens increasing bending moments 3.924, 7.848 and 11.772 Nm. This is evaluated using the following:

$$\sigma = \frac{32M}{\pi d^3}$$

where M-bending moment, σ-bending stress and d-diameter.

Brinell Hardness Test

The samples used for the hardness test were machined to conform to ASTM standard E 10.This was done on the universal testing machine by assembling the brinell test compression attachment to the machine. The compression dial and the ball bolster were inserted. The mercury was adjusted up to zero, and the polished test piece was held against the steel ball indenter of 5mm diameter and the load was applied with quick acting handle. The applied load of 250kg was held for 25 seconds. The specimen was then removed from the machine and the diameter of the impression will be measured with brinell reading microscope and the corresponding load recorded.

RESULTS AND DISCUSSION

Tensile properties

The variations of the tensile properties of the as cast, annealed, water quenched and used engine oil quenched samples are shown in figure 1 and figure 2. The tensile test result of the as-cast sample indicated an ultimate tensile strength of 115.159 MN/m^2 while as the samples were being heat treated the strength reduced to 77.057, 70.772 and 61.146 MN/m^2 for annealed, used engine oil quenched and water quenched respectively. While the percentage reduction in area varied from the annealed sample has the highest of 4.30% and the water quenched sample having the lowest of 1.99%. In case of percentage elongation, the highest is annealed with 2.63% and used engine oil quenched having the lowest of 1.12%. It is observed that both the percentage elongation and reduction in area do not follow any particular trend.The implication of this is that quench medium is a factor that should be considered during material selection, casting and heat treatment.

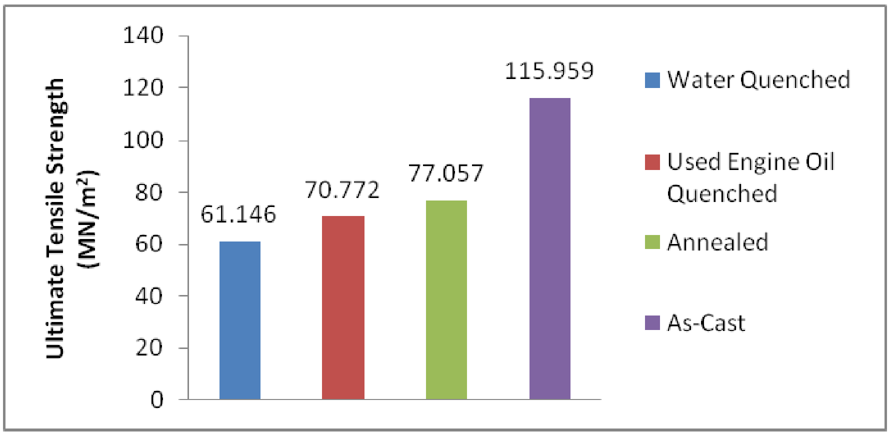

Figure 1: Plot of Ultimate Tensile Strength of Samples

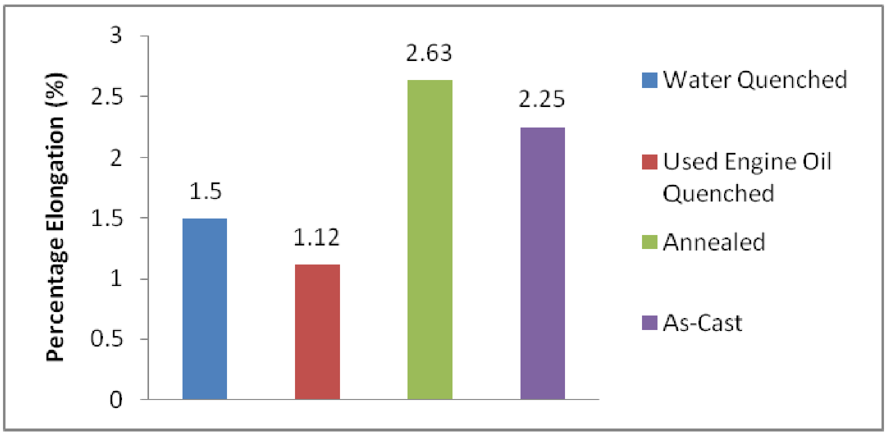

Figure 2: Plot of Percentage Elongation of Samples

The result also showed that the ultimate tensile strength decreased with heat treatment. As the cooling rate of the quenching media used increases, the strength also reduces. It can be said that strength is inversely proportional to the quench severity of the cooling medium. Water with the highest cooling rate has the least tensile strength, while used engine oil quenched sample which has a slower cooling to that of water has a higher tensile strength. Annealing has the slowest cooling rate but has the highest tensile strength of the three heat treated samples, while the as-cast sample has the highest strength for all the tested samples.

Fatigue properties

The variations in fatigue properties of the test specimens are shown in fig 3. In the test, all samples were subjected to same set of moment yielding different stresses and varying number of cycles. For the as-cast sample, the stresses yielded are 319.918, 639.837 and 959.755MN/m and having 100, 400 and 800 cycles respectively. The annealed sample has less stresses yielded but with greater number of cycles i.e. at lower stresses where they will function, they will undergo a high number of cycles. This in fact makes the sample more ductile than the as-cast. The water quenched sample has the lowest number of cycles with stresses less than that of the as-cast sample but higher than that of the annealed sample.

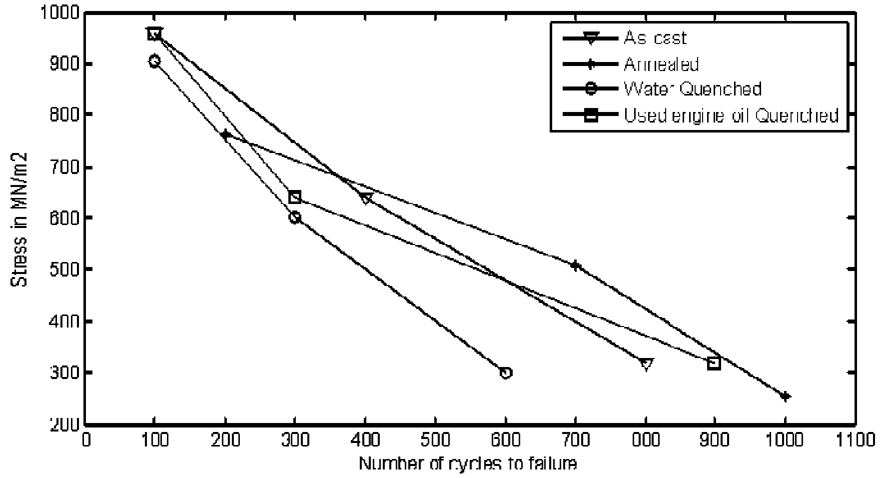

Figure 3: Plot of Fatigue Stress against Number-of-Cycles to Failure

It is observed that the as cast and the used engine oil quenched samples fractured at almost the same number of cycles, which means that depending on the hardness required, the as cast and used engine oil quenched samples can be used interchangeably. It is also observed that there was not much differences in the in the responses observed for all samples, an indication that that all the samples tested find there application in areas with less fatigue so as to make the material perform properly and reduce failure.

Hardness properties

The distribution of the brinell hardness properties of the samples is shown in fig 4. The brinell hardness test result shows that the water quenched sample has the highest hardness, while the as-cast sample has the least hardness. This is an indication that the hardness of Al-20%wtMg increases as the material is heat treated, which is in reverse to the ultimate tensile strength. As quenching is carried out on a metal basically in order to harden it, different quenching media have varying Cooling rates that affect how the hardness is distributed across the metal cross section as the quenching process is taking place.

Water that has a fast cooling rate is observed to have the highest hardness value while the used engine oil quenched has a slower cooling rate to that of water. In annealing the cooling rate is much slower and has the least value. Although too fast cooling rate leads to uneven distribution of hardness, therefore leading to defects and eventually cracks.

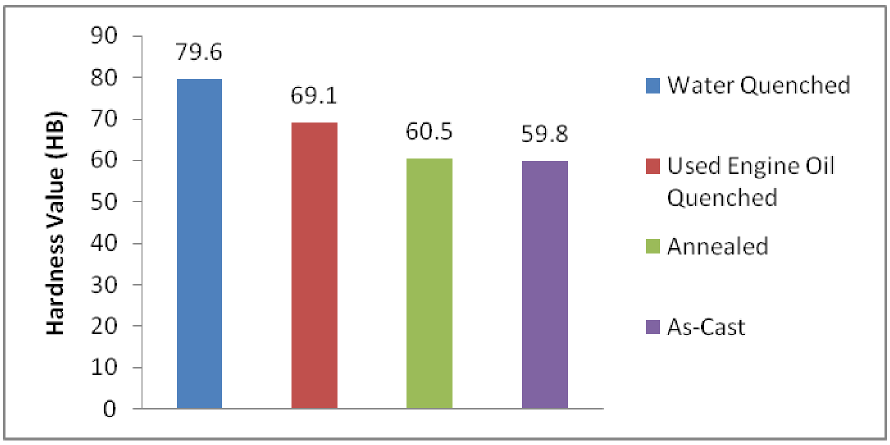

Figure 4: Plot of Hardness values for the samples

Microstructure

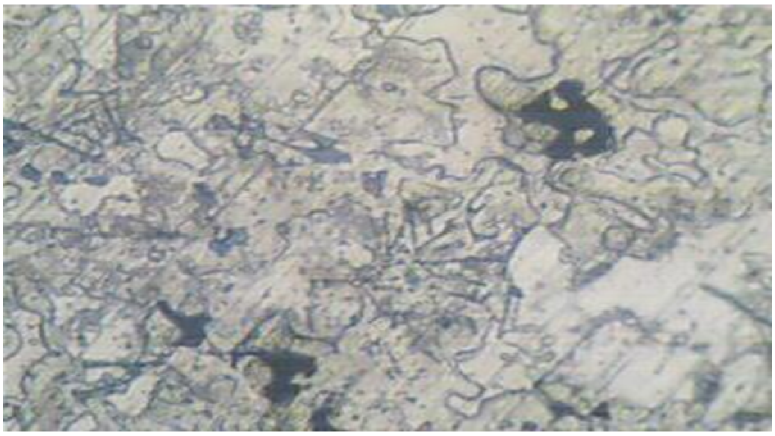

Figure 5: Microstructure of As-Cast Sample

Figure 6: Microstructure of Annealed Sample

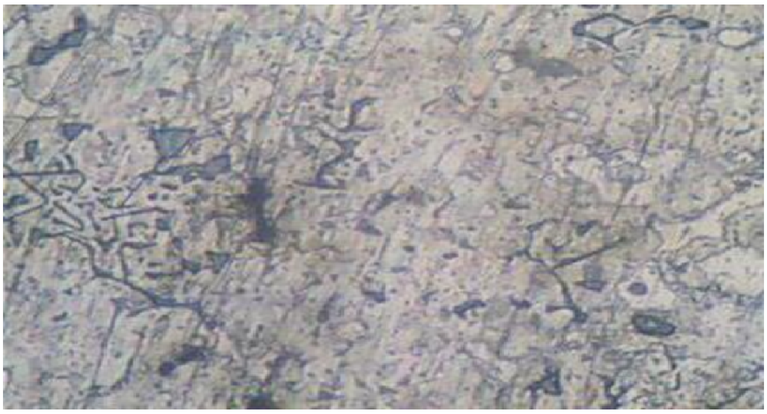

Figure 7: Microstructure of Water Quenched Sample

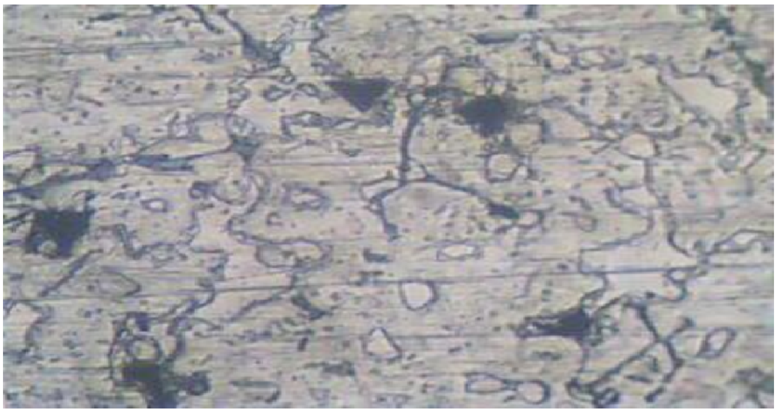

Figure 8: Microstructure of Used Engine Oil Quenched Sample

The microstructure images of all samples were taken and are shown in figure 5, figure 6 figure 7 and figure 8. Aluminium has a face centered cubic crystal structure with an atomic radius of 125pmwhile magnesium has a hexagonal cubic structure with an atomic radius of 150pm(Hatch, 1993). This implies that magnesium atoms would fit into the crystal structure of aluminium thereby filling the inter and intra atomic spaces (interstitial spaces), reducing the possibility of pores.

The as-cast sample, the magnesium atoms fitted well, creating little space for interstitial spaces (pores) along the top right hand corner and towards the bottom left corner as the magnesium and aluminium matrices are evenly distributed along the microstructure. The pores that are present are of irregular shaped (shrinkage pore). This is the reason why the sample failed at a lower number of cycles compared with the annealed sample. The annealed sample has irregular shaped pores (shrinkage pores) to the bottom while the regular shaped pores (hydrogen pores) stretch from the right side to the centre of the specimen. The used engine oil quenched sample has more shrinkage pores distributed to the sides, having very little trace of hydrogen pores. This responsible for the sample having the least number of cycles for all applied moment and samples. Lastly, the water quenched sample has traces of shrinkage pores to its bottom right side and centre right, while also traces of hydrogen pores is visible.

The heating is continued at constant temperature for 1hour several changes will have occurred in the microstructure. On cooling in the different quenching media, some other changes occur depending on the quench severity and cooling rate of the quench medium. Water has a fast cooling rate, as it is used to cool the sample, such cooling rates generally leads to the development of excessive internal stresses, distortion and even crack. From this, the water quenched sample will have a higher number of pores which is shown in its poor response to repeated loading in the fatigue test result.

In case of the used engine oil quenched sample, the cooling rate is slower compared to that of water. This slow cooling rate reduces the possibilities of defect formation. The rate of cooling experienced in annealing is the slowest of all. The sluggishness gives room for pore formation. These can all be seen in the fatigue test result.

CONCLUSION

After the interpretation and discussion of all the results of the samples tested, it can be concluded that Alloying of Al with Mg improved the ultimate tensile strength of aluminium and the Ultimate tensile strength of Al-20%wtMg reduced with increasing cooling rate of quenchant used in cooling. Also, the Hardness of Al-20%wtMg increased by heat treatment and Hardness of Al-20%wtMg increased with increasing cooling rate of quenchant used in cooling. In addition, all the tested samples can function well below stress of $1000MN/m^2$ and the as-cast and used engine oil quenched samples can be used interchangeably in relation to stress limit, but the used engine oil quenched sample is harder than the as-cast sample.

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