The Influence of Silicon Content and Matrix Structure on the Mechanical Properties of Al-Si Alloys

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This work focuses on improving the mechanical properties of locally-produced Al-Si alloys by small- and medium-scale, foundry industries, by considering the influence of percentage silicon content and matrix structure, and their correlation on the mechanical properties of Al-Si alloys. Al-Si alloys of different compositions were cast through sand-casting technique; with some modified with NaCl while others were left unmodified. Micro-structural examination was carried out on the cast samples. Thereafter, they were subjected to the following mechanical tests: tensile, hardness and impact-testing. Also, the experimental data were analysed using a routine for multiple regression analysis. The results obtained show that as percentage silicon and percentage β-phase increases, the tensile and hardness strength increases, while the impact energy decreases, and vice versa. Also, the modified samples had better mechanical properties than the unmodified Al-Si cast alloy. Statistical analysis of the experimental data using multiple regression analysis showed that a high degree of correlation exists among the mechanical properties, the percentage silicon content and the matrix structure (α-phase).

Keywords: β-phase, α-phase, % silicon, Al-Si alloy and matrix structure.

1. Introduction

Engineering has extensively made use of "light alloys" as materials for different application; notable among which is in the automobile and space industry where increasing demand is placed on weight savings, which help to reduce energy consumption and promote increased efficiency of service.

Among the commonly used light alloys, Aluminium alloys are the most widely used. They find application in construction, electrical and electronics, and transport industries to mention a few.

Of the many classes of aluminium alloys, the castable Al-Si alloy is widely used in the automobile industries for the production of cylinder heads and pistons, as well as in the aviation industry because of its high strength-to-weight ratio and easy handability (**Polymear, 1989**).

Advancement in studies on Al-Si alloys by researchers, among whom are **Tyriakioglu *et al* (1997)**, who investigated designing reliable processes for aluminium castings; **Evans *et al* (1997)** who studied the flow of liquid aluminium in thin section castings; and **Halvae** and **Campbell (1997)**, who studied critical mould entry velocity for aluminium bronze castings, to mention a few, have made it possible for the casting technology to be improved to ensure that Aluminium components produced are of high quality (mechanical properties; surface finish).

Regrettably, this level of advancement of casting technology does not apply to the foundry industries in Nigeria and other developing countries in the world, which are still in "limbo". Most cylinder heads and pistons produced by foundries in developing countries usually have very poor surface finishes and

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often-poor, mechanical properties which reduce its service life. This situation is greatly compounded by the lack of mechanical testing and metallographic equipment by most foundries in Nigeria and in other developing countries. This equipment would have helped in checking the quality of products produced, before they are sold on the market. This has led to the preference by car owners and car spare parts dealers, for imported cylinder and piston heads from developed countries such as Britain, Japan, Germany and United States of America, as the catastrophic consequences of using "untested" and "poor quality" products are better imagined than experienced.

This work, therefore, seeks to find a solution to this problem, by investigating the influence of casting parameters on the mechanical properties of Al-Si alloy and the correlation of their effect, so as to establish optimum conditions for increased mechanical properties, simplify error control, reduce the number of variables needed to determine the mechanical properties and hence increased service utilisation.

The technological merits of this investigation are its provision of research data that would help most foundry industries in developing nations, in increasing the quality of Al-Si cast products and its provision of mathematical models which would aid our foundries to rapidly predict the mechanical properties of cast products and hence reduce/minimise delay periods during production.

2. Equipment, Materials and Method

2.1 Equipment

The equipment used at various stages of this research were a gas emission spectrographic analyser, a triple beam balance, a crucible furnace, a tensometer, a Rockwell hardness tester, an impact tester, a roll grinder, a polishing machine, a metallurgical optical microscope with camera and a computer with printer.

2.2 Materials

The materials used for this research work were silicon-carbide powder, alpha micro-polish Alumina 5 micron, iron (iii) chloride, sodium chloride, aluminium-magnesium alloy, aluminium-silicon master alloy, aluminium-silicon alloy, etchants and wooden mould boxes.

2.3 Method

The experimental method for this research work followed this sequence of operations: casting of aluminium alloys, micro-structural examination of cast samples, mechanical testing of cast samples, mathematical and computer-modelling.

2.3.1 Casting

The base composition of the aluminium alloys used for casting are shown in **Tables 1, 2** and **3**. Charge calculations were used to prepare the different heats which were superheated in a crucible furnace and cast in sand moulds. This exercise was repeated, but 0.01% sodium chloride was added to the molten aluminium alloy prior to casting into different moulds. This operation was performed so that the unmodified and modified castings were of the same composition. The chemical compositions of the as-cast Al-Si alloy/modified Al-Si alloy are shown in **Tables 4, 5, 6** and **7**.

2.3.2 Microstructure Examination

The microstructures of the cast samples were examined with the aid of an optical microscope. The surface of each sample specimen for microstructure examination was grinded and polished on a roll grinder and polishing machine respectively, after which the samples were etched lightly with dilute hydrofluoric acid before examining under the microscope. Also, the average proportion of the α-solid solution phase was determined using the linear area analysis method. The photomicrographs of the samples are shown in **Figures 1 - 8** and the average proportion of the α-phase estimated for each sample is shown in **Table 8**.

2.3.3 Mechanical Tests

2.3.3.1 Tensile Test

The tensile strength of each of the cast specimens was determined with the aid of an automated tensometer. Tensile test specimens were prepared and tested in accordance with **Emany-Ghony(1997)** and the results obtained are shown (against percentage silicon) in **Figure 9**.

TABLE 1: *Chemical Composition of Al-Mg Alloy*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Cr
Wt%	98.53	0.438	0.315	0.0717	0.235	0.043	0.012	0.439	0.0073

TABLE 2: *Chemical Composition of Al-Si Master Alloy*

Element	Al	Si	Fe
Wt%	96.83	20.0	0.15

TABLE 3: *Chemical Composition of Base Al-Si Alloy*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Na
Wt%	98.83	0.888	1.072	0.128	0.082	0.150	0.016	0.478	0.007

TABLE 4: *Chemical Composition of Al-Si Alloy with 0.4% Si*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Na
Wt%	97.35	0.4	1.05	0.13	0.24	0.20	0.02	0.51	0.002

TABLE 5: *Chemical Composition of Al-Si Alloy with 5.0% Si*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Na
Wt%	94.06	5.0	0.99	0.15	0.20	0.10	0.01	0.40	0.0012

TABLE 6: *Chemical Composition of Al-Si Alloy with 7.0% Si*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Na
Wt%	91.28	7.0	0.89	0.10	0.25	0.12	0.01	0.34	0.0011

TABLE 7: *Chemical Composition of Al-Si Alloy with 10.0% Si*

Element	Al	Si	Fe	Mn	Cu	Zn	Ti	Mg	Na
Wt%	88.68	10.0	0.75	0.12	0.15	0.05	0.009	0.25	0.001

TABLE 8: *Percentage of (α-phase) Solid-solution Phase in the Al-Si Alloys*

	Percentage Solid Solution Phase (α-Phase)	
% Silicon	Unmodified	Modified
0.4	65.97	91.268
5	41.196	57.989
7	41.038	51.694
10	20.075	22.545

2.3.3.2 Hardness Test

The hardness of the cast specimens was determined with the aid of a Rockwell hardness tester. The specimens that were used for microstructure examinations were the same ones used for the hardness test. This was done to ensure that microstructures were consistent with mechanical properties. The hardness test was then performed in accordance with **Ajayi (1996)**. The results obtained are shown in **Figure 10.**

2.3.3.3 Impact Test

The impact energy of the cast specimens was determined with the aid of a charpy impact tester. The specimens were prepared and tested in accordance with **Oyetunji (2002)** and the results obtained are shown in **Figure 11.**

2.3.3.4 Statistical Analysis

After the results of the tests highlighted above had been obtained, they were investigated by statistically analysing them, using a routine for correlation; multiple linear regression analysis. Correlation between the pertinent variables, such as percentage silicon content, micro-structural constituent (% α-phase), tensile strength, hardness and impact energy was carried out to indicate good correlation. The multiple linear regression analysis was used to determine functional relationships of the following:

1. Tensile strength versus (Percentage silicon + % α-solid solution phase)
2. Hardness versus (Percentage silicon + % α-solid solution phase)
3. Impact energy versus (Percentage silicon + % α-solid solution phase); for both the unmodified and modified cast specimens.

Also, a computer programme which was written to analyse the test results and the detailed, flow chart to determine the effect of % silicon and % α-solid solution phase on the mechanical properties of Al-Si cast alloy is shown in **Figure 12.**

3. Discussion of Results

3.1 Influence of % Silicon on the Microstructure

From **Figures 1, 3, 5,** and **7**, it was seen that, as the percentage of silicon increases, the proportion of the α-solid solution phase (white phase) reduces. This arises because an eutectic composition of Al-Si alloy exists (**Evans *et al*, 1997**) above which excess silicon will be precipitated out of the solid solution as the intermetallic compound, aluminium silicide (dark phase; also known as β-phase) when cooled to room

FIGURE 1: *A Plate showing the Microstructure of 0.4% Si, Al-Si Cast Alloy*

The structure consists of primary alpha-solid solution (white phase) with few dark patches (dispersed phase) of precipitated Aluminium silicide (beta-phase); 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

FIGURE 2: *A Plate showing the Microstructure of Modified 0.4% Si, Al-Si Cast Alloy*

The structure reveals directionally-precipitated Aluminium silicide (dark phase) in a matrix of primary alpha-solid solution (white phase); 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

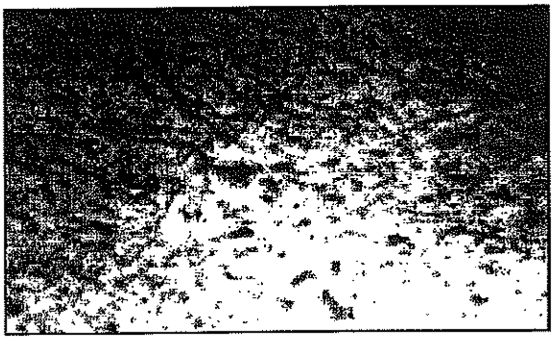

FIGURE 3: *A Plate showing the Microstructure of 5% Si, Al-Si Cast Alloy*

The structure reveals quasi-homogenous distribution of precipitated Aluminium silicide (dark phase) in a matrix of primary alpha-solid solution (white phase); 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

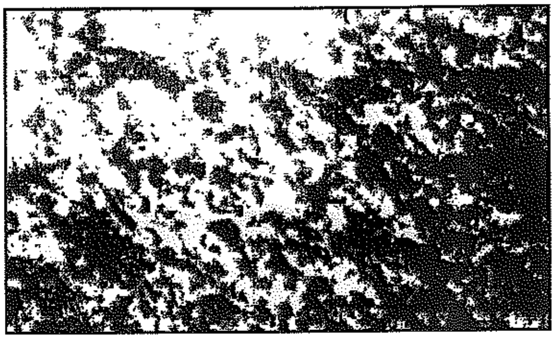

FIGURE 4: *A Plate showing the Microstructure of Modified 5% Si, Al-Si Cast Alloy*

The structure reveals a greater proportion of primary alpha-solid solution (white phase) (compare with unmodified 5% Si) with precipitated Aluminium silicide (dark phase); precipitation mostly occuring along grain boundaries; 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

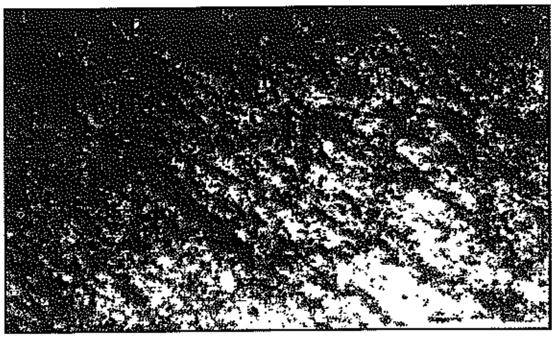

FIGURE 5: *A Plate showing the Microstructure of 7% Si, Al-Si Cast Alloy*

The structure reveals a predominantly Aluminium silicide (dark phase); with some globular (dark) silicon particles dispersed in the structure. The proportion of primary alpha-solid solution (white phase) is less in comparison to the dark phase; 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

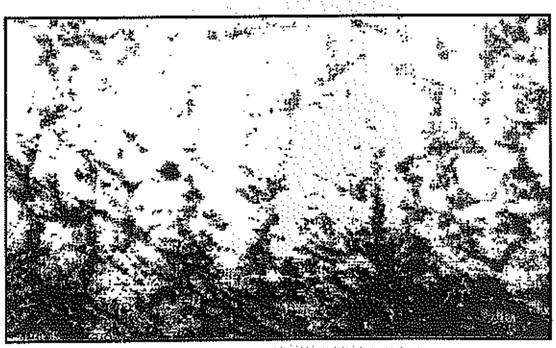

FIGURE 6: *A Plate showing the Microstructure of Modified 7% Si, Al-Si Cast Alloy*

The structure consists of primary alpha-solid solution with almost equi-proportional amounts of precipitated, globular-shaped Aluminium silicide (dark phase) which is fairly homogenously distributed in the structure of the Al-Si cast alloy; 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

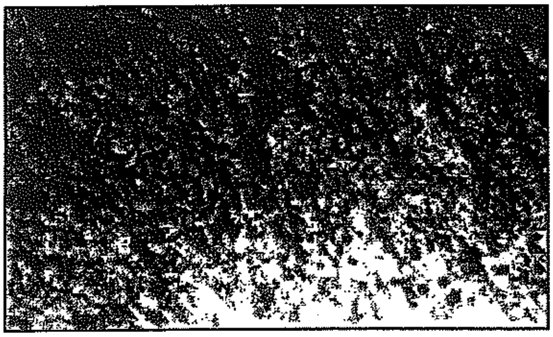

FIGURE 7: *A Plate showing the Microstructure of 10% Si, Al-Si Cast Alloy*

The structure consists of predominantly Aluminium silicide (dark phase), with less amount of primary alpha solid silicon (white phase); 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

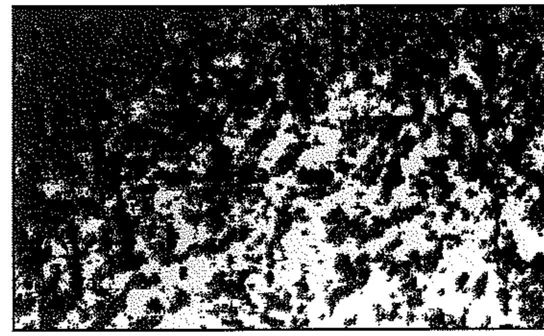

FIGURE 8: *A Plate showing the Microstructure of Modified 10% Si, Al-Si Cast Alloy*

The structure consists of primary alpha-solid solution with globular precipitations of Aluminium silicide (dark phase); fairly homogenously distributed in structure; 200X. Etchant and etching time: Hydrofluoric acid; 55 secs.

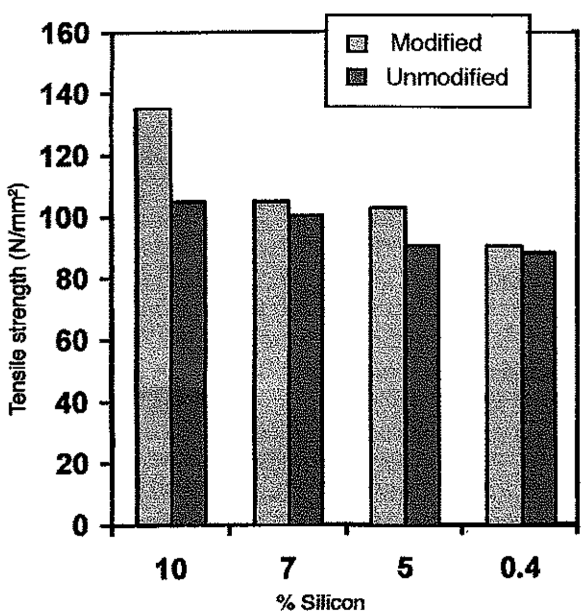

FIGURE 9: *Relationship between % Silicon and Tensile Strength of Modified and Unmodified Al-Si Cast Alloy*

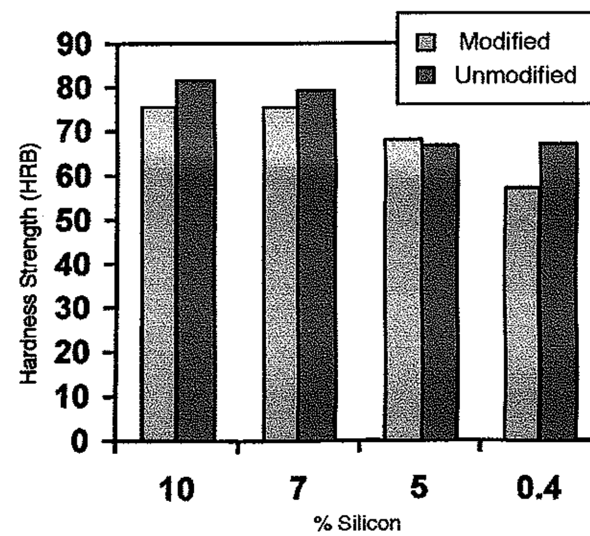

FIGURE 10: *Relationship between % Silicon and Hardness Strength of Modified and Unmodified Al-Si Cast Alloy*

temperature. The aluminium silicide (dark phase) appears as a coarse, intermetallic compound of silicon in a continuous aluminium matrix (**Polymear, 1989**).

3.2 Influence of % Silicon on Mechanical Properties

The results in **Figures 9** and **10** show that as the % silicon content increases in the Al-Si cast alloy, the tensile and hardness strength increases, but from **Figure 11**, it is seen that the impact energy decreases as % silicon increases. The increases in the tensile and hardness strength as % silicon increases is due to the increased proportion of aluminium silicide (β-phase) in the Al-Si matrix. Being harder than the Al-Si solid solution phase (α-phase), it increases the strength and hardness of the Al-Si alloy (**Polymear, 1989**).

However, aluminium silicide apart from being hard, is also brittle, thus increasing proportion of aluminium silicide in the Al-Si matrix, increases its tendency to fail by brittle fracture, hence the lower impact energy values obtained as % silicon increases, which is in accordance with **Dieter (1993)**.

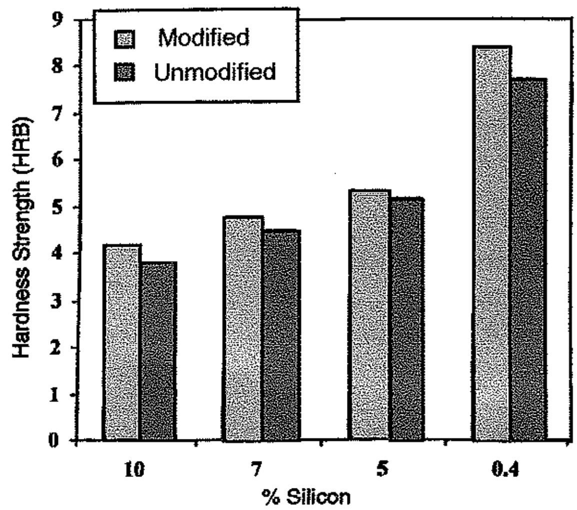

FIGURE 11: *Relationship between % Silicon and Impact Energy for Modified and Unmodified Al-Si Cast Alloy*

3.3 *Influence of Modification on the Microstructure of Al-Si Cast Alloy*

Figures 2, 4, 6 and **8**, in comparison with **Figures 1, 3, 5** and **7** show that modification of Al-Si alloy with NaCl, leads to an increase in the proportion of the α-solid solution phase (white phase) and also produces a refined microstructure. This is due to the fact that NaCl contains sodium, which depresses the eutectic temperature (causes undercooling), hence the rate of nucleation is greater and a much finer silicon grain is produced (**Polukhin *et al*, 1997**). Also, sodium causes a shift of the eutectic composition, making it possible for more silicon to be retained in the α-solids solution phase (aluminium-rich matrix), hence this reduces the proportion of the (β-phase) (**Polymear, 1989**).

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10 CLS
20 SCREEN O
30 COLOR 4
40 LOCATE 5, 10: PRINT "**************************************************"
50 LOCATE 6, 10: PRINT "s.e =standard error, y1=hardness, y2=tensile, y3=import **"
60 LOCATE 7, 10: PRINT "x=%silicon, m$=modified, u$=unmodified, k=% solid solution phase"
70 LOCATE 8, 10: PRINT "**************************************************"
80 REM program to determine effect of x and k on m$ and u$ Al –Si alloy
90 PRINT TAB (10); "select A$ for hardness"
100 PRINT TAB (10); "select B$ for tensile"
110 PRINT TAB (10); "select C$ for impact"
130 INPUT "select your choice"; H$
140 IF H$ = a$ GOTO 180
150 IF H$ = b$ GOTO 230
160 IF H$ = a$ GOTO 280
180 INPUT "do you want it modified or unmodified"; d$
190 IF d$ = m$ GOTO 200 ELSE 210
200 PRINT "y1=21.6854 + 4.872143x + 0.452211k (s.e = 4.56)"
210 PRINT "y1 = 57.4803 + 1.91988x + 2.21E – 05k (s.e = 2.6)"
230 INPUT "do you want it modified or unmodified"; d$
240 IF d$ = m$ GOTO 250 ELSE 260
250 PRINT "y2 = 236. 7117 – 6.86218x – 1.6152k (s.e = 7)"
260 PRINT "y2 = 49.8383 + 4.246x + 0.524k (s.e=4.2)"
280 INPUT "do you want it modified or unmodified"; d$
290 IF d$ = m$ GOTO 300 ELSE 310
300 PRINT "y3 = 12.50667 – 0.76368x – 0.04582k (s.e = 0.88)"
310 PRINT "y3 = 8.397007 – 0.4669x – 0.01169k (s.e=0.59)"
380 IF H$ = F$ GOTO 390
390 ENDS
```

FIGURE 12: *Computer Programme to Determine the Effect of % Silicon Content and Solid Solution Phase on the Mechanical Properties of Aluminum - Silicon Cast Alloy*

3.4 Influence of Modification on the Mechanical Properties of Al-Si Cast Alloy

The results from **Figures 9, 10** and **11** show that modification increases the mechanical properties of the Al-Si cast alloy. This is attributed to the fact that the silicon particles present are refined, hence their "crack initiating effect" is greatly reduced. Also importantly is the fact that sodium present during solidification, leads to a shift of the eutectic point to the right (thus forming solid solution with a greater amount of silicon) (**Askeland, 1992**). This leads to "solid solution enrichment" since more silicon is retained in the solid solution. This solid solution enrichment and grain refinement leads to improvements in the mechanical properties of the Al-Si alloy.

3.5 Statistical Analysis of Experimental Data

The influence of test results provided in the previous sections was further confirmed by statistical analysis of the experimental data using multiple regression analysis (**Mende** and **Sincich (1994)**; **Ruff** and **Wallace (1997)**). Rapid means of assessing the mechanical properties of Al-Si alloys were provided from the relationship obtained. The relationships obtained were as follows:

1. Tensile strength $(N/mm^2) = 49.8283 + 4.246\%$ silicon $+ 0.524\%$ α-phase
   $(R^2) = 0.910$; $(S.E.) = 4.203$ (unmodified)

2. Tensile strength $(N/mm^2) = 236.7117 - 6.56218\%$ silicon $- 1.6152\%$ α-phase
   $(R^2) = 0.9413$; $(S.E.) = 7.032$ (modified)

3. Hardness (HRD) $= 57.4803 + 1.91988\%$ silicon $+ 2.21\text{x}10^{-5}\%$ α-phase
   $(R^2) = 0.910$; $(S.E.) = 4.203$ (unmodified)

4. Hardness (HRD) $= 21.6854 + 4.872143\%$ silicon $+ 0.452211\%$ α-phase
   $(R^2) = 0.881906$; (S.E.): 4.566 (modified)

5. Impact Energy $= 8.397007 - 0.4669\%$ silicon $- 0.04582\%$ α-phase
   $(R^2) = 0.959$; $(S.E.) = 0.59$

6. Impact Energy: $12.50667 - 0.7668\%$ silicon $- 0.04582\%$ α-phase
   $(R^2) = 0.925$; $(S.E.) = 0.88$

Where R^2 = Correlation coefficient; and S.E. = Standard error.

Table 8 shows that the predicted results are close to the experimental results with reasonable degree of error.

4. Conclusion

The observations from the experimental results summarily reveal that as the percentage of silicon increases in the Al-Si alloy, there is an accompanied decrease in the α-solid solution (decrease in (β-phase). This condition leads to an increase in the hardness and tensile strengths of the Al-Si alloy, but affects its impact energy, which decreases as the proportion of the α-solid solution decreases. Modification of the Al-Si cast alloys generally led to an increase in the proportion of the α-solid solution, but with high grain refinement. This microstructural state gave very good mechanical properties relatively to those unmodified. The possibility of rapid predictions of the mechanical properties of the Al-Si cast alloys was affirmed as statistically analysed experimental data showed good correlations between mechanical properties and percentage silicon and microstructural constituent (α-phase).

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