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Effects of Ageing on Mechanical Behaviour of Homogenized Twin Rolled 8011 Type Al-Fe-Si Alloy

By A. O. Ogunsanya, P. S. Olayiwola & D. O. Daramola

Bells University of Technology

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Keywords: *aluminum alloy, cold rolling, orthopaedic, homogenization, characterization.*

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A. O. Ogunsanya α, P. S. Olayiwola σ & D. O. Daramola ρ

Abstract- The use of aluminium-iron alloy sheet is of great importance depending on service requirements for specific application as these materials provide a light weight alternative to steel sheet grades but have limitations in the area of mechanical strength. Exploring ways of improving its mechanical properties particularly its strength has led to development of strength-induce forming processes. In this paper, the effect of ageing on the mechanical properties and morphological structure of homogenized twin rolled 0.85% Fe Al alloy 8011 for potential use in orthopaedic devices was investigated. Mechanical properties of homogenized, cold rolled, hot rolled prior to ageing at 175 ^{0}C of twin rolled Al-Fe-Si alloy was characterized. The result shows that cold rolled sample has better ultimate strength (160MPa) and hardness (60.31HBN) with decrease in impact energy of 3.383joules has compared to as-homogenized and hot rolled samples. Ageing decreases slightly the ultimate strength and hardness with increase in impact energy during 2 - 6 hrs of cold worked samples but it was observed that after 8 hrs, there was increase in ultimate strength and hardness of 166MPa and 54.72HBN respectively with slight decrease in impact energy. Internal residual stresses resulting from working processes are prevented by employing ageing (low temperature annealing) thereby preventing stress corrosion cracking.

Keywords: aluminum alloy, cold rolling, orthopaedic, homogenization, characterization.

I. Introduction

Selections of metallic material for particular applications are governed by the working conditions to which it is subjected, ease of manufacturing and cost. Pure metals are not usually regarded as engineering materials because they are difficult to produce in pure conditions resulting to failure in service. Failure of engineering materials are undesirable for reasons of safety, economy and reliability which may occur due to improper materials selection, casting discontinuities, improper manufacturing process Manufacturing process employed determine the material structure and as a result determine its properties, performance and application in service. Furthermore, changes in one are inseparably related to change in the others [1, 2].

Author α σ ρ: Department of Mechanical & Biomedical Engineering, Bells University of Technology, Ota, Ogun State, Nigeria.
e-mails: olyinkabbey@gmail.com, olayiwola_patrickshola@yahoo.com, dodaramola@bellsuniversity.edu.ng

The use of metallic materials has grown drastically in orthopedic devices intended for orthopedic surgery, including permanent implants (total joint replacement, hip prosthesis etc.) and temporary implants (pins, bone plates, screws etc.) [3,4]. Orthopedic surgery in recent times depends profoundly on the development of biomaterials used for fixation of fractures and joint replacement. Owing to their mechanical strength, metallic materials have been widely used in orthopedic applications of which commonly used are: stainless steel, cobalt-chromium alloy and titanium alloy etc. Development of metallic biomaterials has gained interest and has contributed significantly to the improvement of the health and well-being of mankind. However, the biggest drawback is the non-degradability of these materials in the body physiological environment leading to the demand of secondary surgical procedure for the removal of implants after the bone heals [4].

Presently, a great amount of research is focused on developing biodegradable, low density and highly bioactive implants without compromising on strength. One such material which meets these requirements is magnesium (Mg) and its alloys [5-8]. Mg and alloys modulus and density is very close to that of the human bones [9]. There use reduce the shielding effect of implants and they are lighter than other medical metal, but they are difficult to process, they corrode rapidly and are less biocompatible [10].

Aluminium and its alloys, are the second most commonly used material after steel, exhibits poor casting and mechanical properties which can be improved by the addition of alloying elements such as Mg, Si, Cu, Zn, Mn, Fe, and other element [11], thermal treatment, working process or combination of both [12]. An analysis of both the scientific and branch literature has shown trends of the development and advancement of products made of aluminum and its alloys for electrical, construction, automotive, food, packaging, heat ex-changer and medical implant applications [13] and are widely used in structures and components where light weight or corrosion resistance is required [14]. A thin aluminum strip can be produced by two different processes: (i) Direct chill casting (ii) Continuous casting/Twin roll casting. An ideal twin rolled casting has

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been reported [15]. In 1950, continuous strip casting for aluminum and its alloys has also been reported [16]. In twin rolled casting process, molten metal was directly converted into thick strip. Annealing and cold rolling operations were performed on this thick strip to get the required size, shape as well as mechanical properties [17, 18]. In Twin roll casting, centre-line segregation of second phase particles was most commonly found for high alloying content materials [19–25].

Aluminium alloy 8xxx series have been found to have broader usage as in medical implant applications because of their good physical and chemical properties such as formability, corrosion, light weight as well as the possibility of controlling micro structural composition of the alloy by means of specific thermal and mechanical treatments [26]. The iron composition of AA 8011 ranges from 0.6 – 1% has greatly influenced the mechanical properties of the alloy [27]. Large numbers of iron containing intermetallic phases have been identified in the microstructures depending on solidification conditions and alloy composition and so it tends to combine with other elements to form intermetallic phase particles of various types. In the absence of silicon, the dominant phases that is formed are Al_3Fe and Al_6Fe, but when Si is present, the dominant phases are Al_8Fe_2Si (α-phase) and Al_5FeSi (β-phase). If Mg and Mn are present respectively with Si alternative phase calledπ -phase, $Al_8FeMg_3Si_6$ and $Al_{15}(Fe,Mn)_3Si_2$ are confusingly known as α-phase. There are also other rarer phases which form when other elements are present, example are Ni, Co, Cr, Be. When these low symmetry compounds crystallize, they are prone to grow into long needles/plates that are extremely detrimental to both strength and ductility [28].

During metal working, the optimum level of the iron that will not impact any negative effect on the ductility of the alloy is highly required in order to avoid defects such as cracking due to the low level of material ductility. The processing capabilities and final wrought product strength of the aluminium alloy are greatly affected by the iron level content [29].

Mbuya *et al.* investigated the effect of iron content on the mechanical properties of Al alloys [30]. The result revealed that increased iron content lead decrease in ductility of Al-Si based alloys accompanied by increase in tensile strength. However, the yield stress becomes unaffected by level of iron content, unless the ductility were affected so much that the alloy cannot even reach yield point before brittle fracture occurs. According to Miller *et al*., deep drawing process (DDP) finds application in numerous fields such as in automobile industries where the trend is towards safety and fuel economy [31]. However, the stability of spread of extensively drawn aluminium alloys is often a major problem.

Investigation on the effect of intensive forced melt convection on mechanical properties of Fe-containing Al-Si based alloys was carried out [32]. Their report revealed that, as the equilibrium solid solubility of iron in the aluminium solid solution (α-Al) decreases, iron exists in aluminium alloys in the form of iron-bearing intermetallic compounds. In commercial Al-Si based cast alloys, these compounds are often of the morphologies either as long needles or large plates, which drastically reduce the ductility of the alloys. Chemically, the detrimental effect of iron in aluminium alloys can be minimized by limiting the maximum content of the iron impurity, or by alloying with other element such as manganese [33]. Alloying with 0.9% Mn will results in apparent fragmentation of the β-Al5FeSi-needles [34]. The investigation on the effect of iron in Al-Si casting alloys by [35] concluded that, iron level in Al-Si alloys should be kept at the bearable minimum level in order to avoid the detrimental effect on mechanical properties, mostly ductility and fracture toughness.

Investigation on the effect of cold rolling on bending and tensile behavior of 7075 aluminium alloy report showed that after 58% cold rolling, there was rapid increase in yield strength of 119.25% due to high density of dislocations. Furthermore, increase in the tensile strength and hardness value with decrease in percentage elongation of the rolled material was reported [36]. The effect of hot cumulative roll bonding process on the mechanical properties of AA 5058 revealed that the strength of the sheet increased as a result of work hardening which was caused by an increase in dislocation density and sub-grains [37].

With extensive data available on the thermal treatment of AA 8011 with conventional alloying elements, not much has been documented on the ageing characteristics after homogenized, cold and hot rolling of the alloy, particularly with high iron content reinforcement for medical applications. Hence, the need for research on this area is justified. The main aim of the current research is to study the ageing characteristics of Aluminium Alloy 8011 and its potential use for orthopaedic devices. Twin rolled aluminium alloy 8011 were homogenized at 500 ^{0}C, cold rolled at ambient temperature, and hot rolled below and above recrystallization temperature at 200 ^{0}C and 400 ^{0}C respectively prior to ageing at 175^{0}C. Mechanical properties and morphological structure were investigated. The effect of ageing on homogenized, cold and hot roll twin rolled AA 8011 was then characterized.

II. Problem Analysis

Theoretical modelling of the material strength and capability makes use of some parameters' values deductible from the experimental analysis. It is therefore important to present the theoretical analysis as follows.

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a) Theoretical Analysis

In two-dimensions, stresses are functions of the independent variables x and y, while the transverse stresses are zero, that is;

$$\sigma_{xx} = \sigma_{xx}(x, y)$$

$$\sigma_{yy} = \sigma_{yy}(x, y)$$

$$\sigma_{xy} = \sigma_{xy}(x, y)$$

$$\sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0$$

The stress-strain relations from Hooke's law now reduce to;

$$\epsilon_{xx} = \frac{1}{E}(\sigma_{xx} - \nu\sigma_{yy}) + \alpha(T - T_o)$$

$$\epsilon_{yy} = \frac{1}{E}(\sigma_{yy} - \nu\sigma_{xx}) + \alpha(T - T_o) \quad (2)$$

$$\epsilon_{xy} = \frac{1}{2G}\sigma_{xy}$$

On solving for the stresses, we deduce that;

$$\sigma_{xx} = \frac{E}{1 - \nu^2}[(\epsilon_{xx} - \vartheta\epsilon_{yy}) - \alpha(1 + \nu)(T - T_o)]$$

$$\sigma_{yy} = \frac{E}{1 - \nu^2}[(\epsilon_{yy} - \vartheta\epsilon_{xx}) - \alpha(1 + \nu)(T - T_o)]$$

$$\sigma_{xy} = \frac{E}{1 + \nu}\epsilon_{xy} \quad (3)$$

On introducing Airy stress function, ϕ, and ignoring the body force and inertia terms since the process is stationary, we define as follows;

$$\sigma_{xx} = \frac{\partial^2\phi}{\partial y^2}$$

$$\sigma_{yy} = \frac{\partial^2\phi}{\partial x^2}$$

$$\sigma_{xy} = -\frac{\partial^2\phi}{\partial_x\partial_y} \quad (4)$$

Substituting equation (4) into equation (3)

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)(\sigma_{xx} + \sigma_{yy}) + E\alpha\nabla^2 T = 0 \quad (5)$$

So that, the governing equation in terms of Airy stress function for the plane stress is;

$$\nabla^2\nabla^2\Phi + E\alpha\nabla^2 T = 0 \quad (6)$$

Also for the plane strain, it is given by;

$$\nabla^2\nabla^2\Phi + \frac{E\alpha}{1 - \upsilon}\nabla^2 T = 0 \quad (7)$$

The stress function, ϕ, is obtained by integrating the equation (7) knowing the distribution of the temperature. The constants of integration in the expression for the stress function are obtained by application of known physical traction on kinematics boundary conditions of the problem.

b) Experimental Analysis

i. *Materials*

The material used for the study was two (2) coil slabs of twin rolled AA 8011 with dimensions 1200mm × 140mm × 6.80mm, weighing 2kg obtained from Aluminium Rolling Mills (ARM) Ota, Ogun State, Nigeria. Table 1 show the percent composition with 0.85% Fe present.

Table 1: Chemical Composition of AA 8011

Element	Fe	Si	Mn	Cu	Zn	Ti	Mg	Pb	Sn	Al
% composition	0.85	0.50	0.08	0.07	0.07	0.02	0.02	0.01	0.01	98.37

ii. *Methods*

The two (2) slabs of AA 8011 were sectioned into 8 samples of dimension 300mm × 140mm × 6.80mm using cutting machine. Samples were homogenize at 500 °C for 1 hr, soaked for 2 hrs followed by cold water quenching to obtain a uniform distribution and homogenous composition throughout the alloy and also to improve workability. Samples were further prepared for various characterizations. Two samples were cold rolled in five passes to 50% reduction in thickness (3.4mm thickness) using Two-High Mill. Two samples each were hot rolled below and above recrystallization temperature of the alloy at 200°C and 400°C in four and three passes respectively to 50% reductions in thickness. The remaining samples were kept as as-homogenized samples. Cold rolling was carried out on the samples to 50% cumulative thickness reduction at ambient temperature (32°C). Samples were prepared in accordance to ASTM standard dimensions for non-proportional rectangular test pieces, for the subsequent mechanical test and morphological analysis.

A ductile non-ferrous metal such as aluminium has great tendency to deform plastically to a very large extent during machining operation.

Center lathe machine was used to obtain the samples for tensile test, hardness test, impact test, and morphological analysis (see Figure 1). Four prepared samples each from as-homogenized, cold rolled, thermal treated at 200°C and 400°C were aged at low annealing temperature of 175°C called strain-ageing for 2, 4, 6 & 8 hrs respectively before been normalized in air.

Figure 1: Prepared Sample in ASTM standard dimension

Tensile test samples were shaped in such a way that fracture occurs within the gauge length tested on table top Instron Universal Tensile Testing Machine of Engineering Development Management Institute (EDMI), Akure at strain rate of 10 mm/min. The tensile test samples with gauge dimension 100mm x 40mm x 8mm from as-homogenized, cold rolled, and hot rolled were obtained prior to ageing.

Impact test samples were shaped creating V-notched of 2mm depth at angle 45o tested on Avery Impact Testing Machine of capacity 25J. The test samples were machined into 8mm wide and 100mm long respectively.

WP 300 Gunt Brinell Hardness Tester with 1⁄16 inch diameter (1.588 mm) steel sphere and 100kg load of Federal Institute of Industrial Research Oshodi (FIRO, Lagos) was used to obtain the hardness value of all samples.

The morphological state of the experiment was investigated using standard metallographic procedures. Each sample were ground and polished before being etched in 2g of Sodium Hydroxide (NaOH) (Pellets) in 100 ml of water (H2O) with 15 secs of etching time. Etched samples were washed under running tap of water to remove excessive etchant from the surface before drying in air. Photographic image of the structures were obtained using the digital metallurgical microscope of magnification of X100 with α-aluminum phase as white colour, Mg2Si crystal as dark colour and the Al-Fe-Si crystal as brown colour. crystal as dark colour and the Al-Fe-Si crystal as brown colour.

III. Results and Discussion

a) Aluminium Alloy Sample with Homogenization

The stress-strain curves shown in Figure 2 revealed that the ultimate tensile strength (UTS) of the as-homogenized sample are in the range of 100MPa - 112Mpa while the aged samples for 2, 4, 6 & 8 h have the values of 108MPa, 114MPs, 110MPa and 112MPa respectively. The variation of ductility with percentage elongation (Figure 3) showed that ductility increased as compared to investigation by [38] but slightly decreased during ageing for 2 h, increases for the next 6 h and started to decrease with 8 h of ageing time. The graph showed an increase in hardness values with increase ageing time (Figure 4). Table 2 showed the hardness values obtained for as-homogenized, cold rolled, hot rolled below and above recrystallization temperature before and after ageing.

The impact strength showed better result but decreases progressively with increased ageing time (Figure 5). Table 3 showed the impact strength values obtained for as-homogenized, cold rolled, hot rolled below and above recrystallization temperature before and after ageing.

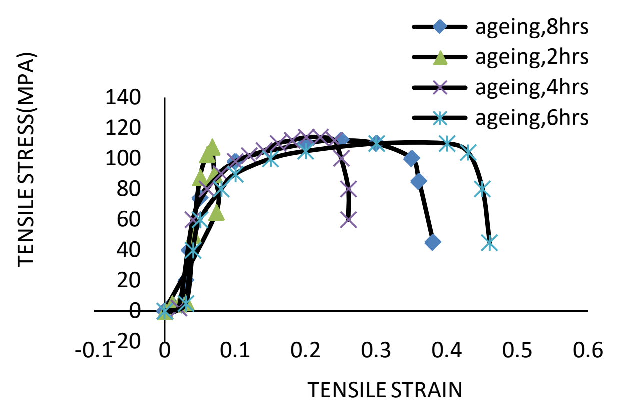

Figure 2: Stress-Strain Curve of As-homogenized Samples with 2 - 8 hrs of Ageing Time

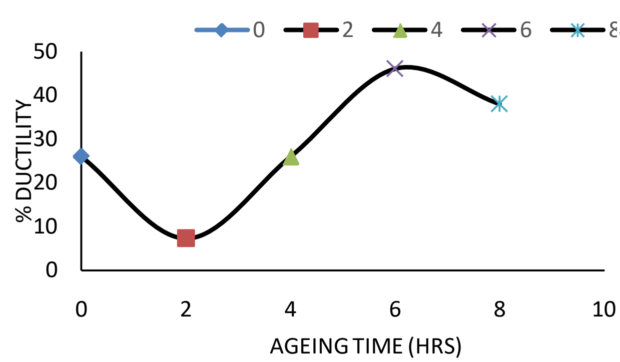

Figure 3: Variation of % Ductility with Ageing Time for As-homogenized Samples

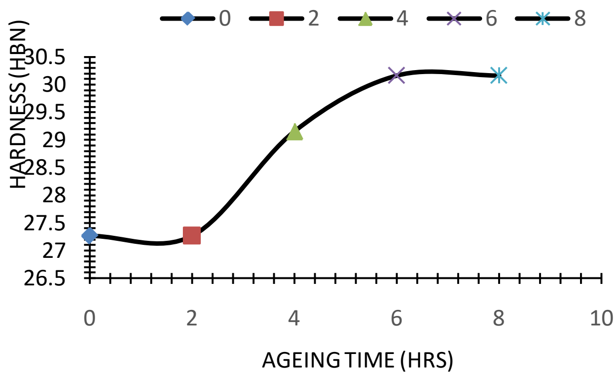

Figure 4: Variation of Hardness with Ageing Time for As-homogenized Samples.

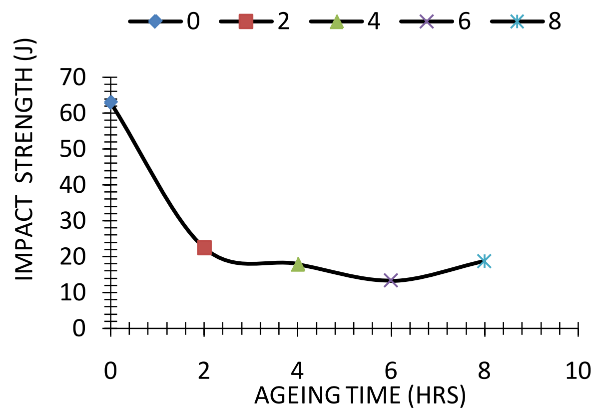

Figure 5: Variation of Impact Energy (J) with Ageing Time for As-homogenized

Table 2: Hardness values of as-homogenized sample, cold rolled sample, hot rolled at 200°C and at 400°C samples before and after ageing

Samples	No-ageing	2hrs	4hrs	6hrs	8hrs
As-homogenized (HBN)	27.27	27.27	29.16	30.16	30.16
Cold Rolled (HBN)	60.31	54.61	54.61	53.59	54.72
Thermal treated at 200^{O}C (HBN)	59.12	57.93	53.59	49.58	43.685
Thermal treated at 400^{O}C (HBN)	54.70	49.25	48.07	48.02	46.525

Table 3: Impact Strength of as-homogenized sample, cold rolled sample, hot rolled at 200°C and at 400°C sample before and after ageing

Samples	No-ageing	2hrs	4hrs	6hrs	8hrs
As-homogenized	62.92 J	22.46 J	17.95 J	13.26 J	18.67 J
Cold Rolled	3.38 J	6.76 J	7.60 J	8.25 J	8.17 J
Thermal treated at 200^{O}C	3.85 J	5.14 J	8.12 J	8.71 J	9.85 J
Thermal treated at 400^{O}C	3.65 J	5.01 J	5.44 J	5.92 J	6.14 J

b) Aluminium Alloy Sample with Cold Rolled

Figure 6 showed that the samples deformed at 50% revealed the UTS of 160MPa while UTS displayed decreased for 2 - 6 h of ageing but there was shape increase in UTS to 166MPa after 8 h ageing samples. The graph displayed increase in ductility with 2 h ageing and further decrease with increase in ageing time (Figure 7). The hardness values of the samples deformed at 50% increased then decreased with increased ageing time (Figure 8). Figure 9 revealed increased impact energy with increased ageing time.

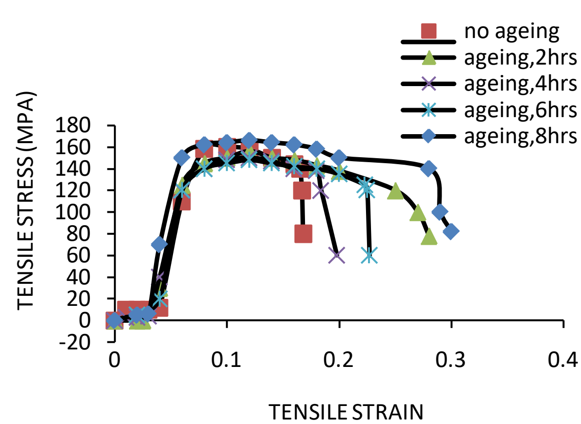

Figure 6: Stress-Strain Curve of Cold Rolled Samples with 2 - 8 hrs of Ageing.

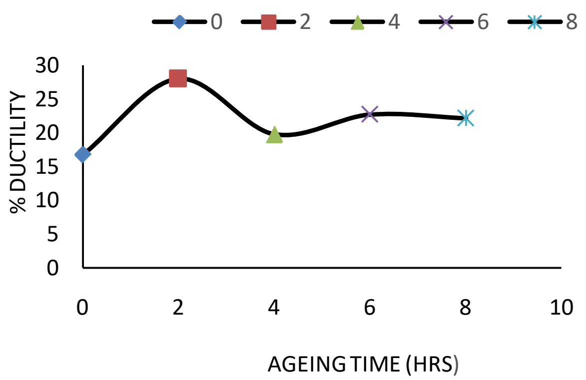

Figure 7: Variation of % Ductility with Ageing Time of Cold Rolled Samples.

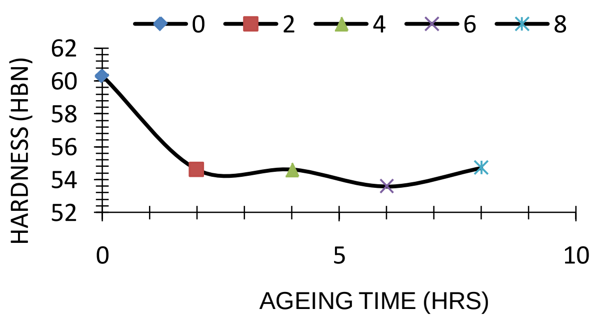

Figure 8: Variation of Hardness with Ageing Time of Cold Rolled Samples.

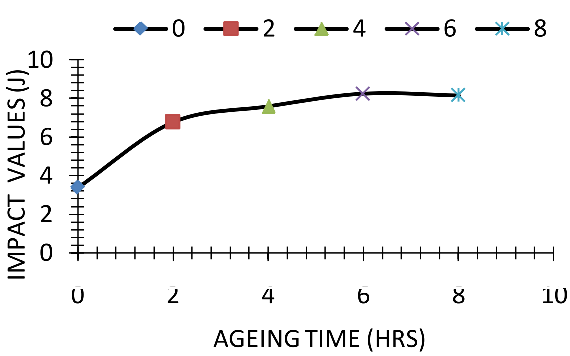

Figure 9: Variation of Impact Energy with Ageing Time of Cold Rolled Samples.

c) *Aluminium Alloy Sample with Hot Rolled below Recrystallation*

The samples deformed at 50% revealed values of UTS of 143MPa (Figure 10) and decrease in strength with increased ageing time. The graph displayed decreased in ductility at 50% deformation and then showed increase in ductility with increased ageing time (Figure 11). Both hardness and impact strength decreased with increased ageing time (Figure 12 & Figure 13) but show a better result as compared to cold rolled samples in term of impact strength.

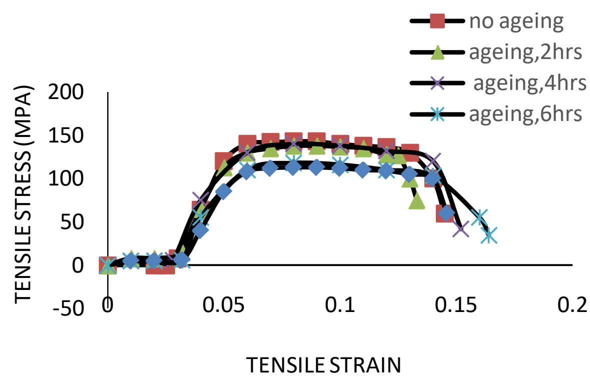

Figure 10: Stress-Strain Curves for Thermal Treatment at 200 ^{o}C with Ageing Time.

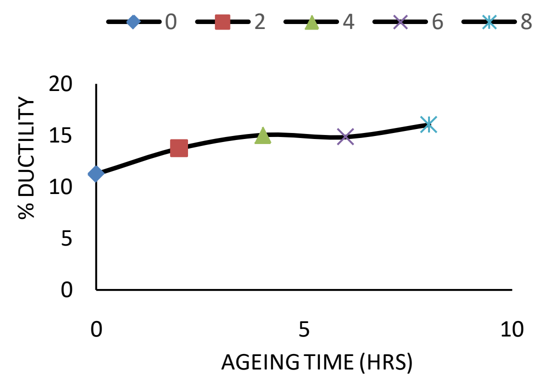

Figure 11: Variation of % Ductility with Aging Time for Thermal Treatment at 200 ^{o}C.

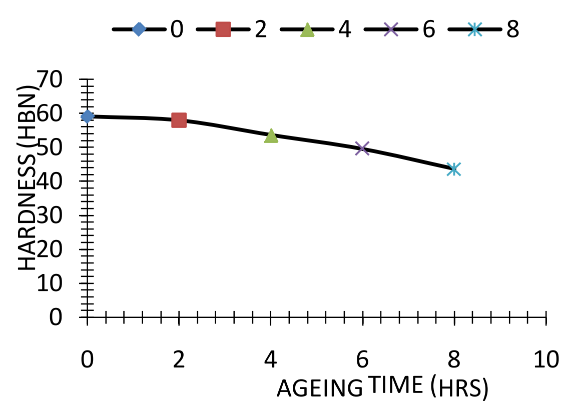

Figure 12: Variation of Hardness Values with Ageing Time for Thermal Treatment at 200 ^{o}C.

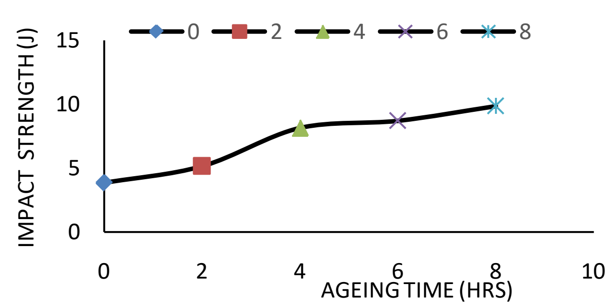

Figure 13: Variation of Impact Strength with Ageing Time for Thermal Treatment at 200 ^{o}C.

d) Aluminium Alloy Sample with Hot Rolled above Recrystallation

The value of 120MPa was displayed by sample deformed at 50% while the other samples for ageing are in a range of 116MPa - 125MPa respectively (Figure 14). The ductility increased with increased ageing time (Figure 15). Hardness values decreased with increased ageing time (Figure 16) while Figure 17 revealed that the impact strength increases with increased ageing time.

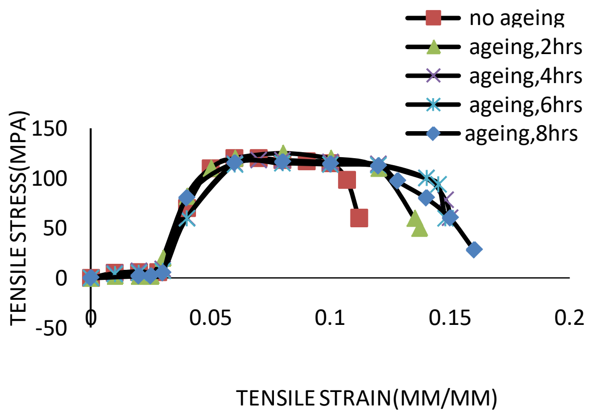

Figure 14: Stress-Strain Curves of Thermal Treatment Samples at 400 °C with Ageing Time

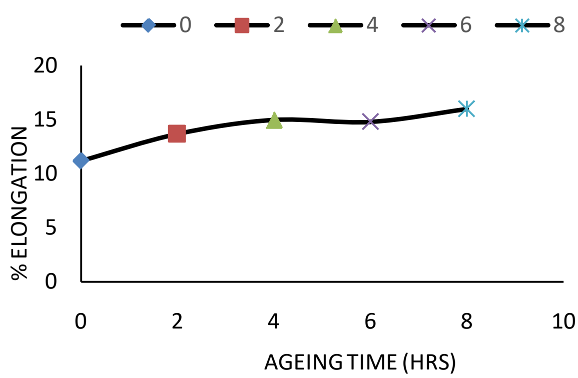

Figure 15: Variation of % Ductility with Ageing Time for Thermal Treatment at 400 °C

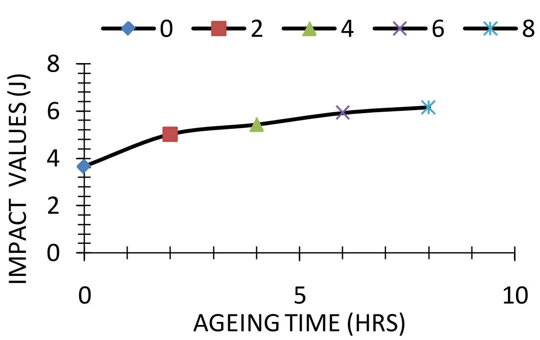

Figure 16: Variation of Hardness with Ageing Time for Thermal Treatment at 400°C.

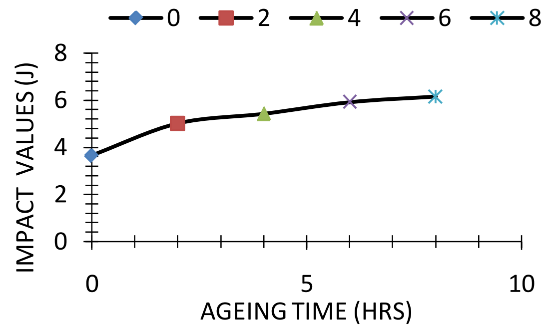

Figure 17: Variation of Impact Energy (J) against Ageing Time for Thermal Treatment at 400°C.

e) Effect of Plastic Deformation and Ageing on Ultimate Tensile Strength of Homogenized AA 8011

Elastic behaviour occurs at a strain of about 2×10^{-3} and maximum tensile strength of 110MPa was achieved for As-homogenized (Figure 2). The effect of ageing improved the Ultimate Tensile Strength to 114MPa. The slight improvement in strength might be due to Guinier-Preston (GP) zones and precipitating second phase particles from solid solution obtained from quenching clustering together resisting the movement of dislocations that generate elastic strain in the surrounding matrix lattice that resisted dislocation slip and thereby increase the strength. Figure 18 shows the heat treatment of the aluminium alloy. The solid solubility limit decreases with decrease in temperature that is the phase diagram show solvus forming supersaturated solid solution and then, reject finely dispersed precipitates at the heat treatment temperature of 500 °C. The aluminium-iron system rich in α-Aluminium was a typical precipitation-hardening system that exists as a homogeneous α-solid solution at high temperatures but on cooling becomes saturated with respect to the second phase (Al-Fe-Si), forming coarse precipitates and occur at the grain boundaries of α-Aluminium matrix and this might be the reason for any improvement in mechanical properties of AA 8011. Rapid quenching of the alloy suppresses the separation of the second phase and no time available for the diffusion to occur to bring about composition changes. The ageing of the alloy for a sufficient length of time at slightly higher temperature of 175 °C caused fine precipitation to occur inside the grain. Due to limited diffusion rates at these low temperature, the solute atoms move through only few interatomic distance giving rise to extremely fine precipitation that can occur by nucleation and growth process. The fluctuation in the solute concentration provides smaller clusters of solute atoms in the crystal lattice of the aluminium which act like nuclei foe the precipitation. The growth rate of these nuclei is controlled by the rate of atomic migration, so that precipitation increases with the increasing temperature. However, the size of the precipitates become finer as the ageing temperature at which precipitation occur is lowered. As the precipitate size increases, loss of coherency at the interface occurs when equilibrium precipitate Al-Fe-Si forms by then over-ageing had already occur.

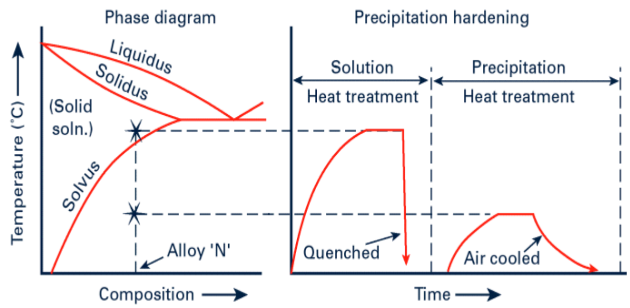

Figure 18: Heat Treatment of Aluminium Alloy.

The effect of plastic deformation at ambient temperature contributes greatly to the mechanical properties of the metal. At 50% percentage deformation, there was progressive increase in UTS from 108MPa to 160MPa and elastic behaviour of 4×10^{-3} respectively (Figure 6). The increase in strength was due to the interaction between the dislocations and precipitate particles, hindering the motions of dislocation there by leading to strength increment. The rapid increased in the value of the UTS of the cold rolled sample up to 50% deformation was attributed to the array of defects such as high density of dislocation produced in the alloy [38]. The very high density of GP zones generates a sufficiently high internal strain to impede dislocation movement. The coherent precipitate (second phase particles) caused further improvement in strength because higher internal strain generated than GP zones. As this particles grow in size, they provide greater resistance to the movement of dislocation slip that cut through and continues to move through the matrix. Deterioration displayed during the 2 - 6 h of ageing might be due to the released of stress carried by coherent precipitate. Cracks that occurs in this particles affect the load bearing capacity of the alloy, thereby limiting its work hardening behavior. Higher level of load transfer to the second phase intermetallic particles lead to flow stress increase in the matrix as previously reported by [39]. Rapid improvement in UTS of 166MPa after 8 h of ageing was attributed to precipitates having large coherency strains or interfacial energies, defect such as the dislocations, sub-grains and grain boundaries acting as the sites for nucleation of the precipitates. Because of the interactions between dislocations and precipitates are on a much finer scale than interactions between dislocations and grain and sub-grain boundaries, the effect of plastic deformation at temperature below (200 ^{0}C) and above (400 ^{0}C) recrystallization has effect on the strength of the alloy (Figure 10). Hot rolling and deformation prior ageing causes deterioration in strength owing to coarsening in the incoherent particles. The degree of recrystallization normally affects the crystallographic texture, which does affect strength and anisotropy of the properties of the aluminium alloy (Figure 14).

f) Effect of Plastic Deformation and Ageing on the Ductility of Homogenized AA 8011

The variation of ductility with 50% deformation showed increase in ductility (Figure 3). The simultaneous increase in ductility of the alloy which could attributed to the micro structural changes. The fine grains formed during deformation might facilitate an increased in grain boundaries sliding and hence grain rotation which could improve ductility. The increase at 50% deformation therefore should have been linked to grain boundaries sliding as previously reported by [40]. Deformation at ambient temperature displayed decrease in ductility and this might be due to dislocations generation which interacted and impeded each other, hindering their motion thereby decreasing the ductility of the alloy [30]. Decreased in ductility were also seen during ageing (Figure 7). Deformation below and above recrystallization temperature of the alloy showed increased in ductility. Ductility increased as the ageing time increased (Figure 11 and Figure 15).

g) Effect of Plastic Deformation and Ageing on the Hardness of Homogenized AA 8011

The Brinell Hardness values of the investigated AA 8011 samples with As-homogenized, cold rolled to 50 % deformation, hot rolled to 50 % deformation at 200 ^{0}C and 400 ^{0}C revealed that cold sample showed highest hardness value followed by hot rolled at 200 ^{0}C while As-homogenized sample showed the lowest value. But during ageing, as-homogenized samples revealed increased in hardness values but the same cannot be said of cold rolled samples, hot rolled samples at 200 ^{0}C and 400 ^{0}C which showed decreased in hardness values (Figure 4, 8, 12, 16). The increased in the hardness value of cold rolled sample could be attributed to high dislocation density (strain Hardening tendency) there by increasing the stacking faults of the alloy under investigation where as decreased in hardness value after ageing of the alloy was as a result of decrease in dislocation density in the interior sub-grains. The rearrangement of the dislocations was assisted by the thermal activation that is ageing temperature, that causes slip, cross-slip and climbing of dislocation over small distance. This observation is in agreement with the previous report by [41].

h) Effect of Plastic Deformation and Ageing on the Impact Strength of Homogenized AA 8011

The impact strength sample of as-homogenized showed an improved value but decreased in impact

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strength were revealed during ageing of the samples (Figure 5). This could be due dislocation generation and interaction. During cold and hot rolling of the alloy, dislocation density increases at 50 % deformation; causing fragmentation of interdenditic particles in the alloy that showed a deficient in the impact strength of the samples. Whereas deformation prior to ageing of the samples revealed increased impact strength. This is attributed to the interaction provided by the precipitates with the dislocation in the alloy.

i) Effect of Plastic Deformation and Ageing on the Microstructure of Homogenized AA 8011

The micro structural analysis reveals homogenous and even distribution of both Al-Fe-Si crystals with more of the crystals and coarse grains structure and the α-Aluminium crystals (see Plate 1a). Homogenization, quenching in water and ageing produce fine and small volume of Al-Fe-Si crystals in α-Aluminium matrix for enhanced strength, hardness and ductility (see Plate 2: a-d).

In the cold rolled sample, the Al-Fe-Si crystals are found at grain boundaries, distorted and in the rolling direction and are finely distribution, which serves as obstacles to the motion of dislocation leading to pile-up of dislocations at the grain boundaries during plastic deformation. The fine and smaller volume fraction of intermetallic phase (Al-Fe-Si phase) precipitated exceeds that of α-Aluminium phase that has some of its crystals diffused into the matrix consequent upon the applied rolled load (Plate 1b). These features promote strength and hardness while sacrificing ductility and toughness. Homogenization, quenched rapidly in water, cold rolled and ageing leads to the annihilation, polygonisation and rearrangement of dislocations of the Al-Fe-Si crystals and α-Aluminium exhibiting decrease in rate of strain-hardening that is strength and hardness decreased but enhanced ductility and impact energy as a result of consequence of dynamic recovery leading reduction in lattice energy occurring without a significant change in the microstructure (see Plate 3: a-d). In the hot rolled below recrystallization temperature sample, distortion of Al-Fe-Si crystals is less pronounced has compared to the cold rolled sample, with a considerable decreased strength and hardness while slight increase in impact energy and ductility (see Plate 1c).

Hot rolled above recrystallization temperature, revealed fine and recrystallized crystals of Al-Fe-Si crystals, α-Aluminium crystals and other intermetallic crystals are seen in Plate 1d.

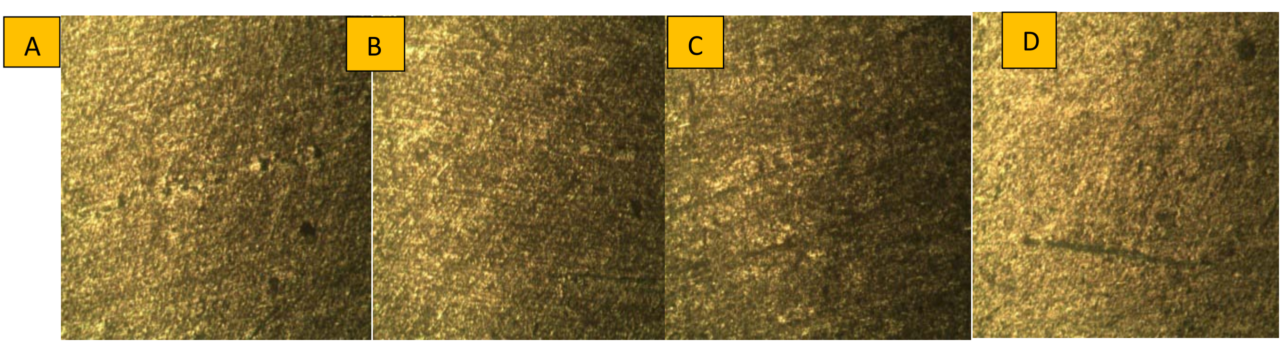

Plate 1: Optical micrographs of (a) as-homogenized (b) cold rolled (c) hot rolled at 200°C (d) hot rolled at 400°C; White spots (second phase particles): Al-Fe-Si, yellowish back ground: α-Aluminium, Black spots: Al-Fe. X100

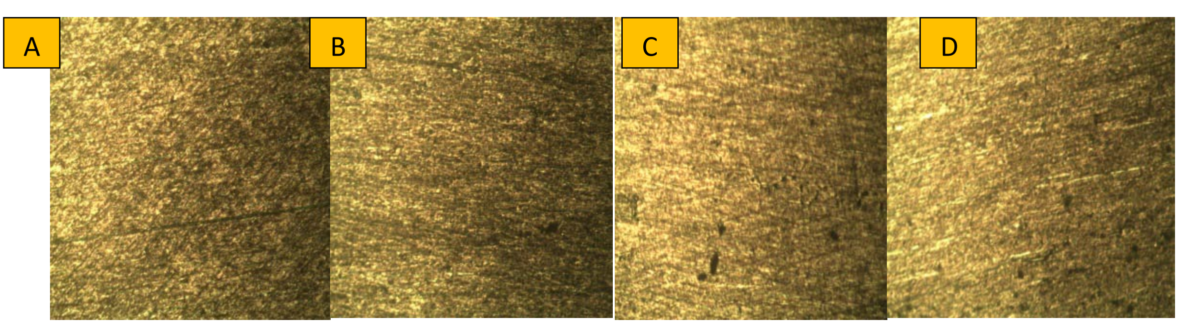

Plate 2: Optical micrographs of As-homogenized Aged at (a) 2hrs (b) 4hrs (c) 6hrs (d) 8hrs; White spots, the interdendritic of intermetallic particles been distributed in α-Aluminium (yellowish back ground), Black spots are Al-Fe. X100

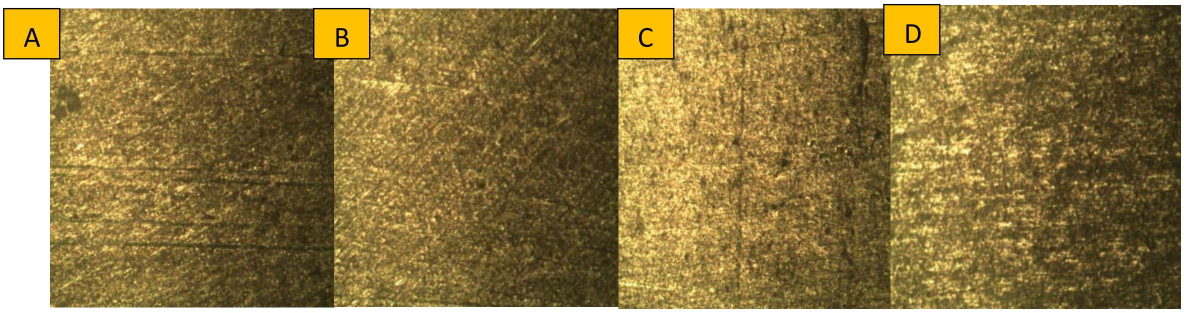

Plate 3: Optical micrographs of cold rolled samples, aged at (a) 2hrs (b) 4hrs (c) 6hrs (d) 8hrs; White spots are interdendritic particles elongated along rolled direction in the Aluminium matrix (yellowish back ground), Black spots are particles of Al-Fe. X100

Homogenization, quenched in water, hot rolled below and above recrystallization temperature prior to ageing rearranged the distorted Al-Fe-Si crystals and α-Aluminium leading to decreased in strength and hardness while promoting or enhancing ductility and impact energy (see Plate 4 &5).

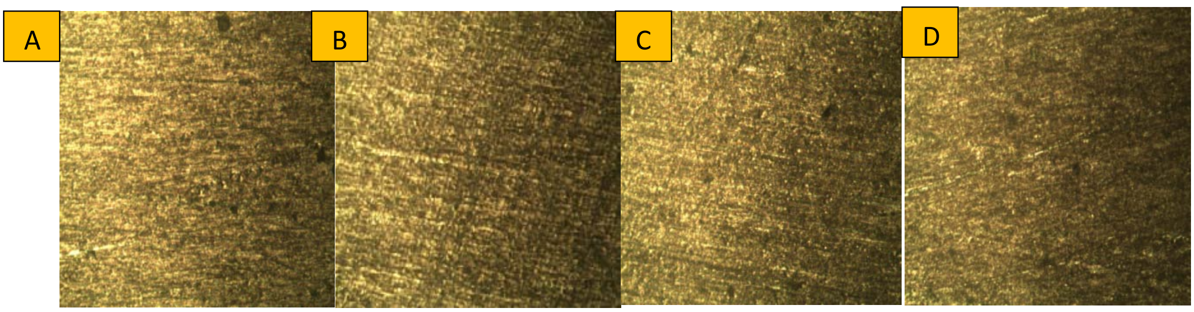

Plate 4: Optical micrographs of hot rolled samples below recrystallization temperature, aged at (a) 2hrs (b) 4hrs (c) 6hrs (d) 8hrs; White (second phase particles): Al-Fe-Si, Brown: α-Aluminium, Black: Iron (Fe). X100

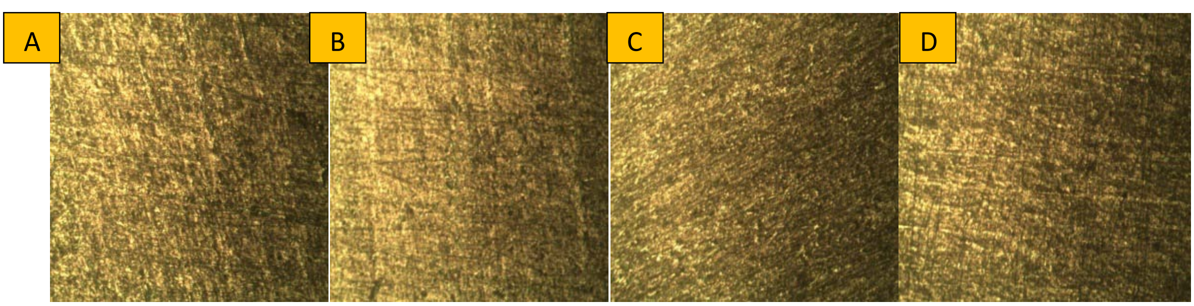

Plate 5: Optical micrographs of hot rolled samples above recrystallization temperature, aged at (a) 2hrs. (b) 4hrs. (c) 6hrs. (d) 8hrs; White (second phase particles): Al-Fe-Si, Brown: α-Aluminium, Black: Iron (Fe). X100

IV. Conclusion

Based on the research finding, the following conclusions were drawn.

i. It can be seen that cold rolling increased; tensile strength, hardness and decreased ductility and toughness.
ii. Hot rolling below and above recrystallization temperature also decreased strength and hardness of the alloy and increased ductility and toughness.
iii. Homogenizing time has more influence on the tensile strength and hardness of the alloy to the other two parameters, viz., aging temperature and aging time.
iv. Homogenizing time (500 ^{0}C), aging temperature (175 ^{0}C), aging time (8 hrs) was found out to achieve the maximum tensile strength of 166 MPa and hardness of 54.72 HBN.
v. Ageing temperature remove internal residual stresses due to the working process that can lead to stress corrosion cracking.

vi. Lattice energy occurring at the recovery stage during ageing lead to slight decreased in tensile strength and hardness while ductility and toughness increased.
vii. The effective utilization of tensile for AA 8011 for achieving the optimal combination of enhanced tensile strength has been attempted.
viii. The alloys also possess excellent ductility as a results of its soften characteristics.
ix. Hot/cold working process helps to improve the mechanical property of Al-Fe-Si alloy and severe plastic deformation techniques will improved the corrosion resistance.
x. The choose of suitable materials and processing techniques by highlighting the recent trends in the emerging area of Al-Fe-Si based materials for orthopedic implants.

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