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Original Research Article

INFLUENCE OF QUENCHANTS ON TOUGHNESS AND HARDNESS PROPERTIES OF 6063 ALLOYS

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ABSTRACT

This study investigated the effect of quenchants on the mechanical properties of two 6063 aluminum alloys. The samples were heat treated to 530°C for 2hrs subsequently quenched in air, brine solution, engine oil and water. Standard specimens from the quenched alloys were subjected to tensile, hardness and impact tests. The microstructure of these alloys after heat treatment and quenching were examined using optical microscope while the Rockwell Hardness were also determined. The results showed that the tensile strength of both samples significantly improved in brine solution and the least strengths were obtained from the alloy samples quenched in air. The specimen quenched in water showed the highest hardness value of 11.02 HRC and 10.3 HRC for both alloys A and B respectively while the best toughness was for the samples quenched in air for both aluminum alloys. The study concluded that brine solution would be a reasonable quenching medium in obtaining an improved strength and hardness of the aluminum alloys.

1. INTRODUCTION

The 6xxx aluminum alloys have found applications in automotive structures, as they offer an attractive combination of strength, formability, corrosion resistance, surface properties and good weldability (Ravikumar *et al.*, 2014). Since there is an ever-increasing demand for high strength, low-cost materials, investigation of processing microstructure relationships is strongly required. Heat treatable 6xxx aluminum alloys are of special interest for they offer hardening possibilities that lead to specific properties (Mrowka-Nowotnik *et al.*, 2009). Heat treatment operation is vital in the production of any engineering components in order to achieve better mechanical properties of the metal. Mechanical properties of aluminum are strongly connected to their microstructures obtained after heat treatments (Mebarki *et al*., 2004).

Aluminum is solution treated at temperatures generally in the range of 400 to 540 °C (750 to 1000°F), during which some alloying elements are re-dissolved to produce a solute-rich solid solution (Patricia *et al*., 2009). If an aluminum alloy is slowly cooled from an elevated temperature, alloying elements precipitate and diffuse from solid solution to concentrate at the grain boundaries, small voids, on undissolved particles, at dislocations, and other imperfections in the aluminum lattice (Croucher, 1982). Currently, there is a strong interest in the effect of cooling rate on the mechanical properties and microstructure of industrial processed aluminum alloys.

Quenching in many ways is the most critical step in the sequence of heat treating operations. The objective of quenching is to preserve as nearly intact as possible the solid solution formed at the solution heat treating temperature, by rapidly cooling to some lower temperature, usually near room temperature (Azomaterials, 2004). The speed of quenching is important and the result can be affected by excessive delay in transferring the work to the quench. Generally, very rapid precipitation of constituents commences at around 450 ^{o}C for most alloys and the work must not be allowed to fall below this temperature prior to quenching (Gutensohn *et al.,* 2004). Rapid quenching creates a saturated solution and allows for increased hardness and improved mechanical properties of the material (Rollanson, 1998). Studies have shown that the highest degrees of corrosion resistance have been obtained through the maximum rates of quenching (Callister, 1997). In general terms, liquid quenching is performed in water, oil and more recently, in aqueous polymer solutions. Water and oil quenching cover the extremes in terms of cooling rates, with water being the fastest and oil being the slowest. Investigation of the effect of using vegetable oils (groundnut, melon, palm kernel, shea butter and palm oil) as quenching media for pure commercial aluminum has been reported by Adekunle *et al.* (2012). Abubakre *et al.* (2009) investigated the quenching properties of selected media using 6061 Aluminum Alloy. They reported that increasing solution treatment temperature improved soluble precipitates in the alloy, and the heat extraction capacity of the quenching medium also contributed to the formation of fine precipitates.

This study experimentally determined the effect of quenching in air, brine, engine oil and water on the mechanical properties of 6063 aluminum alloys. The mechanical properties of interest are strength, toughness, hardness and microstructural changes occurring during quenching.

2. MATERIALS AND METHODS

2.1. Materials

The materials and equipment used for the experiment were 6063 Aluminum alloy, quenching media (water, air, brine solution, engine oil), Morgan crucible melting furnace, die mould, muffler heat treatment furnace, Chemical Analyzer, lathe machine, impact testing machine, tensile testing machine, hardness testing machine, grinding machine, rotary wheel polishing machine, etching reagent (Keller's reagent) and metallurgical microscope.

2.2. Sample Preparation

Ingot of 2 brands of 6063 Aluminium alloy designated as A and B were broken separately into smaller sizes, heated in an oil-fired Morgan crucible furnace to a temperature slightly above the melting temperature of aluminum alloy (600^{o}C) and cast into billets of rod. Cast rods were machined on a lathe machine in preparation for heat treatments and mechanical tests. Specimens for tensile, hardness and impact tests were machined according to ASTM standards.

2.3. Heat Treatment

The alloy samples were heat treated to a temperature of 530 ^oC and held at this temperature for 2 hours (Abubakre *et al.,*2009, Yakubu and Salawu, 2015). Specimens were quenched in four different media: water, air, brine solution and engine oil. After the solution heat treatment of these specimens, they were age hardened to about 180 ^oC. Experiments were carried out in triplicate for ease of reproducibility. The Rockwell hardness test was used to measure the depth of indentation produced by the load on the indenter and the hardness values were obtained directly in HRC. The amount of energy absorbed by the specimens during fracture was measured using a Charpy impact test machine. The Charpy impact values of each specimen were obtained from the impact testing machine in foot-pounds (ft.lb).

2.4. Microstructural Analysis

The specimens for the microstructural examination were prepared by grinding on hand grinding deck of abrasive papers. Polishing was done on a Universal Rotary wheel using alumina as the polishing medium. Etching was done by swabbing the polished surface of the specimen with the etching reagent (Keller's reagent). A binocular metallurgical microscope was then used to view the micro-structural changes that took place in the prepared samples. The as-received samples were also examined as control specimens.

3. RESULTS AND DISCUSSION

3.1. Chemical Analysis of Alloy Samples

Table 1 shows the average value of the chemical compositions of samples A and B obtained using Chemical Analyzer located at Aluminum Rolling Mills Ota, Ogun State. It can be seen that the two samples have the same proportion of Silicon and Titanium. Sample A has the highest content of Magnesium and Nickel, while sample B has the highest content of Manganese, Iron, and Zinc.

Table 1: Chemical composition of 6063 aluminum alloys

Composition (%)	Mg	Si	Mn	Fe	Ti	Pb	Cu	Zn	Sn	Ni	Al
Sample A	0.499	0.453	0.015	0.325	0.011	-	0.002	0.007	0.001	0.006	98.64
Sample B	0.039	0.613	0.06	0.588	0.14	0.023	0.065	0.145	0.002	-	97.97

3.2. Tensile Test

The tensile test samples were tested to fracture on a tensile testing machine. From the data generated, ultimate tensile strength, percentage elongation, yield stress (MPa), fracture stress, stress at break (MPa) and energy at break (J) were determined. The results are as presented in Figures 1 – 5.

3.3. Rockwell Hardness Test

The results obtained from hardness test conducted using the Rockwell hardness test method and obtained average values after three indentations are presented in Figure 6.

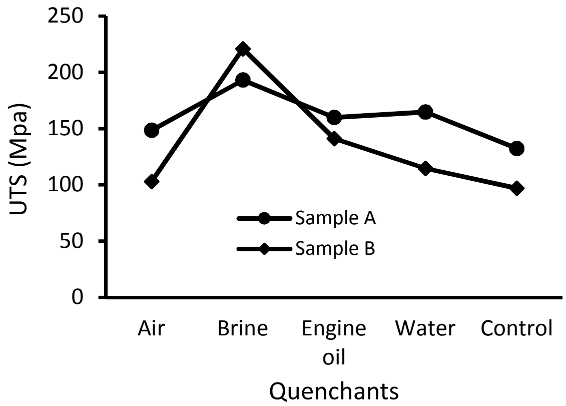

Figure 1: Effect of quenching media on the ultimate tensile stress (UTS)

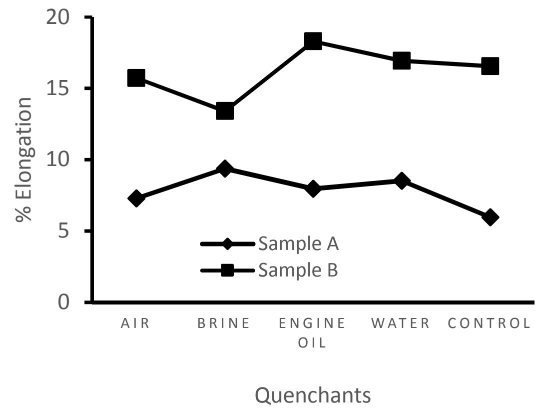

Figure 2: Effect of quenching media on the strain at break (percentage elongation)

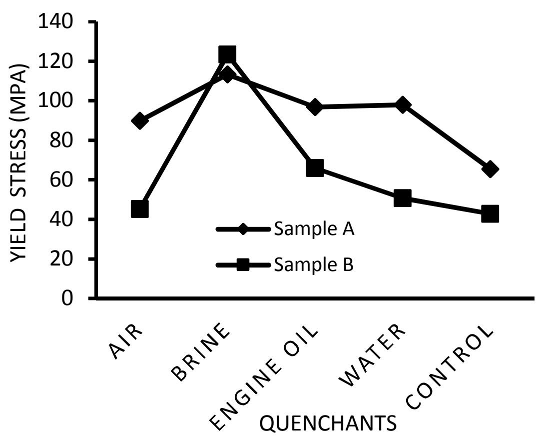

Figure 3: Effect of quenching media on the yield stress

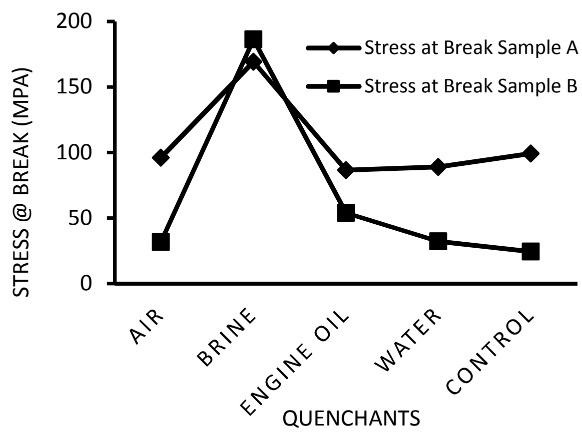

Figure 4: Effect of quenching media on the stress at break

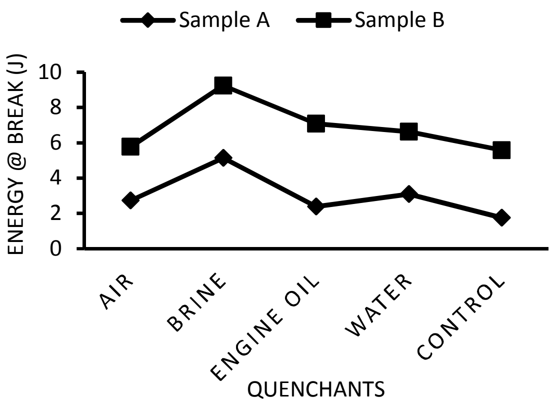

Figure 5: Effect of quenching media on the energy at break

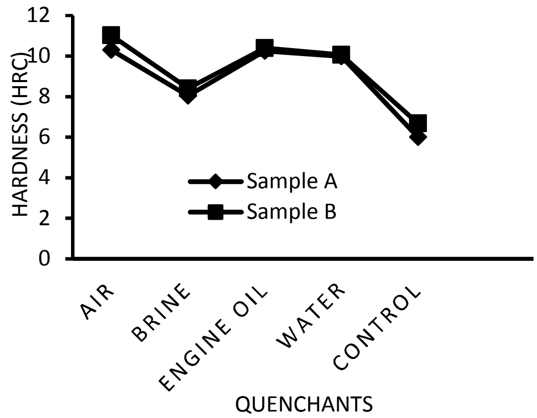

Figure 6: Effects of Quenching media on Rockwell Hardness of 6063 Aluminium alloy

3.4. Charpy Impact Test

Three samples per medium, heat treated at 530°C and quenched in water, air, brine solution and engine oil were tested using Charpy Impact testing machine. The Charpy Impact values of the respective samples in each medium were obtained in foot pound (ft.lb) and the values were converted to Joules (J). The result of impact test conducted after quenching in different media is shown in Figure 7.

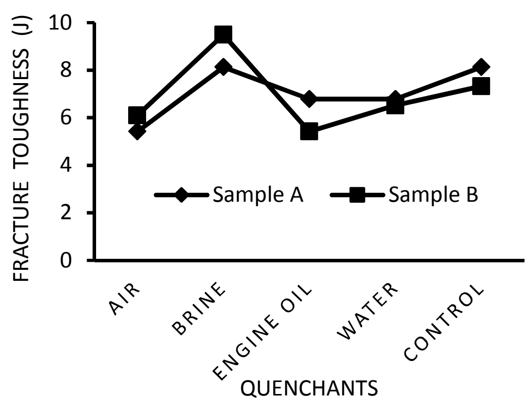

Figure 7: Variation of fracture energy of alloy samples quenched in different media.

3.5. Microstructural Analysis

The microstructural photographs of the specimens, heat treated and quenched in water, air, brine solution and engine oil are shown by Plates a, b, c and d for sample A, Plates e, f, g and h for sample B and Plates i and j for the control specimens.

Plate a: Sample A(water)x100

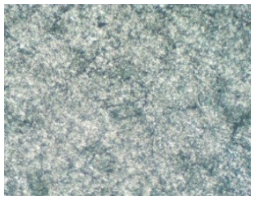

Plate b: Sample A(air) x100

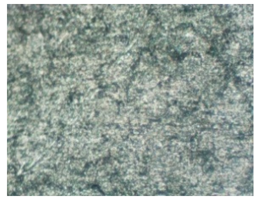

Plate c: Sample A (brine solution) x100

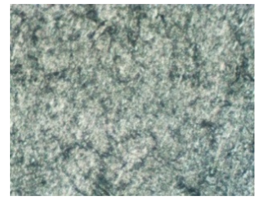

Plate d: Sample A (engine oil) x100

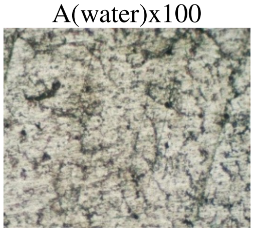

Plate g: Sample B 15% brine x100

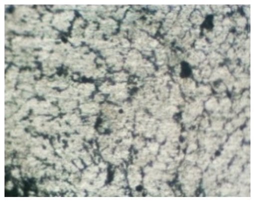

Plate h: Sample B in engine oil. x100

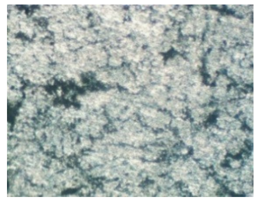

Plate e: Sample B(water) x100

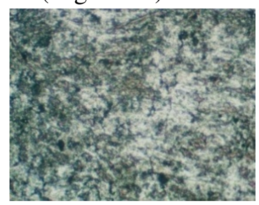

Plate f: Sample B (air) x100

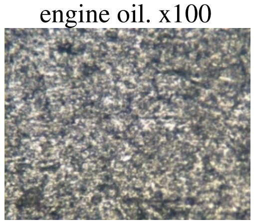

Plate i: Sample A as-received specimen (Mag. x100)

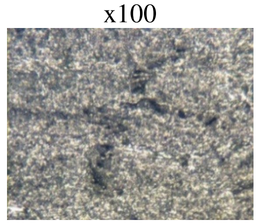

Plate j: Sample B as-received specimen. (Mag. x100)

The results obtained from the tensile test, shown in Figures 1-5, show that the maximum tensile stress of the heat-treated specimens improved against the as-received specimen for both samples A and B. The as-received aluminum alloy sample A had a mean maximum tensile stress of 132.28 MPa while the specimens heat treated to 530^{o}C for 2 hrs and quenched in air, brine solution, engine oil and water had mean maximum tensile stresses as 148.57 MPa, 193 MPa, 159.91 MPa and 164.67 MPa respectively. The highest value was obtained when aluminum alloy sample A was heat treated at 530^{o}C and quenched in brine solution (193MPa). The specimens quenched in water also showed a high increase in the maximum tensile stress (164.67MPa) and likewise the specimens quenched in engine oil (159.91MPa). Since the maximum tensile stress is a measure of the tensile strength of the material, it can be deduced from the experiment that aluminum sample A had improved strength when heat treated at 530^{o}C by quenching in brine solution. For sample B, the as-received specimens had a mean maximum tensile stress of 96.91MPa. The specimens heat treated at 530^{o}C and quenched in air, brine solution, engine oil and water have mean maximum tensile values of 102.86 MPa, 220.82 MPa, 141.07 MPa and 114.43 MPa respectively. The highest value of the maximum tensile stress obtained was for specimens quenched in brine solution. Although, the specimens quenched in other media have improved mean values of the maximum tensile stress, they were not as high as that obtained for the specimens quenched in brine solution. This showed that, out of the quenching media used in this experiment, sample A had improved strength when quenched in brine solution, after heat treatment of 530^{o}C. Abubakre *et al.* (2009) found that 6061 aluminum alloys quenched in water had the highest tensile strength of 109 N/mm^2. Similarly, Yakubu and Salawu (2015) obtained the highest tensile strength of 110N/mm^2 for 6061 Aluminum Manganese Alloy specimens solution heat-treated at 530^{o}C for 1.5 hrs and quenched in water. Dobrzański *et al.* (2008) showed that highest tensile strength of 283Mpa was attainable in AlSi9Mg solution heat treated @ 520°C for 6hrs while quenched in water @ 20°C. Sarada et al. (2016) produced aluminum composite of Al 6061-TiO2 subjected to solution heat treatment 530°C for 1.5 hrs followed by quenching in different media reported that ice quenched samples had the highest ultimate tensile strength of 140.8 Mpa followed by water with a value of 138.4 Mpa. This is also evidenced from the yield stresses of the various specimens. The mean value of yield stress of the as-received specimen A was 65.47MPa, whereas, the specimens quenched in air, brine solution, engine oil and water have mean yield stress values of 89.94MPa, 113.26MPa, 96.85MPa and 98.03MPa respectively. The optimum yield stress was obtained when the specimen was heat treated and quenched in brine solution. The yield stress of the as-received specimen B had a mean value of 42.78 MPa. The specimens quenched in air, brine solution, engine oil and water had mean yield stress values of 45.23 MPa, 123.41 MPa, 65.97 MPa and 50.64 MPa respectively. The highest yield stress value was obtained for sample B heat treated and quenched in brine solution. Therefore, based on the results of this experiment, sample B showed the best improvement in strength when heat treated at 530°C and quenched in brine solution, compared with other quenching media used.

Abubakre *et al*. (2009) obtained a yield Strength of 70.89 N/mm^2 for 6063 aluminum alloy solution heat treated at 450 °C for 2 hrs later quenched in water. Also, a highest yield strength of 678.18 (MPa) was obtained for steel heated to 730°C and soaked in water for 45 min (Adeniran *et al*., 2015). Yakubu and Salawu (2015) obtained highest yield stress of 71.90 N/mm^2 in water, though, Sarada *et al*. (2016) had the highest in ice (140.8 Mpa) followed by water (133.9 Mpa).

Also obtained from the result was the strain at break, which is also known as the percentage elongation. This is a measure of the ductility property of the material. The mean value of the strain at break of the as-received specimens for sample A was 0.05972 while those for heat-treated specimens quenched in air, brine solution, engine oil and water were 0.07286, 0.09381, 0.07964 and 0.08516 respectively. This indicated that the heat treatment carried out improved the ductility of the material for each quenching media used when compared with the value obtained from the as-received. However, the medium which improved the ductility most was the brine solution, having a mean percentage elongation of 0.09381 compared with others. For sample B, the mean percentage elongation (strain at break) of the as-received specimens obtained was 0.16546 while those for specimens quenched in air, brine solution, engine oil and water have mean values of 0.15724, 0.1341, 0.18296 and 0.16933 respectively. The most improved ductility was obtained when the material was quenched in engine oil. However, the percentage elongation value decreased for specimens quenched in air and brine solution when compared with the as-received specimen. Dobrzañski *et al.* (2008) obtained 8% elongation in AlSiMg heat treated @ 520°C for 6hrs quenched in water and Abubakre *et al.,* (2009) had 7.00 percentage elongation in water after solution heat treatment @ 530°C. Also, Yakubu and Salawu (2015) reported that 7.02% elongation was observed in water, whereas, Adeosun et al., (2010) stated that 25% elongation can be obtained through deformation, homogenization, SHT and water quenched processes.

The hardness values obtained from the Rockwell hardness test of each specimen is presented in Figure 6. The mean hardness value was plotted against the quenching media. From the results, it was observed that the subjection of the specimens to a heat treatment at 530°C and quenching in the various media improved the resistance to indentation (hardness) of the specimens. The hardness values in HRC, increased as compared to the values of the as-received specimens. For sample A, specimens heat treated at 530°C and quenched in water, had the highest hardness values with the mean values of 10.30 HRC, which was greater than the mean value of the as-received samples, obtained as 6 HRC. The mean hardness values of the samples quenched in brine solution, engine oil and air were 10.25, 9.99 and 8.04 HRC respectively which also showed improvement when compared to that of the as-received samples. The as-received specimen's mean value for sample B was obtained as 6.68 HRC, which was higher than that of the as-received sample A (6HRC). Sample B specimens, heat treated at 530ºC and quenched in the various media, also increased in the hardness values, when compared with those of the as-received. The mean values for heat-treated specimens quenched in water, brine solution, engine oil and air were 11.02, 10.40, 10.06 and 8.41 HRC respectively. It can be deduced from the results that the best and most improved hardness was obtained by quenching the material in water when heat treated at 530ºC. The least improvement in the hardness of the material was obtained when the material was quenched in air. Moreover, Balamugundan *et al.* (2014) also obtained the highest value of 140BHN for Al 6066 quenched in water. The differences in this research and others may be attributed to the different quenchants used and the compositions of the materials. The highest values of 10.30 and 11.02 for materials A and B for hardness were for the use of air as a quenchant. This is at variance is at variance with the value obtained by Tiwary *et al.* (2014) that obtained the highest quench severity in brine when compared with oil or distilled water. Though, there are variety of quenchants for industrial heat treatment (water, brine, mineral and vegetable oils, etc.) as observed by Callister (2007), brine has more quenching severity than water (Totten and Howes, 1997).

For sample A, three as-received samples were tested under the Charpy Impact testing machine and their mean value was estimated at 8.13 Joules. The specimens heat treated at 530ºC and quenched in water, air, brine solution and engine oil were also tested and their mean values were obtained 5.42, 8.13, 6.78 and 6.78 Joules respectively. It was observed that there was decrease in the Charpy Impact values obtained from the heat-treated specimens quenched in water, brine solution and engine oil compared to the as-received specimen. The air-quenched specimens however, had a mean Impact value which was equal to the as-received mean value. For sample B, the as-received samples mean Impact value was estimated at 7.32 Joules. When specimens were quenched in water, air, brine solution and engine oil, the mean impact values obtained were 6.10, 9.49, 5.42 and 6.51 Joules respectively as shown in Figure 7. From the results, it was observed that heat treating to 530ºC, followed by subsequent quenching in water, brine solution or engine oil, lowered the maximum amount of energy the material could absorb before fracture, therefore, quenching in these media did not improve the toughness of the materials. However, heat treating to 530ºC, followed by subsequent quenching in air showed improvement in the energy absorbed by the material in sample B while in sample A, the same value was obtained with that of the as-received specimen. Steel heated to temperature of 730 ºC and later soaked in water for 60 min had an impact energy value of 14.92 J as obtained by Adeniran et al. (2015).

The result of the microstructural examination is as presented in Plates a - j. The specimens quenched in air, brine solution, engine oil and water for sample A showed improved strength when compared with the as-received specimen. This is evidenced from the formation of finer precipitates of Mg_2Si on the Al-matrix when compared with the as-received specimen, which has a coarse Mg_2Si precipitated on the Al-matrix. The finer the precipitates formed on the matrix, the higher the values of the maximum tensile stress obtained, which therefore, improves the strength of the material. Also, it would be observed that the improvement in strength from the microstructural examination was as a result of formation of more volumes of Mg_2Si precipitates as compared to formation of dispersed precipitates in the as-received specimen. The change in the microstructure of these specimens, when compared with the as-received specimen was induced as a result of solutionizing temperature (530ºC) and rate of quenching, produced by the various quenching media. It can also be seen from the microstructure photographs obtained that the specimen quenched in brine solution had the finest precipitate of Mg_2Si on the Al-matrix, which thus, implied that the strength of sample A was best improved when heat treated at 530ºC and quenched in brine solution. In sample B, the microstructural examination showed that the specimens quenched in the four media gave improved strengths when compared with the as-received specimen. This was evidenced from the formation of more volumes of Mg_2Si precipitate of the heat-treated specimens when compared with the dispersed precipitates formed in the as-received specimen. The optimum strength was observed in the specimen quenched in the brine solution after heat treating to 530ºC. The Mg_2Si precipitates are more evenly distributed in the brine solution-quenched specimen. The specimen quenched in engine oil also showed improved strength, through the even distribution of the precipitate on the Al-matrix is not as that shown by the specimen quenched in brine solution. Therefore, it can be deduced that the microstructure of the aluminum alloy was altered by the heat treatment at 530^oC and quenching in the media used in this experiment.

It is therefore not a surprise that the highest values for Ultimate Tensile Strength, yield stress, toughness and Charpy test were obtained using brine as a quenchant. However, for ductility and hardness, the highest values were obtained using air as a quenchant.

4. CONCLUSION

It can be concluded that both aluminum alloy samples showed an improvement in strength and ductility when heat treated at 530^oC and quenched in brine solution, however, their ductility increased when compared with the as-received sample. The engine oil-quenched sample showed the highest improvement in the ductility. The highest hardness value was obtained for both samples quenched in air. From the impact test, both samples had highest impact energy when quenched in brine solution and decreased in impact energy was observed in other media. It can be concluded that for both samples A and B their strengths can be best improved if heat treated at 530 ^oC and quenched in brine solution, also, sample B behaved better in the heat treatment processes carried out in this experiment in terms of improvement in strength, hardness and impact energy. This can be confirmed by the higher values of maximum tensile stress, hardness and Impact energy obtained in sample B compared with sample A.

5. CONFLICT OF INTEREST

There is no conflict interest associated with this work.

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