Effect of Cooling Rates and Rapidly Quenched on Al-Si Alloy

Sajed H. Mohammed*, Farah T. M. Noori

Department of Physics, College of Science, University of Baghdad, Baghdad, IRAQ.

*Correspondent contact: sajedalrawi3@gmail.com

ABSTRACT

Due to its unique properties, the material could be applicable in the automotive industry for the manufacture of exhaust valves, for wear parts, and probably as a material for selected aggressive environments. The solidification behavior of the Al-80.5 % Si-19.5 (A), Al-79% Si21% (B) and Al-77.5 % Si-22.5 % (C) alloys at slowly cooling and Rapidly quenched are reported and discussed. The samples were characterized by X-ray diffraction to calculated lattice constant, optical microscopy and mechanically by (Tensile test, and Hardness) in order to evaluate the response of the heat treatment on the different starting microstructures and mechanical properties. It was found that the lattice parameters for all Si contents decreases with increasing Si content in the solid solution. All mineral compounds formed during hardening were examined by optical microscopy. The highest maximum tensile strength was 120 MPa in the sample Al-22.5Si (Slowly cooled) and 126MPa in the sample Al-22.5Si (rapidly quenched) in the same weight, and highest hardness was 77 HB in the sample Al-22.5Si (Slowly cooled), and 81 HB in the sample Al-22.5Si (rapidly quenched).

KEYWORDS: Casting; Aluminum alloys; Microstructure; XRD and Mechanical properties.

INTRODUCTION

The modern world requires the use of light structural materials to improve fuel economy, energy consumption and emissions of gas in industrial application. The properties (low density, high strength stiffness to weight ratio, good formability and good corrosion resistance) make aluminum alloys an ideal material for the manufacturing of components for automotive and aerospace applications [1]. Aluminum-silicon base alloys are widely used in aerospace structural application and the automobile industry due to their low thermal expansion coefficient, high wear resistance and good cast ability [2]. Aluminum-Silicon (Al-Si) alloys are the most important of the Al alloys, these are classified in three groups: hypoeutectic (<11 wt. (%)) Si, eutectic (11-13 wt. (%)) Si, and hypereutectic (>13 wt. (%)) Si. The hypereutectic alloys are attractive to the automotive industry and desirable for wear resistant applications, where high strength and low weight ratio are required [3].

The cooling rate during solidification is an important factor that determines the microstructure formation in castings and hence the mechanical properties of foundry alloys. In general, the enhanced cooling rate is used for the microstructure refinement of different foundry alloys, including widely spread Al-Si alloys [4]. In addition to chemical composition, the structural and mechanical properties of alloys depend on many factors that act during solidification. Important factors are the structure of the melt, the crystallization rate, and the temperature gradient at
the liquid–solid interface. As a rule these factors are varied simultaneously, giving rise to contradictory information on the structure and mechanical properties of Al–Si alloys [5]. The cooling rates for this process were estimated within the range of 105 to 106 Ks⁻¹, much faster than the conventional solidification rates which are 102 Ks⁻¹ or less [6]. Since the introduction of rapid quenching of metallic melts by Duwez, a great variety of techniques have been developed to obtain alloys produced by rapid solidification. Although, the effects of rapid solidification vary widely from system to system, the major effects are: (i) Decreased in grain size, (ii) Increased in chemical homogeneity, (iii) Extension of solid solubility limits, (iv) Creation of metastable crystalline phases, and (v) Formation of metallic glasses [7].

EXPERIMENTAL PROCEDURE:
Six specimens of (Al-Si) alloy were melted in different proportions as shown in table 1 using a crucible made from graphite in gas furnace which was adjusted at 735°C. The obtained material was poured into a preheated to 300°C cast iron metal mold because it has about the best thermal fatigue resistance and that best in aerospace industry, the term vacuum casting likely will be interpreted as the use of a vacuum during the melting of metal material that available because contain low losses of alloying elements by oxidation, very close compositional tolerances, precise temperature control, low level of environmental pollution, removal of undesired trace elements with high vapor pressure and removal of dissolved gasses, such as hydrogen and nitrogen. To study the influences of cooling rate a three different composition samples were quenched in cooled water by ice.

**Table 1.** Weight fractions associated to different elements present in the Al-Si specimens

| Specimen No. | Al%   | Si%   | Cooled Conditions         |
|--------------|-------|-------|---------------------------|
| 1.           | 80.5  | 19.5  | Slowly cooled             |
| 2.           | 79    | 21    | Slowly cooled             |
| 3.           | 77.5  | 22.5  | Slowly cooled             |
| 4.           | 80.5  | 19.5  | Rapidly quenched         |
| 5.           | 79    | 21    | Rapidly quenched         |
| 6.           | 77.5  | 22.5  | Rapidly quenched         |

**X-Ray diffraction**
X-ray diffraction (XRD) technique was used for additional identification of the phases present in investigated alloys. X-rays produced by Empyrean Cu anode tube operating at 45 kV and 40 mA between 25-100 degrees run at a scan rate of 0.033deg/s.

**Optical Microscopy**
Microstructural features were observed using Olympus optical microscope at a magnification of 100X and 200X on a polished surface of the alloys. Polishing was performed with graded abrasive (180, 220, 320, 400, 600, 800, 1000, 1200, and 1500) grit followed by diamond paste of 1.5 and 1 micron. Etching was performed with Keller’s solution (1 volume part of hydrofluoric acid (48%), 1.5 volume part of hydrochloric acid, 2.5 volume parts of nitric acid and 95 volume parts of water) for about 30-50s in order to reveal the microstructure with grain boundaries. Photomicrographs were shot by using 5mm Olympus camera. The area of the grey silicon grains before and after annealing were measured using Reichert optical microscope at a magnification of 100X on polished surfaces of the alloys.

**Tensile strength Test**
The tensile properties of the alloy were studied by performing a test employing the universal testing machine (Model: WP 310 Materials testing, 50kN, Germany). Sample dimensions were taken in accordance with ASTM B-557 [9]. For a uniaxial tensile test, the Young’s modulus (E) is defined as the ratio between stress and strain during the elastic region. For metallic specimens, it is given as:

\[ E = \frac{P}{A \times \varepsilon} \]  
(1)

Where: P is the load measured during the elastic region through a load cell; A is the cross-sectional area of the specimen; \( \varepsilon \) is the elastic strain.

**The Brinell hardness Test**
The Brinell harness number is attained by dividing the applied load by the indentation surface area. When the indentation is drawn, two diameters of the impression, \( d_1 \) and \( d_2 \), were measured using a special microscope with a calibrated graticule and then the average values were calculated as shown in the following equation (2) and shown in Figure 1.
\[ BHN = \frac{P}{\pi \left( D - \sqrt{D^2 - d^2} \right)} \]  

Figure 1. Sample of Brinell hardness Test.

Where:
P is the test load [kg], D is the diameter of the ball [mm], d is the average impression diameter of indentation [mm].

**RESULTS AND DISCUSSION**

**X-ray diffraction**

X-ray diffraction (XRD) is widely used to examine the lattice constant (a) of various alloy appears in Table 1. Figure 2 that determine the amount of retained-Si upon rapid quenching, the lattice parameter of \( \alpha \)-Al phase was determined using Bragg’s formula for both slowly cooling and rapidly quenched. The lattice parameters for all Si contents are given in Table 1. The lattice parameter of \( \alpha \)-Al phase decreases with increasing Si content in the solid solution. The quantity of decrease has been detected via the closest distance of approach of the constitutional atoms that agree with Farah Tariq [8] and Orhan UZUN et al. [9] that mean all added Si amount were nearly solved in \( \alpha \)-Al for each melt-spun Al-Si alloys. However, because of the very weak and broad Si reflections in the melt-spun ribbons, a certain Si amount could be lost in the background.

**Table 1.** The lattice constant of Al-Si alloy at (a) slowly cooled and (b) rapidly quenched.

| Sample | a (Al) | a (Si) |
|--------|--------|--------|
| A      | 5.4265 | 4.0469 |
| B      | 5.4249 | 4.0474 |
| C      | 5.4230 | 4.0469 |

| Sample | a (Al) | a (Si) |
|--------|--------|--------|
| A      | 5.4249 | 4.0462 |
| B      | 5.4235 | 4.0468 |
| C      | 5.4198 | 4.0456 |

Figure 2. XRD pattern for (a) Al-Si alloy with slowly cooled, (b) Al-Si alloy with rapidly quenched.
Optical microscopy
Figure 3 shows the images taken by the optical microscopy of Al–Si alloys obtained by casting of levitated melts for 20.5 wt. %. The 20.5 wt. % Si alloy has an anomalous finest-grain eutectic structure and also that Si wt. percentage in the Aluminum-Silicon alloys can be classified into three main classifications: Hypoeutectic (<12 wt. % Si), Eutectic (12-13 wt % Si), and Hypereutectic (14-25 wt. % Si) [3].

(a) \( \alpha \)-Al Primary Si Particles

(b) Primary Si Particles \( \alpha \)-Al

Figure 3. As received microstructure, (a) Al-Si alloy with slowly cooled, (b) Al-Si alloy with rapidly quenched.

Tensile Test
The results of the tensile strength are shown in Table 2, Figure 4 seen that the tensile strength increases proportionally. The highest UTS was 126 MPa, in sample 6 (Si content was 22.5% Si), this is due to the rapid cooling of the samples that agree with Suk Bong Kang et.al [2].

| Specimen No. | Al% | Si% | Tensile Strength (MPa) | E. % |
|--------------|-----|-----|------------------------|------|
| 1            | 80.5| 19.5| S.c.                   | 90   |
| 2            | 79  | 21  | S.c.                   | 104  |
| 3            | 77.5| 22.5| S.c.                   | 120  |

Table 2. Tensile Strength [Al-Si] of alloys at slowly cooled (S.c.) and rapidly quenched (R.q.).

The Brinell hardness Test
The Hardness results shown in Table 3 and Figure 5, it increased proportionately with the increase in Si contents. The highest hardness value was 81 HB, in sample 3 (Si content was 22.5% Si) this may be due to increment of silicon amount which is hard precipitates which increased hardness of Al-Si alloy that agree with Farah Tariq [8].

| Specimen No. | Al% | Si% | Hardness (HB) |
|--------------|-----|-----|---------------|
| 1            | 80.5| 19.5| S.c.          | 60   |
| 2            | 79  | 21  | S.c.          | 67   |
| 3            | 77.5| 22.5| S.c.          | 77   |
| 4            | 80.5| 19.5| R.q.          | 64   |
| 5            | 79  | 21  | R.q.          | 72   |
| 6            | 77.5| 22.5| R.q.          | 81   |

Table 3. Hardness test outcome.
CONCLUSIONS
1. In this work, the Al-Si alloy (in wt %) was prepared at slowly cooling and rapidly quenched are reported.
2. The lattice parameters for all Si contents decreases with increasing Si content in the solid solution.
3. The highest maximum tensile strength (UTS) was 120 MPa in the sample Al-22.5Si (Slowly cooled) and 126MPa in the sample Al-22.5Si (rapidly quenched) in the same weight, and highest hardness was 77 HB in the sample Al-22.5Si, and 81 HB in the sample Al-22.5Si.

REFERENCES
[1] Hirsch, J.; Al-Samman, T. Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications. Acta Mater. 2013, 61, 818–843.
[2] Suk Bong Kang et al, Effect of Cooling Rate on Microstructure and Mechanical Properties in Al-Si Alloys, Proceedings of the 12th International Conference on 675 Aluminium Alloys, September 5-9, 2010, Yokohama, Japan©2010 The Japan Institute of Light Metals pp. 675-680.
[3] Miguel Angel Suarez et al, Study of the Al-Si-X System by Different Cooling Rates and Heat Treatment. Materials Research. 2012; 15(5): 763-769
[4] Alexander Chaus et al, Effect of Rapid Quenching on the Solidification Microstructure, Tensile Properties and Fracture of Secondary Hypereutectic Al-18%Si-2%Cu Alloy, Metals 2020, 10, 819; doi:10.339
[5] S.P. Nikanorov et al, Structural and mechanical properties of Al–Si alloys obtained by fast cooling of a levitated melt, Materials Science and Engineering A 390 (2005) 63–69
[6] Pavel Nová, Tomáš Vanka, Kateřina Nová, Jan Stoulił, Filip Průša, Jaromír Kopeček, Petr Hašíld and František Laufek, “Structure and Properties of Al–Si Alloy Prepared by Mechanical Alloying” Materials 2019, 12, 2463.
[7] Xiaoyang Liu, Keito Sekizawa, Asuka Suzuki, Naoki Takata, Makoto Kobashi and Tetsuya Yamada “Compressive Properties of Al-Si Alloy Lattice Structures with Three Different Unit Cells Fabricated via Laser Powder Bed Fusion” Materials 2020, 13, 2902;
[8] Farah Tariq Mohammed, MSc in physic’ Lattice strain & grain morphology of Al-Si alloy system “Baghdad, 2002.
[9] Orhan UZUN, Tuncay KARAASLAN, Mustafa KESKIN,” ITAK Production and Structure of Rapidly Solidified Al-Si Alloys”Turk. J. Phys. 25 (2001) , 455 – 466.