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Effects of Precipitation Hardening Heat Treatment on Mechanical Properties of Recycled Aluminium, Silicon Alloy

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ABSTRACT: The objective of this research was to determine the effect of precipitation heat treatment on mechanical properties of recycled Aluminium- Silicon alloy. Aluminium block engine scrap was melted and cast via sand casting method the samples were machined into standard specifications of hardness, tensile and impact with lathe machine. The samples where solution treated at 500°C, 515°Cand 530°C in a heat treatment furnace to obtain solid solution and quenched in water at room temperature. The samples where aged at 200°C, 175°C and 150°C for 3 hours each to obtain precipitation hardening. The samples where then subjected to tensile strength test, impact test and hardness test before and after heat treatment to study the effect of precipitation hardening heat treatment on the mechanical properties. From the results of the control sample, solution temperatures and ageing temperatures, the control sample has a UTS, impact energy, and Vickers hardness of (135.36 Mpa, 1.04J, and 96.9 HV) respectively, and at 500°C &200°C (180.32Mpa, 1.04J and 130.7HV) respectively, at 515°C &175°C (201.18Mpa, 1.13J and 154.6HV) respectively and at 530°C &150°C (185.19Mpa, 1.08J and 113.2HV) respectively. It was observed an increase in the tensile strength with UTS of 201.18Mpa, impact energy of 1.13Joule and hardness of 154.6 HV values. This shows that 175°C ageing temperature has the best evaluation of tensile strength, impact strength and hardness at room temperature.

Keywords: Heat treatment, mechanical properties, Aluminium, silicon and alloy
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INTRODUCTION

Alloys are created by combining a metal with another metal to enhance its properties. For instants, steel is stronger than iron which its primary element. The physical properties, such as conductivity and density, of an alloy may not differ greatly from those of its component elements, but engineering properties may be considerably different from those of the constituent materials. (Yang et al., 2006)

Aluminium–silicon (Al–Si) alloys are the most widely used in foundry application due to their excellent castability and high strength-to-weight ratio. However, their thermal stability and mechanical properties can be limited. Researchers have explored the addition of alloying element like copper, zinc, magnesium, and transitional metals to modify mechanical properties and corrosion resistance at elevated temperatures. (Narayanan et al., 1994). Recycling Al scraps to produce new Al metal and alloys are an alternative to primary Al production. The chemical composition of this alloy is strictly related to the scrap quality, resulting in impurities and challenging alloying element management. Iron (Fe) plays a crucial role in distinguishing primary and secondary Al alloys, forming brittle intermetallic compounds that influence final mechanical properties (Timelli, 2011).

Precipitation-hardenable Al alloys have the potential for being used in the manufacture of several parts and components in the automotive and aerospace industries, including strategic power train components (Kaufman et al., 2004; Chaudhury et al., 2006; Ran et al., 2008), due to their inherent lightness and good weight-to-strength ratio (Abid et al.,2010). Among them, Al-Si alloys have shown excellent formability and corrosion resistance in practical application (Peng et al., 2008). However, the limited thermal stability and strength loss about 150°C necessitate the development of new Al-Si based grades with sufficient thermal stability. Recent finding involves alloying elements like Cu, Zn, Mg and transitional metals to modify mechanical properties and corrosion resistance at elevated temperatures. (Voorhees et al., 2006 and Kasprzak et al., 2009 and Kasprzak et al., 2010). Thus, search for new Al-Si based grades with sufficient thermal stability at continuously increasing temperatures are going on (Voorhees et al., 2006 and Kulekci, 2008). According to recent findings, alloying elements, such as Cu, Zn, Mg and transitional metals are being used in the base Al-Si chemistry to modify mechanical properties and corrosion resistance at elevated temperature (Vargel, 2004; Voorhees et al., 2006; Sigworth et al., 2006; Kulekci, 2008; Sigworth, 2008; Kasprzak et al., 2013; Kasprzak et al., 2014). As documented in the literature, the effects of Mg content on the mechanical properties and quality index of Al–Si casting alloys were examined in a number of studies. (Ibrahim et al., 2016) reported that increasing the Mg content from 0.25 to 0.44 % in a sand cast Al–Si–Mg alloy results in increasing the strength of the alloy without any appreciable change being observed in its quality index. A further study (Chen et al., 2006 and Ninive et al., 2014) investigated the influence of Mg content on the tensile properties and quality index of Al–Si–Mg casting alloys containing Mg in the range of 0.06–0.44 %. It was observed that increasing Mg levels in this range resulted in increasing the strength and raising the quality index of the alloys. The improved quality of the casting, in this case, is related to the fact that the amount by which alloy ductility is decreased as a result of adding Mg is less than the amount by which the strength is increased; thus, the overall effect of increasing Mg from 0.06 to 0.44 % is an increase in the quality index. (Andersen et al., 1998) studied the influence of Mg content (0.3, 0.5, and 0.7 %) on the quality index of Al–Si–Mg casting alloys investigated under conditions of various iron levels, solidification rates, and heat treatments. It was concluded that the quality index value of 355 alloys may be optimized if the Mg content does not exceed 0.5 % in order to avoid the precipitation of the

p-$Al_8Mg_3FeSi_6$phase.

Therefore, this research aims at evaluating the effect of heat treatment on mechanical properties of Al-Si alloys, building upon existing studies on the influence of Fe, Mg content on mechanical properties and quality index

MATERIALS AND METHOD

Materials

The materials used in this research include; aluminium engine block scrap, sand for molding; molding boxes, crucible, binder, water, spade, pipe, saw blade, vernier calliper, measuring tape.

Equipment

The following equipment were used; Charcoal fired crucible furnace for melting of the aluminium scrap obtained from the foundry workshop; polyester for surface polishing of sample and spectrometer to determine the chemical composition of Al alloy; Muffle electrical resistance furnace used for the heat treatment with heating capacity of 1800ºC from the heat treatment lab; research and development centre in defence industries corporation of Nigeria (DICON and ABU Zaria, spring balance to measure the quantity of aluminium used; A lathe machine used for the machining of A356 alloy rods for the production of the tensile, hardness and impact test samples. Hounsfield Tensometer was used in conducting tensile test for the determination of the tensile strength and the percentage elongation, Vickers/micro hardness tester was used for hardness test.

Test sample preparation

Casting of test samples

Aluminium engine block scraps used in this research work were obtained from Farin-gada market in Jos north, plateau state and reduced to smaller sizes using a sledged hammer. The aluminium scrap was charged into the charcoal fired crucible furnace and heated for 950ºC till homogenous melt was achieved before pouring into an already prepared sand mould. The alloy was left to cool for about 20 minutes after which the cope and drag was separated and the sand mould destroyed in order to remove the as-cast rod samples.

Machining of test sample

The resulting as-cast rod sample was machined using the lathe machine to the desired standard dimension required for the Hounsfield Tensometer tensile machine, Hounsfield Tensometer Charpy Impact and Micro/Vickers hardness testers. The dimension and technical data of the sample are given below.

Precipitation hardening heat treatment

A total number of twenty-one (21) test samples were heated in the muffle furnace at a temperatures 500ºC, 515ºC and 530ºC for solutionizing heat treatment and then held for 6 4, and 2 hours respectively. The solutionized samples were rapidly quenched in a bath of water. The as-quenched samples were then aged in the electrical furnace using the varying ageing temperatures of 200ºC, 175ºC and 150ºC and ageing time of 3 hours. The aged samples were then left to cool in air.

Mechanical tests

Impact test

Impact testing of all these specimens was conducted and each samples diameter and Notched diameter was measured with vernier calliper. Three samples were tested from control samples and each heat-treated condition and as-cast samples. The tests were carried out using Charpy impact test method on Hounsfield balance impact-testing machine. The sample was fixed and held firmly on the Charpy with pin through the notch diameter after which the Charpy arms where release. The amount of impact energy absorbed by the specimen before yielding was read off on the calibrated scale attached to the machine as a measure of impact strength in Joules. The average values from three test samples are reported here.

Impact energy conversion

ft.pounds → joules
1 ft.pounds → 1.35581795 joules

Tensile test

Tensile testing was performed using a Housefield Tenaometer with a capacity of 20KN testing (Model 8801, UK) Yield strength, ultimate tensile strength, Young's modulus, Strain, percentage elongation of the A356 aluminium alloy as-cast and heat-treated condition were measured. The diameter and working length of the control and heated samples were measured and recorded using vernier calliper. The test is made by gripping the ends of a suitably prepared samples test piece in a tensile test machine and then applying a continually increasing uni-axial load until such time as failure occurs (Pezda, 2014; ASTM, 2016)

Ultimate tensile strength (UTS) $\frac{\text{maximum load applied}}{\text{cross -sectional area}}$ =N/mm² equation (4)

Area = $\frac{\pi d2}{4}(mm^2)$ equation (5)

Where d= diameter (mm)

Strain $\varepsilon = \frac{\Delta l}{l}$ where ΔL =extension that is, change in lenth while L = original length (mm) equation (6)

% elongation = $\frac{\Delta l}{l} \times 100$ equation (7)

Modulus of elasticity $\epsilon = \frac{UTS}{\varepsilon}$ N/mm² equation (8)

Hardness test

The hardness of both as-cast and heat-treated A356 aluminium alloy was measured in HV scale using a Micro/Vickers hardness tester at an applied load of 4.904N. The control and the heat-treated samples were subjected to hardness test using Micro/Vickers hardness tester. The control and heat-treated samples underwent hardness testing, following metallographic polishing to ensure parallel surface. A major load is then applied and held for a set time period. The force on the indenter is then decreased back to the minor load. The Micro/Vickers hardness number is calculated from the depth of permanent deformation of the indenter into the sample. The average hardness value was determined from multiple readings on each sample in accordance with (ASTM 2016).

HV= $\frac{0.102.\ F}{S}$ where equation (9)

S = $\frac{1}{2.\sin 136°/2}.d^2$ =0.5393 d² equation (10)

Therefore, HV= $\frac{0.102.F}{0.5393.d^2}$ equation (11)

Where f= force (N); and d= diagonal (mm) s = surface indentation

RESULT AND DISCUSSION

Chemical Composition analysis of Aluminum alloy

The composition of as-cast material obtained from as-cast was shown in table 1. This finding is similar with (Adeyemi et al., 2013). Utilizing as pectrometer, the chemical composition of the aluminium alloy was analyzed, revealing the presence of elements beyond aluminum, as presented in (Table1). The results indicate that aluminium has the highest percentage composition, followed by silicon. This is found similar to Raj et al., (2016)

Effect of heat treatment on mechanical properties

Following solution treatment and aging, a noticeable colour change in the Al alloy samples occurred, indicating strength hardening due to heat treatment. To investigate the impact of heat treatment on mechanical properties, tensile strength, hardness, and impact tests were conducted. The results, displayed in the tables 2, 3 & 4 above, demonstrate the effects of heat treatment under various conditions.

Tensile strength

The ultimate tensile strength (UTS) of Al A356 alloy was investigated in as-cast, solution-treated, and aged conditions. The control samples exhibited UTS of 135.36MPa, 6% elongation, and a modulus of elasticity of 2,256MPa. The effects of solution treatment and aging on UTS were analyzed, and the results are presented in (Table 2). The solution treatment at 500°C and aging at

Table 1: Chemical composition of sample.

Element	Si	fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
% composition	5.79	1.08	1.43	0.431	0.377	0.043	0.084	0.98	0.049
Element	Ag	B	Be	Bi	Ca	Co	Li	Na	P
% composition	0.0037	0.0011	0.0049	0.0059	0.0001	0.021	0.215	0.0053	0.0010
Element	Pb	Sn	Sr	V	Zr	Al			
% composition	0.133	0.032	0.128	0.012	0.0094	89.1			

Table 2: Tensile strength test results: solution heat treatment temperature and ageing temperature

Sample	Diameter (mm)	Ultimate tensile strength (Mpa)	strain	% elongation	modulus of elasticity (Mpa)
Control	9.03	135.36	0.06	6	2,256
500 °C and 200	9.33	180.32	0.02	2	9,016
515 °C and 175 °C	9.07	201.18	0.03	3	6,706
530 °C and 150 °C	9.27	185.19	0.03	3	6,173

Table 3: Impact strength test results: Solution heat Treatment temperature and ageing Temperature.

Sample	Notched Diameter (mm)	Impact energy Joules (J)
Control	7.57	1.04
500 °C and 200	8.0	1.04
515 °C and 175 °C	8.0	1.13
530 °C and 150 °C	7.93	1.08

Table 4: Vickers hardness hv tests results: solution heat treatment temperature and ageing temperature

Sample	Diameter (mm)	Force Newton (N)	Vickers Hardness (HV)	Average Vickers Hardness (HV)
Control	0.1390	4.904	96.0	96.9
	0.1371		98.7	
	0.1391		95.9	
500 °C and 200	0.1203	4.904	128.3	130.7
	0.1186		132.0	
	0.1187		131.7	
515 °C and 175	0.1187	4.904	183.5	154.6
	0.1152		140.0	
	0.1150		140.4	
515 °C and 175	0.1115	4.904	149.2	113.2
	0.1390		96.1	
	0.1402		94.4	

200°C resulted in a UTS of 180.32MPa, 2% elongation, and a modulus of elasticity of 9,016MPa, indicating increased stiffness compared to other heat-treated samples. This is because, if the part is heated for too long the precipitates grow too large and the primary failure mechanism changes which reduces the strength of the material (Michael et al., 2010) this phenomenon is known as over aged this finding is similar as been found by Tan and Mohammad (2010). This suggests that the material can be used as a replacement for steel in beam applications. Further analysis revealed that the optimal combination of solution treatment and aging was at 515°C and 175°C, respectively, resulting in a UTS of 201.18MPa, 3% elongation, and a modulus of elasticity of 6,706MPa. Figure 5 illustrates the improvement in ultimate tensile strength at this optimal combination. In summary, the study demonstrates that the Al A356 alloy's tensile strength can be enhanced through solution treatment and aging, making it a viable alternative to steel in certain applications.

Impact test

Table 3 shows the impact properties of Al A356 alloys in as-cast, solution-treated, and aged conditions were evaluated using the Charpy test. The finding is similar to (Raj et al., 2016). The as-cast sample exhibited impact energy of 1.04 Joules. In contrast, the samples subjected to solution treatment and aging at various temperatures showed significant improvements in impact energy:

-500°C solution treatment and 200°C aging: 104Joules
-515°C solution treatment and 175 C aging: 1.13Joules
-530°C solution treatment and 150°C aging: 1.08Joules

The results indicate that the as-cast samples impact energy increased at an aging temperature of 175°C, suggesting enhanced resistance to wear and scratch deformation compared to the other samples. This is illustrated in (**Figure 6).**

Hardness test

Table 4 shows the hardness properties of Al A356 alloys in as-cast, solution-treated, and aged conditions were investigated using micro/Vickers hardness testing (Raj et al., 2016). The results show that the as-cast condition's hardness improved at a solution temperature of 515°C

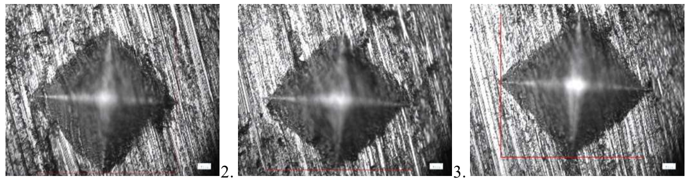

Figure 1: micro views for hardness control sample

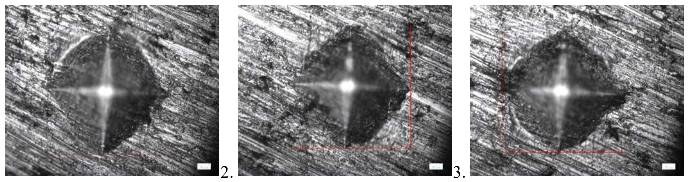

Figure 2: micro view at solution and ageingtemperature 500&200

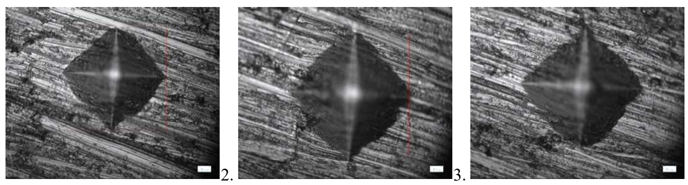

Figure 3: micro view at solution and ageingtemperature 515&175

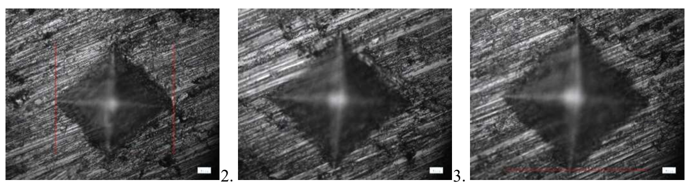

Figure 4: micro view at solution and ageingtemperature 530&150

and aging temperature of 175°C, as illustrated in (Figures 1, 2,3, & 4). These findings are similar as been found by Akhil et al. (2014).

Conclusion

This study investigated the effects of solutionizing and age hardening temperatures on the mechanical properties of Al-Si alloys. The results show that heat treatment significantly enhanced the mechanical properties of the alloy, with the optimal solutionizing and aging temperatures being 515℃ and 175℃, respectively. At these temperatures, the ultimate tensile strength, impact energy and Vickers hardness reached their highest values, indicating improved strength, toughness, and resistance to cracks and wear. These findings suggest that the alloy is suitable for applications requiring high mechanical properties. Notably the temperature combination 515℃ and 175℃, yields optimal properties suitable for engineering applications.

Recommendation

Optimization of the precipitation hardening process parameters such as solutionizing temperature, solutionizing time, ageing temperature, ageing time on the tensile strength, impact and the hardness of the alloy should be investigated using Taguchi optimization technique. Microstructural studies of the developed age hardened structure should be studied. Mechanical properties (yield strength and compression) studies of the developed age hardened should be studied.

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