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Metallurgical study of cast aluminium alloy used in hydraulic brake calliper

Olawale O. Ajibola[1-2], Daniel T. Oloruntoba[1], and Benjamin O. Adewuyi[1]

[1]Metallurgical and Materials Engineering Dept., Federal University of Technology, Akure, Nigeria

[2]Materials and Metallurgical Engineering Department, Federal University Oye Ekiti, Nigeria

ABSTRACT: Reports of many functional deficiencies are these days rampant in many aluminium products flooding the Nigeria markets. These emanate from the local aluminium manufacturing, cottage foundry industries and much more from goods imported in the country. The study investigates the metallurgical properties of as-received and cast aluminium alloy samples used in the floating piston/calliper of the automobile hydraulic master brake cylinder. Commercially available aluminium alloy is procured from which callipers were cast and characterised. The study compares the physical properties by Hardness test, microstructural properties using high resolution metallurgical microscope, X-Ray Diffraction, chemical composition using Atomic Absorption Spectrophotometry. The as-received samples are characterised by poor metallurgical qualities such as variation in weight and density, low HBN, low tensile strength, high porosity and sand inclusions from the previous poor casting practices, hence abnormalities result under usage. The aluminium alloy was technically cast at pouring temperature higher than 750 ^{o}C using sand mould of high permeability. The casting gave higher HBN values of eutectic-AlSi structured aluminium alloy. The tensile strength calculated as approximate relationship between the hardness and the tensile strength, gave lower 329.09 Mpa and 154.78 Mpa strength for as-received samples as compared with the cast alloy having 353.58 Mpa and 226.49 Mpa tensile strength values respectively.

KEYWORDS: cast aluminium alloy, x-ray diffraction, microstructure, characterization, atomic absorption spectrophotometry.

1 INTRODUCTION

The metals sector in Nigeria is still struggling to reach its full potential particularly in the development and consumption of key metallic products as Iron, Steel, Copper, Aluminium, Tin, Lead, Zinc etc. and in exploitation of key noble metals such as gold and silver [1]. It is very unfortunate that Nigeria exports many of her resourceful minerals and metal scrap only to import the finish products from other countries. The aftermath is that Nigeria market is flooded with many substandard products among which the automotive and automobile industries (Figure 1). The use of aluminium is very prominent in the automotive and automobile industries [2]. Aluminium alloy spare parts are easily produced or imported even at lower cost than steel or any other metals which in many instances do not match many international standard practices and specifications [3, 4].

Good engineering material design and standard manufacturing practices play vital role in the proper component selection for engineering application [5]. Aluminium and its alloys are part of the major engineering materials that are indispensable for now being prominent for its light weight and corrosion resistance among other properties. For its wide areas of applications, aluminium and its alloy attract different areas of research focuses. The need for improved properties to prevent failure most especially during service is of great priority. It is observed that commercially pure aluminium contains a minimum of 99 percent aluminium and is a soft and ductile metal used for many applications where high strength is not necessary while aluminium alloys on the other hand, possess better casting and machining characteristics and better mechanical properties than the pure metal.

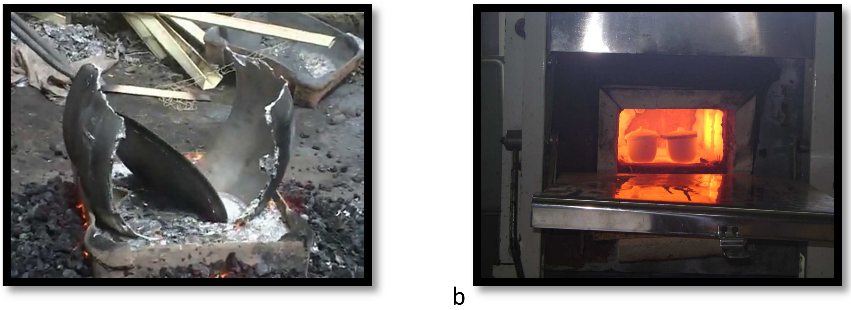

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Figure 1: Re-melting of aluminium in (a) an open earth-made furnace and (b) electric furnace.

Microscopic examination is performed to study the metallographic features of specimen using high magnification microscopes. These examinations may involve the optical or scanning electron microscopy. Optical microscopic examination is used to determine grain size, microstructure and inclusion type and content. XRD is used in studying the structure of alloys and in the determination of compounds that make up the alloy. X-ray diffraction analysis makes use of Braggs' law [6, 7, 8, 9].

Owing to the improved properties, the usefulness of aluminium and aluminium alloys in domestic, laboratories and industries cannot be overemphasized. This is seen around us today as at least one part of equipment or a whole machine is made from aluminium alloy [10]. From the long list of the equipments and machine parts made from aluminium, the hydraulic brake piston/calliper has been selected for this study (Figure 3).

The wear and corrosion behaviours of many alloys have been widely studied and reported in the literature [11, 12, 13, 14]. The impact of friction causing wear on the two rubbing contact surfaces cannot be under-estimated in engineering processes [15]. Many reports are available on the qualities of materials used in different machine parts and equipments used in different media. Wear and corrosion of aluminium in various media and environments such as water, acids, alkaline, bases and agro-fluids have been widely studied and published in literature [16, 17, 18, 19, 20] but much report is not available on studies previously made on wear, corrosion and the synergies between aluminium alloys and hydraulic fluids. Hence, the present work investigates the metallurgical properties of as-received and cast aluminium alloy samples used in the floating piston/calliper of the automobile hydraulic master brake cylinder (Figure 2).

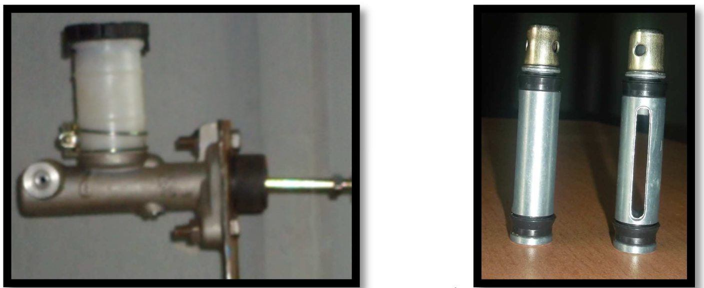

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Figure 2: Photographs showing of (a) as received master brake cylinder and (b) floating calliper

2 MATERIALS AND METHOD

2.1 MATERIALS SOURCES

The as-received aluminium alloy samples (marked as A and C) from the new and the scrap respectively were sourced from the floating calliper of automotive hydraulic brake cylinders produced by Star Co. Ltd, Japan for Nissan Bluebird 2.0 model engine. The new aluminium alloy samples were procured from the local automobile spare part shop and designated as Sample A from which Sample B was produced. Another set of scrap of floating calliper was obtained auto-mechanic workshop, designated as Sample C from which Sample D was produced for the experiment.

2.2 METHODS

2.2.1 PREPARATION OF MOULD, CASTING AND CHARACTERISATION OF ALUMINIUM SAMPLES

Cast aluminium alloy samples were produced from the as-received samples by sand casting method. The moulding sand was prepared from fine and coarse sand particle sizes. The sand particle size distribution of moulding sand used is shown in Table 1. The sand particle size distribution controls the permeability which is the amount of air can be trapped through the sand. The coarse particle size results in high permeability while fine particles give low permeability of moulding sand. Then the moulding sand was added to the pattern and rammed properly. The moulds were prepared from two set of mixing ratios of moulding sand [a mixture of Coarse (80%) + Fine (20%) and a mixture of Coarse (20%) + Fine (80%)]. To study the effect of casting process (the pouring temperature and particle size of moulding sand) on the properties of cast aluminium alloy, a total of six specimens were produced as follows: First the molten metal was poured at temperature of 700 ^{o}C into two moulds (mould 1 and 2) having coarse (-1180+300) and fine (-300+75) particles sizes (in µm) of moulding sand respectively (Tables 2). The casting is repeated at the pouring temperatures of 750 ^{o}C for (mould 3 and 4) and 800 ^{o}C for (mould 5 and 6) as shown in Table 3. The six trial specimens were produced and the hardness values in HBN were determined from which specimen with the highest HBN was selected for further used.

Table 1: Particle size (µm) distribution of moulding sand

Sieve range (µm)	+1180	-1180 +850	-850 +600	-600 +425	-425 +300	-300 +212	-212 +180	-180 +150	-150 +125	-125 +75	-75
% distribution	1.21	3.49	7.53	10.61	11.47	14.23	13.52	13.62	11.66	8.13	2.06

Table 2: Sand mixing ratios and Particle size ranges (µm)

Set	Sand mixing ratio	Sand particle size ranges (µm)
Set 1	Coarse (80%) + Fine (20%)	-1180+300 (coarse) and -300+75 (fine)
Set 2	Coarse (20%) + Fine (80%)	-1180+300 (coarse) and -300+75 (fine)

Table 3: Effect of casting temperatures and particle sizes on BHN of trial specimens

Mould no	Casting temperature (^{o}C)	Sand particle size ranges (µm)	(BHN)
Mould 1	700	Coarse (80%) + Fine (20%)	62.4
Mould 2	700	Coarse (20%) + Fine (80%)	47.2
Mould 3	750	Coarse (80%) + Fine (20%)	63.1
Mould 4	750	Coarse (20%) + Fine (80%)	52.3
Mould 5	800	Coarse (80%) + Fine (20%)	65.7
Mould 6	800	Coarse (20%) + Fine (80%)	54.2

2.2.2 CASTING AND PRODUCTION OF SPECIMENS

As-received aluminium alloy samples (new and scrap) sourced from automobile cylinder respectively marked as samples A and C, were in batches weighed into a melting pot, melted and held at temperature range of 700 to 800 ^{o}C in electric furnace under a controlled atmosphere. Sample A was melted and sand cast to get Sample B while Sample C was melted and sand cast to get Sample D for the experiment.

The mould was produced from a mixture of Coarse (80%) + Fine (20%) particle size ranges of moulding sand of a relative high permeability. The molten metal was sand cast into rod of 300 mm long by 30 mm diameter, from which callipers 100 mm long by 12 mm diameter were machined (Figure 3).

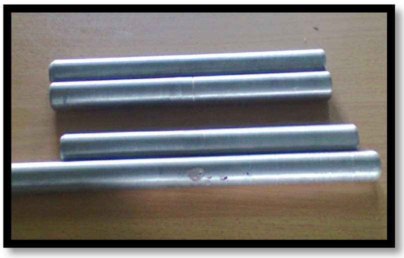

Figure 3: Turned aluminium alloy before slicing

Figure 4: Sliced specimen

Other test specimens were sliced to 15 mm thick by 25 mm diameter coins for hardness tests and microstructural examination (Figure 4). Powder specimens were also produced for both as-received and cast samples for XRD studies. The cast samples obtained from sample A and C were designated as samples B and D respectively.

2.2.3 GRINDING AND POLISHING OF SAMPLES

The surface of the aluminium alloy sample were grinded and polished with different types of polishing grit which include 50/60 µm, 100/120 µm, 220 µm, 320 µm, 400 µm, 600 µm, 800 µm and 1200/2400 µm on the grinding and polishing machines at Engineering Materials Development Institute (EMDI), Akure. The polished surface was cleaned with distilled water, dried-up with cotton wool and kept in the desiccators.

2.2.4 DETERMINATION OF CHEMICAL COMPOSITIONS OF SAMPLES

The chemical compositions of aluminium alloy samples were determined using Atomic Absorption Spectrometer (AAS) Thermo series 2000 model at the Project development and design laboratory, Materials and Metallurgy division, Federal Institute of Industrial Research, Oshodi. (FIIRO), Lagos. The results of chemical composition are presented in Table 4.

2.2.5 MICROSTRUCTURAL EXAMINATION OF SAMPLES.

Microstructures of the as-received and cast aluminium alloy samples obtained from different pouring temperatures were examined under higher resolution metallurgical microscope with digital camera in the laboratory of Metallurgical and Material Engineering Department of Obafemi Awolowo University, Ile-Ife. The sections and surfaces were examined under x800 magnifications. The micrographs are presented in Figures 5 to 8.

2.2.6 THE HARDNESS TESTS OF ALUMINIUM ALLOY SAMPLES.

The hardness of samples was determined using Brinell Hardness Testing Machine at the Department of Metallurgical and Material Engineering, Obafemi Awolowo University (OAU), Ile-Ife. The test was conducted by pressing a tungsten carbide sphere 10 mm in diameter into the test plate surface for 10 seconds with a load of 1500 kg, and then the diameter of the resulting depression is measured. An average of four BHN values was measured out over an area of the specimen surface. On a typical plate each test would result in a slightly different number. The BHN is determined using equation 1.

$$HBN = F/ [\pi D/2(D-\sqrt{D^2-D_i^2})] \quad (1)$$

Where
BHN = the Brinell hardness number
F = imposed load in kg
D = diameter of the spherical indenter in mm
D_i = diameter of the resulting indenter impression in mm

The results of hardness tests of six trial specimens (Table 2) and the four selected samples used in the study are presented in Table 4. The tensile strength of the all the samples is calculated as an approximate relationship between the hardness and the tensile strength as TS (MPa) = 3.55 x HBN (for HBN ≤ 175) where HBN is the Brinell hardness number of the material as measured with standard indenter and load.

2.2.7 X-RAY DIFFRACTION ANALYSIS OF SAMPLES

The powder of each sample produced for XRD was studied under higher resolution x-ray using X-Ray Mini-Diffractometer MD-10 model with digital facilities in the laboratory of the Centre for Energy Research and Technology (CERT) of Obafemi Awolowo University, Ile-Ife. The grain sizes of the particles of as-received and cast aluminium alloy were examined by XRD. The diffractograms of morphology are shown in Figures 9 and 10.

3 RESULTS AND DISCUSSION

3.1 PREPARATION OF CAST ALUMINIUM ALLOY SAMPLES AND CHARACTERISATION OF THE SAMPLES

The mechanical (hardness, strength, toughness etc) and metallurgical properties could be enhanced by proper management of casting process and other controlling factors. The pouring temperature for aluminium alloys usually ranges from 675 to 790 °C, although thin-wall castings can be poured at temperatures as high as 845 °C. From the casting of the trial specimens (Table 3), it was obtained that when the grain size of sand was fine, the hardness was increased very rapidly from 700 ^{o}C to 750 ^{o}C but increasing slowly from 750 ^{o}C to 800 ^{o}C because at high temperature the crystal of molten metal start to burn and gases escaped out which are entrapped in the cast specimen. But from coarse sand, the hardness increased by more rates at pouring temperature from 750 ^{o}C to 800 ^{o}C than 700 ^{o}C due to fast cooling rate at higher grain size of sand. The aluminium alloy samples were characterised by AAS to ascertain the chemical composition of the materials. The micro-structural examination was carried out to reveal the micro structure of the alloy and to compare the similarities and differences between the grain sizes and structures of as-received and cast samples. The hardness values are compared as means of identifying their behaviour under friction with respect to their composition and micro-structure. With these, some reasons for their corrosion and wear behaviours are understood.

3.2 CHEMICAL ANALYSES OF ALUMINIUM ALLOY SUBSTRATES

The results of chemical compositions of As-received Aluminium alloy and Cast aluminium alloy substrate used in this experiment are presented in Table 4. As-received aluminium alloy sample A was sourced from un-used spare calliper; sample B was cast from sample A. Sample C was sourced scrap of callipers obtained from automobile repair shop from which sample D was produced by casting.

The chemical compositions of sample A (control sample) and cast aluminium alloy (sample B) used in the experiment in Table 4 shows that 98.87 %Al, 0.38 %Si, 0.40 %Mg, and 0.23 %Fe were present in the sample A, that 98.44 %Al, 0.32 %Si, 0.29 %Mg, and 0.16 %Fe were present in sample B while equal amount of 0.001 %Mn, 0.01 %Cu, 0.001 %Zn, 0.001 %Cr and 0.001 %Ti were present in both sample A and B.

From the melting and casting process, there is reduction in the amount aluminium, silicon, magnesium and iron content of Sample A during the process of melting and casting to produce Sample B and likewise Sample C to Sample D. This is because at higher temperature the crystal of molten metal start to burn and gases escaped out according to Mahipal et al, 2013[21]. Also, holding the molten alloy at high temperature resulted in some of the metal and some alloying elements (such as Si, Mg, and Fe) oxidised and dissolved into the slag. Equal amount of 0.001 %Mn, 0.01 %Cu, 0.001 %Zn, 0.001 %Cr and 0.001 %Ti were present in both as-received and cast aluminium alloys. The Atomic Absorption Spectrometry (AAS) shows silicon and magnesium as principal alloying elements as applicable to wrought aluminium alloys of 6000 series. The cast samples contain Silicon, copper and Magnesium which may characterise the standard designated 3xxx.x group of cast aluminium alloy. This type of Al-alloy is easily machined and can be precipitation hardened but not to the high strength that can be reached by 2000 and 7000 series.

There is greater silicon content in Sample C compared with the Sample A but there is reduction in the Aluminium content of Sample B, C and D as compare to Sample A. Close similarities are obtained from the chemical compositions and optical microscopy of sample A and B and the scrap based alloys sample C and D. The casting process reduces the %composition of Al, Si, and Fe obtained in the cast alloy (sample B) produced from sample A from un-used calliper while there is corresponding decrease in the %composition of Al, Si, Mg and Fe; and increase in the %composition of Mg, Mn and Cu in the scrap base cast alloy. Comparing sample A and C, the much differences in the composition of the major alloying metals (Si, Mg, Cu, Zn and Fe) results from the diversities in the chemical composition differences of the base materials from which the callipers were produced by the manufacturers. Also, there are significant changes in the HBN values resulting fro the casting process.

Table 4: Chemical composition, HBN and strength of aluminium alloy samples

Elements	Sample A	Sample B	Sample C	Sample D
Al	98.87	98.44	98.39	97.43
Si	0.38	0.32	0.72	0.46
Mg	0.40	0.29	0.36	0.41
Fe	0.23	0.16	0.26	0.24
Mn	0.001	0.001	0.001	0.002
Cu	0.10	0.10	0.12	0.18
Zn	0.001	0.001	0.002	0.001
Cr	0.001	0.001	0.001	0.001
Ti	0.001	0.001	0.001	0.001
Average BHN	92.7	99.6	43.6	63.8
Strength (MPa)	329.09	353.58	154.78	226.49

3.3 MICRO-STRUCTURAL EXAMINATIONS OF ALUMINIUM ALLOY SAMPLES

The micro-structural examinations carried out revealed the microstructures of the alloy and compare the similarities and differences between the grain sizes and structures of as-received and cast samples (Figures 5, 6, 7 and 8). The microstructure obtained from as-received and cast aluminium alloy samples studied under higher resolution metallurgical microscope with digital camera under x800 magnifications are shown in Figures 5 to 8. This is reflected in the results of the hardness tests and tensile strength obtained on the aluminium alloy samples in Table 4.

The grains in sample A and C are coarse compare to the fine grains in sample B and D and because of the fineness and closeness of the grains, the sample will be more prone to corrosion. The cast sample are characterised by inclusions from casting sand as revealed in the X-ray diffraction study. The lumpy grains may be attributed to inclusions interacting with the grains during the solidification process. However, the grain sizes could be refined under a controlled artificial aging process. But this can be relieved by cooling, passing through natural aging as the grain size will be coarse but will have higher corrosion resistance but lower hardness as compared to when it is refined by artificial aging.

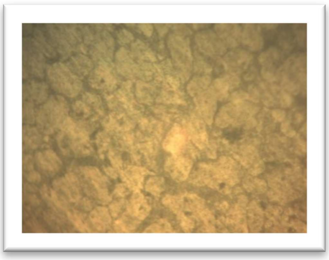

Figure 5: Micro-structure of sample A under magnifications of x800

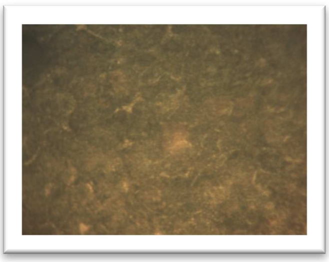

Figure 6: Micro-structure of sample C under magnifications of x800

Figure 7: Micro-structure of sample B magnified at x800

Figure 8: Micro-structure of sample D magnified at x800

3.4 HARDNESS AND STRENGTH OF SAMPLES

The results of the hardness tests of Aluminium alloy samples were determined using Brinell Hardness Testing Machine. Table 4 reflects average BHN obtained hardness tests of four point tests of As-received aluminium alloy and Cast aluminium alloy which agrees with the ASTM B647-84 (2006), B648-78 (2006) and B724-00 (2006) international standards practices. From the results of the hardness tests, sample B has lower BHN than sample A, while BHN in the sample D is greater than sample C due to the higher alloying effect of silicon, magnesium and iron in Sample D as shown in the Table 4. The aluminium alloy technically cast at pouring temperature higher than 750 ^{o}C using a mould of high permeability of moulding sand gave higher HBN values with eutectic-AlSi structure aluminium alloy which is agreement with [21]. The grain size of cast aluminium alloy had been modified by faster rate of cooling and higher permeability of moulding sand.

Tensile strength of the all the samples is calculated as an approximate relationship between the hardness and the tensile strength, TS (MPa) = 3.55 x HBN (for HBN ≤ 175), where HBN is the Brinell hardness number of the material as measured with a standard indenter and load.

The tensile strengths were calculated as 329.09 Mpa, 353.58 Mpa, 154.78 Mpa and 226.49 Mpa for samples A, B, C and D respectively. Sample D will be able to withstand higher stress compare to Sample C. There is a great reduction in the hardness and strength of Sample A when cast to give Sample C. This is as result of the grains forming larger grains during the casting process. The same effect is seeing in the casting of Sample B to give Sample D. With higher hardness property exhibited by cast alloy, the cast sample will be of more abrasion/ wear resistance than the as-received sample.

3.5 X-RAY DIFFRACTION STUDY

The peaks in the above diffractograms were obtained from the result of the analysis being interpreted by 'Search and Match Method'. Each of peak value was compared with the database of the standard values of compounds under this radiation. The difference between the peak value of the results got and the standard values in the database is not more than 0.03. This method is based on Bragg's law which states that $n\lambda=2dSin\theta$: where n-order of reflection, d-inter granular space and λ- wavelength. In addition to this, the grain sizes of compounds in the Al-alloy samples is determined by using Scherrer equation which is given by; $D= 0.9\lambda/\Delta\ (2\theta)\ Cos\theta$. Where D is the grain size, Λ is the wavelength; (2θ) is diffraction angle. The diffractograms of surface morphology are shown in Figures 9 and 10.

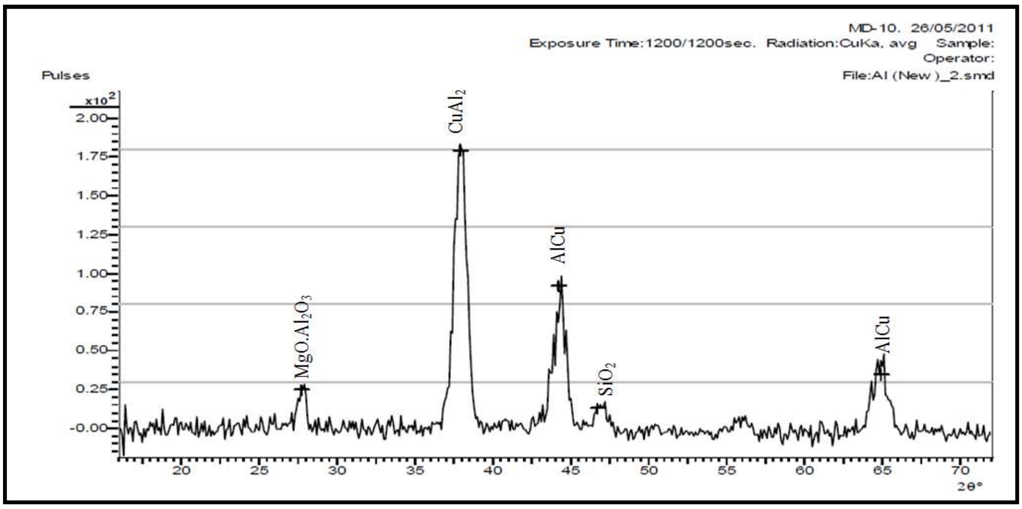

Figure 9: XRD analysis of As-received aluminium alloy sample

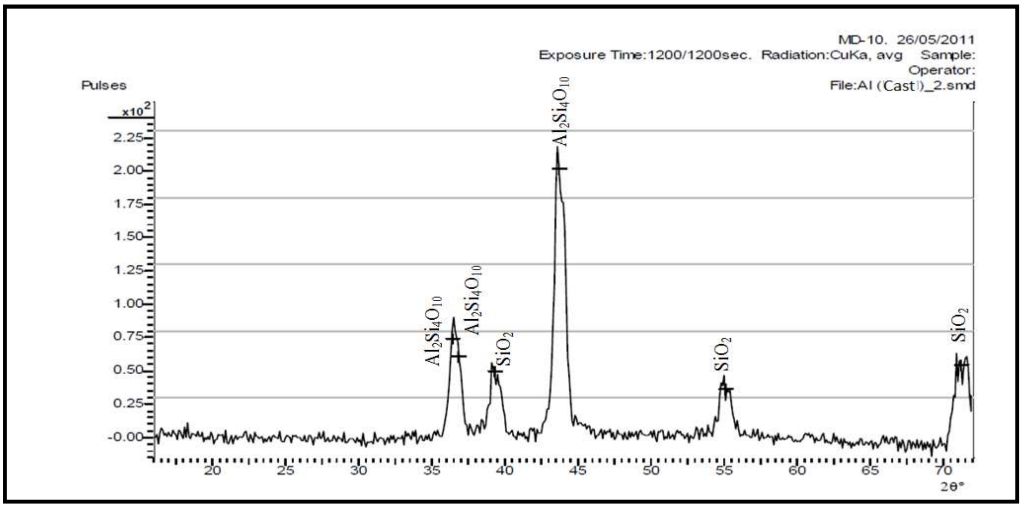

Figure 10: XRD analysis of cast aluminium alloy sample

3.5.1 XRD ANALYSIS OF AS-RECEIVED ALUMINIUM ALLOY FROM SAMPLE A

From Figure 9, the following peak values were shown at the diffraction angle (2θ); (i) 27.69^o (ii) 37.86^o (iii) 44.20^o (iv) 46.70^o (v) 64.80^o. By the Search and Match method, the given closest values in the database, the phases of compounds found to be present are: Tetragonal crystal structure $MgO.Al_2O_3$ (Magnesium Aluminium Oxide) with the diffraction angle (2θ) of 27.68^o, Tetragonal crystal structure $CuAl_2$ (Aluminium copper) with 37.8674^o, Monoclinic structure AlCu (Aluminium copper) with 44.1875^o, Monoclinic structure SiO_2 (Silicon Oxide) with 46.71^o and AlCu (Aluminium copper) with 64.7793^o. The grain sizes D of compounds in the Al-alloy samples is calculated using Scherrer's equation, for first peak D=0.05Å, second peak, D=0.14Å, third peak grain size=0.24 Å, fourth peak grain size=0.60Å and fifth peak grain size=0.1Å

3.5.2 XRD ANALYSIS OF CAST ALUMINIUM ALLOY FROM SAMPLE B

In Figure 10, the diffraction angle (2θ) from the results of XRD analyses are: i. 36.35^o, ii. 36.78^o, iii. 39.25^o iv. 43.66^o v. 55.00^o vi. 71.17^o were found to be of closest search match to i. 36.3582^o ii. 36.8058^o iii. 39.2411^o iv. 43.6492^o v. 55.0069^o and vi. 71.1864^o.

In which the following phases of compounds and crystal structure were detected at different peaks: $Al_2Si_4O_{10}$ (Aluminium silicate) at diffraction angle (2θ) of 36.3582^o with Triclinic crystal structure, $Al_2Si_4O_{10}$ (Aluminium silicate) at 36.8058^o with Triclinic crystal structure, SiO_2 (Silicon Oxide) at 39.2411^o [Monoclinic crystal structure], $Al_2Si_4O_{10}$ (Aluminium silicate)

43.6492° [Triclinic crystal structure], SiO_2 (Silicon Oxide) at 55.0069° [Tetragonal crystal structure] at SiO_2 (Silicon Oxide) at 71.1864° of Hexagonal crystal structure.

At a constant wavelength, the grain sizes of compounds in the Al-alloy samples calculated using Scherrer's equation: for the first peak D = 0.04Å, for second peak, D = 3.38Å, third peak grain size = 0.6Å, fourth peak grain size=0.34Å, fifth peak grain size = 0.14Å and the sixth peak grain size = 0.11Å

Generally, the results are characterised by poor metallurgical qualities such as variation in weight and density, low HBN, low tensile strength, high porosity, irregular microstructure and casting defects such as sand inclusions resulting from the poor casting practices.

Improved, long lasting contact surfaces interaction of aluminium alloy product with hydraulic fluid such as brake fluid (to reduced wear and corrosion) could be achieved by surface coating such as electroplating or electroless plating [5, 23, 24, 25]. The moderate magnesium quantity in aluminium alloy examined, makes it less flammable and this will contributes to its use in automobiles. Further more, Al-alloy has little casting quality to produce Al-alloys because of its silicon content, though Al-alloy with higher silicon content will possess better casting quality. Al-alloy can however be forged to produce products such as floating piston in automobile master break cylinder which usually comes in contact with un formulated types of hydraulic oils available today. Brake fluids must not corrode the metals used inside components such as callipers, master cylinders, etc. They must also protect against corrosion as moisture enters the system. Additives (corrosion inhibitors) are added to the base fluid to accomplish this. The absorption of moisture into the fluid increases the tendency for corrosion. Most automotive professionals agree that glycol based brake fluid should be flushed, or changed, every 1-2 years [26].

4 Conclusion

The study has been carried out to investigate the metallurgical properties of Al-alloy sourced from the floating piston in automobile hydraulic master brake cylinder. Based on above findings on this Al-alloy substrate, the following conclusions are reached. The samples are characterised by poor metallurgical qualities such as variation in weight and density, low HBN, low tensile strength, high porosity, irregular microstructure and casting defects such as sand inclusions resulting from the poor casting practices. Al-alloy resistance to corrosion could be improved by casting but with corresponding reduction in the tensile strength. Cast aluminium alloy will only be useful in areas where low strength and good corrosion resistance are needed as in the case of piston/calliper in the automobile master break cylinder [28,29]. Nevertheless, cast aluminium alloy faces the problem of ductility and uniform property. Therefore, the calliper should be forged which is believed will have more uniform properties and better ductility than castings, or else, coating method such as electroplating or electroless plating of Ni and surface heat treatment [23, 24, 27] could be applied to reduced wear and corrosion.

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