EFFECT OF COOLING RATE ON MECHANICAL PROPERTIES OF EUTECTIC AND HYPOEUTECTIC Al-Si ALLOYS

Dr. Zeyad D. Kadhim
Materials Engineering. Dep. College of Engineering.
University of Al-Mustansiriya- Baghdad-Iraq

ABSTRACT

In this research the effect of cooling rate and mold type on mechanical properties of the eutectic and hypoeutectic (Al-Si) alloys has been studied. The alloys used in this research work were (Al- 12.6%Si alloy) and (Al- 7%Si alloy).The two alloys have been melted and poured in two types of molds with different cooling rates. One of them was a sand mold and the other was metal mold. Mechanical tests (hardness, tensile test and impact test) were carried out on the specimens. Also the metallographic examination was performed.
It has been found that the values of hardness for the alloys(Al-12.6%Si and Al-7%Si) which poured in metal mold is greater than the values of hardness for the same alloy when it poured in a heated metal mold at different temperatures or in sand mold. The strength and impact resistance for the alloys (Al-12.6%Si and Al-7%Si) are greater when these were poured in a metal molds than that when it poured in a sand mold.

Furthermore, the higher cooling rates enhance the strength, hardness and impact resistance for the two alloys, while the low cooling rates reduces these mechanical properties.

The percentage of elongation and the amounts of formed porosity decreased when the cooling rates increased.

الخلاصة

درس في هذا البحث تأثير معدل التبريد ونوع القالب على الخواص الميكانيكية لسبائك (المنيوم – سليكون) اليوتكتيكية و تحت اليوتكتك. السبائك المستخدمة في هذا العمل البحثي كانت (سبيكة المنيوم –٦، ١٢% سليكون) و (سبيكة المنيوم – ٧ % سليكون). السبيكتين تم صهرها و صبها في نوعين من القوالب و بمعدلات تبريد مختلفة . أحدهما كان قالب رملي و الاخر كان قلب معدني . الاختبارات الميكانيكية (الصلادة ، أختبار الشد ، أختبار الصدمة) تم أجراها على العينات. أنجز الفحص المجهري أيضا.
لقد وجد بأن قيم الصلادة للسبائك (المنيوم –٦، ١٢% سليكون و المنيوم – ٧ % سليكون) و التي صبت في القالب المعدني هي أكبر من قيم الصلادة لنفس السبائك عند صبها في قالب معدني مسخن عند درجات حرارية مختلفة أو في قالب رملي.
المقاومة ومقاومة الصدمة للسبيكتين هي أكبر عند صبها في قوالب معدنية من تلك المصبوبة في قالب رملي.
علاوة على ذلك ، معدلات التبريد العالية تحسن من المقاومة ، الصلادة و مقاومة الصدمة للسبيكتين بينما معدلات التبريد الواطئة تقلل من تلك الخواص الميكانيكية.
أن النسبة المئوية للاستطالة و كمية المسامية المشكلة تقل عندما تزداد معدلات التبريد.

Keywords: cooling rate, eutectic, hypoeutectic alloys, mechanical properties, molds.

1-Introduction

Alloys with silicon as the major alloying addition are the most important of the aluminum casting alloys mainly because of high fluidity imparted by the presence of relatively large volumes of the Al-Si eutectic. Other advantages of these castings are high resistance to corrosion, good weldability and the fact that silicon reduces the coefficient of thermal expansion. [1]

The static fracture toughness of a series of eutectic AI-Si casting alloy with different microstructural features has been evaluated by Hafiz and Kobayashi . Fracture toughness was found to be strongly associated with the size and morphology of silicon particles. [2]

One of the major problems associated with the casting of aluminum alloys is the formation of micrometer scale cavities called microporosity. Microporosity is a leading cause in the reduction of mechanical properties. Particularly, fatigue resistance, as well as a loss of pressure tightness and a degradation of the surface appearance in cast parts[3, 4]

For aluminum alloy A356 permanent mold castings, it was observed that local fatigue resistance varied substantially along the solidification path while tensile strength was little affected. The amount of Al–Si eutectic and the density of micropores are increased along the solidification path. [5]

Haizhi studied the fatigue and wear properties of Al-Si alloy. The silicon phase is important to both of these properties. Coarse silicon usually reduces fatigue life due to microcrack initiation. Higher silicon content usually increases the wear resistance of Al-Si alloy as it increases the alloy's hardness. Intermetallic precipitates and casting defects also influence fatigue and wear performance. Fine precipitates can usually strengthen the alloy while sharp and coarse precipitates degrade these two properties. Casting defects such as porosity and inclusion usually reduce the alloy's fatigue and wear resistance due to microcrack initiation. [6]

Taylor discussed the various sources of iron and how it enters aluminum alloys, the way that iron leads to the formation of complex intermetallic phases during solidification, and how these phases can adversely affect mechanical properties, especially ductility, and also lead to the formation of excessive shrinkage porosity defects in castings. [7]

It was found there are no differences in ultimate tensile strength as well as bulk hardness between the sulfurized alloy and normal A356; it is evident that yield strength and ductility of the A356 alloy are reasonably altered with the presence of sulfure. The A356 alloy containing sulfur exhibits greater ductility and lower yield strength in comparison with the normal A356 alloy. [8]

The effect of cast Al-Si-Cu alloy solidification rate on alloy thermal characteristics has been studied by L.A. Dobrzański et al. It was found that the solidification parameters are affected by the cooling rate. The formation temperatures of various phases are changed with an increasing cooling rate. Also increasing the cooling rate increases significantly the Al nucleate temperature, nucleation undercooling temperature, solidification range and decreases the recalescence undercooling temperature. These phenomena lead to an increased number of nucleus that affect the size of the grains and the Secondary Dendrite Arm Spacing (SDAS). [9]

Abdulwahab, et al. have made a comparative study of the hardness values and impact energy of as-cast and age-hardened Al-Si-Fe-MnCr alloy produced when various addition of MnCr (0.1-0.5%) were made to Al- Si-Fe alloy so as to give a series of alloys with constant composition of Si and Fe. The alloy was solution treated and aged at 490oC and 200oC respectively for six hours. These treatments introduced the formation of complex precipitates in the alloys. It was found that the reprocessed (age–hardened) alloys showed an excellent combination of hardness and impact energy values than the as-cast alloys. [10]

The effects of eutectic silicon particles on tensile properties and fracture toughness of three A356 aluminum alloys were investigated by Kyuhong Lee. et. al. These A356 alloys were fabricated by casting processes such as low-pressure-casting, casting-forging, and squeeze-casting, and their tensile properties and fracture toughness were analyzed in relation with microfracture mechanism study. Microfracture observation results showed that eutectic Si particles segregated along solidification cells were cracked first, but that aluminum matrix played a role in blocking crack propagation. The cast-forged alloy had the best hardness, strength, ductility, and fracture toughness because of the matrix strengthening and homogeneous distribution of eutectic Si particles due to forging process. [11]

The strength and fracture studies of as-cast Al-Si-Cu alloys have been investigated. As cast alloys have been characterized using XRD and optical microscope. To evaluate the strength of these alloys, a tensometer has been employed and the fracture surfaces have been observed under SEM to understand the mode of fracture. It has been observed that the fracture surface of the alloys mainly shows brittle characteristics. The porosity and blowhole present in the cast alloy has been the dominating factor for low strength of the alloys. [12]

The influence of microstructure and process history on mechanical behavior of cast Al-Si alloys is reported. Metallographic and image analysis techniques have been used to quantitatively examine the microstructural parameters of the α-Al phase and eutectic silicon. The results showed that secondary dendrite arm spacing SDAS and length of eutectic silicon particles increase with section thickness, and consequently mechanical properties decrease. [13]

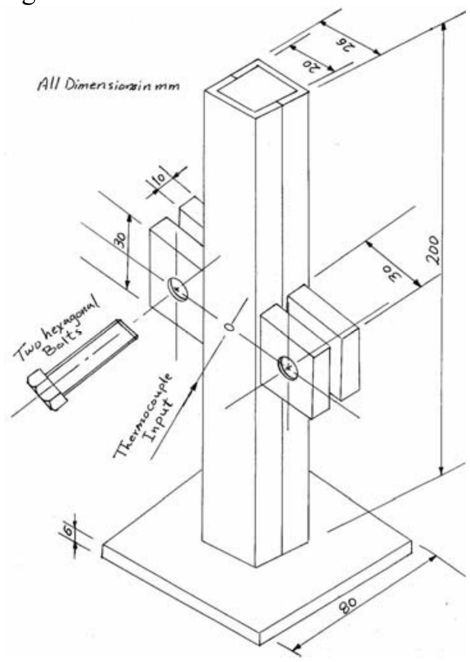
2- Experimental Procedure

In present work, the casting process was carried out by using sand and metal molds to cast the eutectic alloy (Al-12.6% Si) and the hypeoteutic alloy (Al-7%Si). These alloys have been prepared before casting process Table (1).

Table (1) Chemical compositions of the alloys studied

Alloys	Elements (Wt%)					
	Si	Mg	Fe	Cu	Mn	Al
Al-12.6%Si	12.6	0.75	0.86	0.85	0.11	Remainder
Al-7%Si	7	0.30	0.20	0.01	0.006	Remainder

After charging the crucibles with the alloys, it were put inside a resistance electric furnace and heated up to (650 ºC). The molten alloys were pouring in the molds, as soon as the mold cavity was filled with metals, it is allowed to cool and solidify. The metal molds have been previously heated for different temperatures (25°C, 100°C and 250°C) .So the cooling rate for the two alloys became (1°C/sec, 4°C/sec and 7°C/sec). In the case of sand mold, the cooling rate was (6 °C/sec).The samples that produced from the casting process have square cross sections with dimensions (20x20x200)mm³.A thermometer with chromel-alumel thermocouple (K-type) covered by a hastalloy was used to measure the temperature. The thermometer was put in the center of the mold cavity as shown in the figures below.



Fig(1) Metal mold

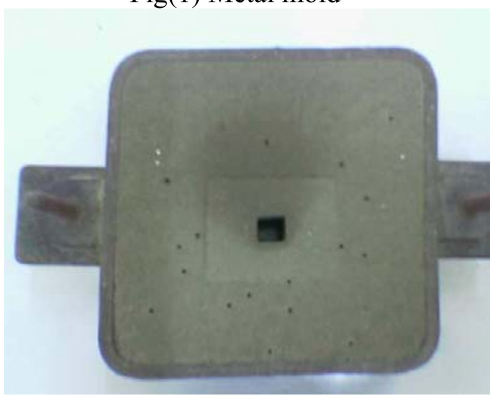


Fig (2) Green sand mold (upper part)

For metallographic examination, all castings were sectioned vertically across the centerline to observe the internal porosity; (see figs (1, 2)) their surfaces were grounded by using 250, 500 and 1000 SiC emery papers. Primary and final polishing was performed using alumina slurry with particle size of 50 μm and diamond paste with particle size of 1 μm. Finally all polished samples were cleaned by water and alcohol and then dried. The samples were etched using 0.24% hydrofluoric acid (HF). Each sample was then observed and photographed at a magnification of X300.

The tensile test was performed using UTS apparatus with 200 kN loading capacity. The tensile flat test specimens were prepared with the gauge length section has the dimension of 12.5 mm width and 50mm gauge length according to ASTM designation: E8M-03. [14] The tensile test was achieved at room temperature in ambient air at a cross-head speed of 2 mm/min.

The hardness test was carried out by using the Vickers Microhardness technique with load (20 gm).

The impact test was carried out according to the recommended standard charpy V-notched method. The specimen is supported at each end and notched at the midpoint between the supports. The notch is on the face directly opposite to where the pendulum strikes the test piece. The specimen has a square cross-section of side 10mm and length 55mm.

The percentage porosity of specimen was calculated from the following relationship:-

$$\%\text{Porosity} = \frac{\rho_{\text{pfs}} - \rho_{\text{o}}}{\rho_{\text{pfs}}} \times 100$$

Where ρpfs is the density of the pore-free sample and ρo is the observed density of the sample.[15]

In order to obtain the maximum density or pore-free density of a sample, the sample was compressed to about 80% of its original thickness under a compressive load after which its density was evaluated using the common Archimedean method. [15]

3-Results and Discussion

It was found that strength of alloy Al-12.6%Si has changed when changing the cooling rate. It can be seen that the strength value reach to (194 MPa) when the cooling rate has a value (7 ºC/sec).Fig (5) the eutectic structure of this alloy can be observed from the microstructure Fig (13).

The strength of this alloy became (160 MPa) when the cooling rate is low (1ºC/sec). It can be seen that from the Fig (5). And this is due to the formed cavities. These cavities are bigger as a result of small porosity which join together to form big cavities Fig (10).

However, when the cooling rate is very low so there is an evolution of hydrogen gas bubbles due to a sudden decrease in hydrogen solubility during solidification (gas pores). Combined gas-shrinkage porosity may also exist. [3, 4]

The values of strength, microstructure and the formed porosity were differs when the (Al-7%Si) alloy was poured in molds.

It was found that the strength of Al-7%Si became (183 MPa) when the pouring of this alloy in a metal mold with cooling rate (7 ºC/sec).Fig (5) This is due to defects formation. However, the percentages of defects (porosity) were low, and have a small size; this can be seen from the metallographic. Fig (16)

The strength of this alloy was differing as result to the change in cooling rate. When the cooling rate became (1ºC/sec) the defects (cavity) size became big and the percentages of defects (porosity) were high. Fig (14)

The strength value of this alloy was (150 MPa) when the cooling rate was (1ºC/sec) and this is a less value of strength due to size of the formed porosity was too big , where the small porosity (microporosity) meet each other to form a big porosity (cavities). And this is also could be seen when pouring the alloy in a sand mold which the cooling rate (6ºC/sec).

The alloy (Al-12.6%Si) has a hardness value of 58 HV while the Vickers hardness value for the alloy (Al-7%Si) was 48 HV. These alloys were cast in sand casting process where the cooling rate was (6°C/sec).

These values were changed when the alloys casted in a metal mold as shown in Fig (6).It can be seen that the highest values were 64 HV and 52 HV for (Al-12.6%Si) and (Al-7%Si) alloys respectively.

From these results, it can be remarked that the values of hardness increased due to the big amount of the volume fraction for Si in matrix so the eutectic alloy (Al-12.6% Si) has a high value of hardness, However high cooling rate make high hardness value for these alloys. Also the percentage of porosity was less when the cooling rate was high.

The values of hardness for the two alloys were low when the cooling rate low due to the formation of cavities and porosities (microporosity and

macroporosity). The increment in cavities and porosities are as a result of joining the gas porosities to the shrinkage porosities inside the casting because there is no degasser has been used.
The solidification mode in the alloy (Al-7%Si) is a denderatic, so the formed porosity in this casting has small size but the amounts was high as compared with the casting (Al-12.6%Si) in which the solidification mode is planner. And the small amounts of the formed porosity in the alloy (Al-12.6%Si) make cavities which can be seen in the upper part of cast as pipe. Thus these modes have an effect on the formed porosity and the mechanical properties.
From the values of the absorbed energy to break samples by shock, it can be seen that the highest value was for the sample of (Al-12.6%Si) alloy which is casted in a metal mold with a cooling rate of (7°C/sec) and this is due to the formed porosity was low as compared with the other samples which have a different cooling rates. Fig (7)
Fig (8) shows the effect of cooling rate on the elongation of these alloys , it can be seen that the increments in cooling rates make the percentage of elongation low and this is because of the high cooling rates make an increments in defects ((point and line defects (dislocation)). So there is an increase in strains thus the extension will be low.
It can be Concluded that the ductility of these alloys are low. While the alloys that solidified with low cooling rates have high ductility.
However alloys having coarse eutectic exhibit low ductility because of the brittle nature of the large silicon plates. Fig (10) Rapid cooling greatly refines the microstructure and silicon phase assumes a fibrous form with result that the ductility is much improved. Fig (13) [1]
Microporosity formation is generally attributed to two factors: shrinkage, coupled with a lack of interdendritic feeding during mushy zone solidification (shrinkage pores), and evolution of hydrogen gas bubbles due to a sudden decrease in hydrogen solubility during solidification (gas pores). Combined gas-shrinkage porosity may also exist.

However, Fig (9) shows that the high cooling rates decrease the amounts of porosities. This is because there is no sufficient time for formation big amounts of gas porosity or joins this porosity with shrinkage porosity and makes cavities. So the percentage of porosity was high when the cooling rate low.

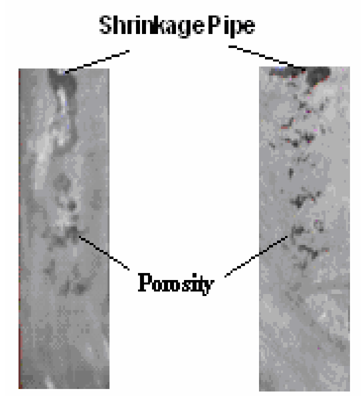


Fig (3) Shows Al-12.6% Si Casting after sectioning that cut from the centerline with cooling rate (1%˚C/sec)

Fig (4) Shows Al-7%Si casting after sectioning that the cut from the centerline with cooling rate (1%˚C/sec)

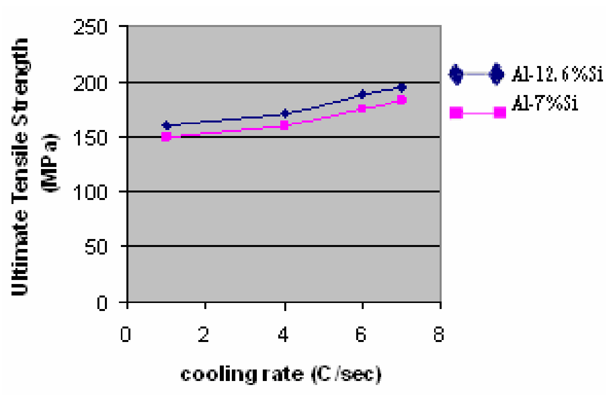


Fig (5) the effect of cooling rate on ultimate Tensile strength for two alloys a- Al-12.6% Si b- Al-7%Si

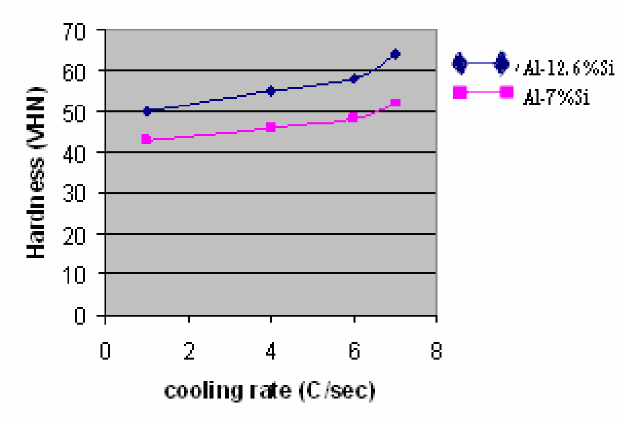


Fig (6) the effect of cooling rate on hardness for two alloys a- Al-12.6% Si b- Al-7%Si

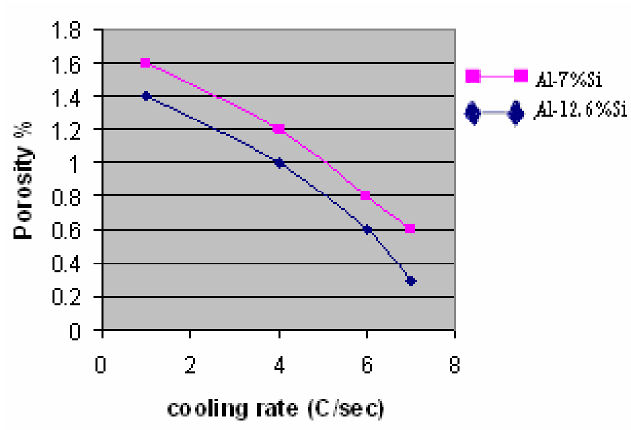


Fig (9) the effect of cooling rate on the percentage of porosity for two alloys a- Al-12.6% Si
b- Al-7%Si

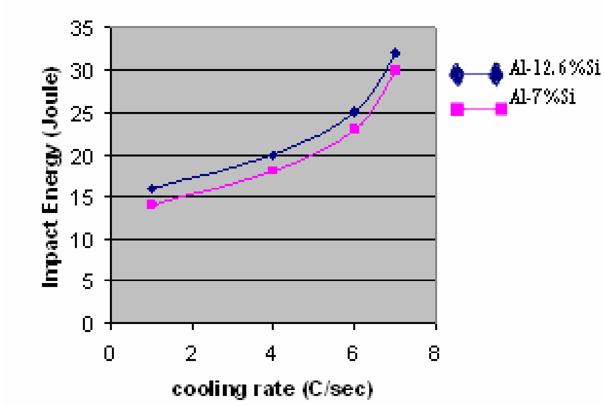


Fig (7) the effect of cooling rate on the impact energy for two alloys a- Al-12.6% Si b- Al-7%Si

Porosity
(Gas and Shrinkage)

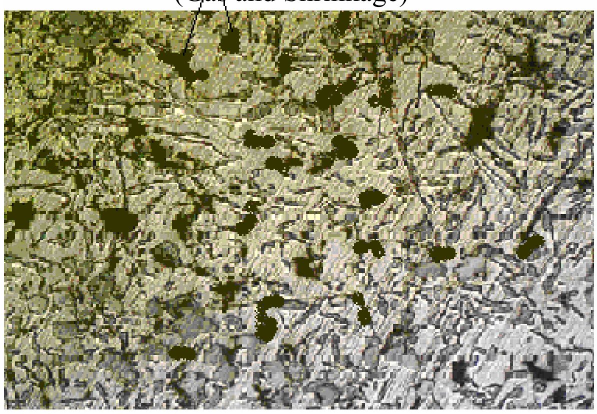


Fig. (10) The microstructure for cast Al-12.6%Si with cooling rate 1ºC/sec Magnification (300X), shows the porosity and the eutectic layers.

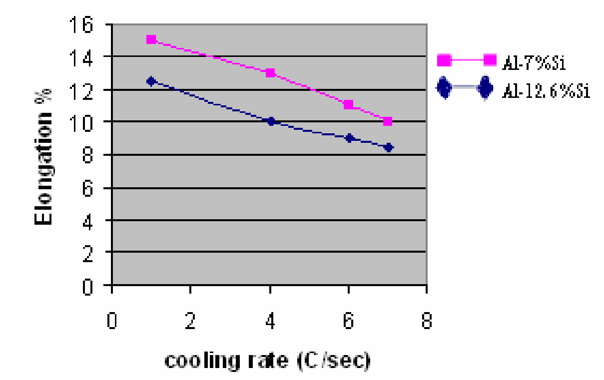
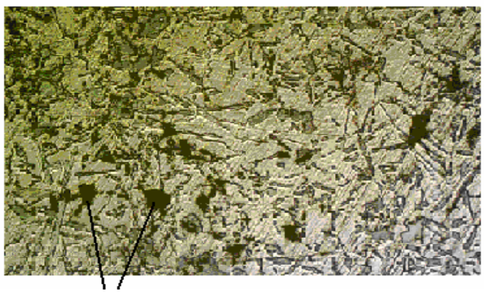


Fig (8) the effect of cooling rate on the percentage of elongation for two alloys a- Al-12.6% Si
b- Al-7%Si



Porosity (Gas and Shrinkage)

Fig. (11) The microstructure for cast Al-12.6%Si with cooling rate 4ºC/sec Magnification (300X), shows the porosity and the eutectic layers.
Porosity (Gas and Shrinkage)

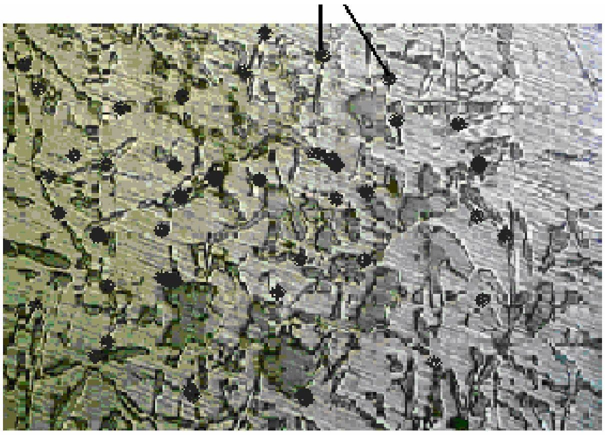
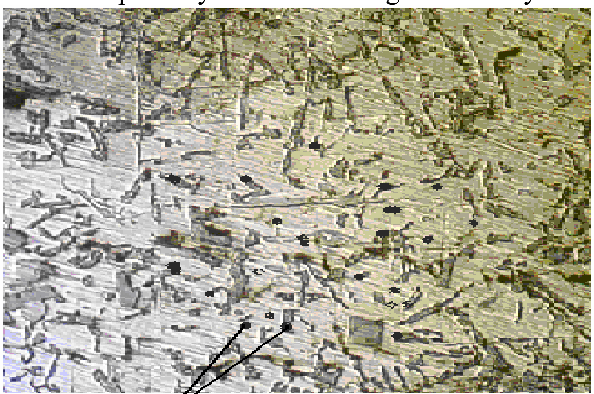
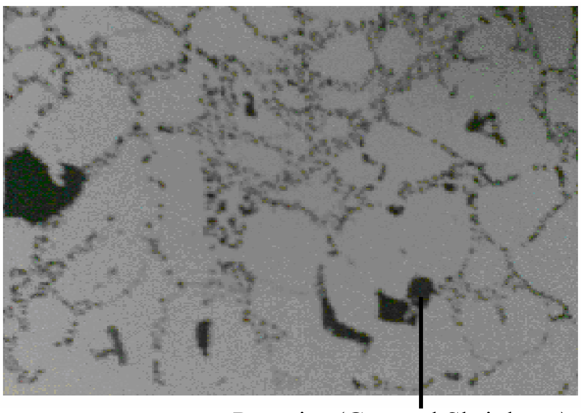


Fig. (12) The microstructure for cast Al-12.6%Si with cooling rate 6ºC/sec Magnification (300X), shows the porosity and the refining eutectic layers.



Porosity (Gas and Shrinkage)

Fig. (13) The microstructure for cast Al-12.6%Si with cooling rate 7ºC/sec Magnification (300X), shows the porosity and the refining eutectic layers.



Porosity (Gas and Shrinkage)

Fig. (14) The microstructure for cast Al-7%Si with cooling rate 1ºC/sec Magnification (300X), shows the formed porosity.

Porosity (Gas and Shrinkage)

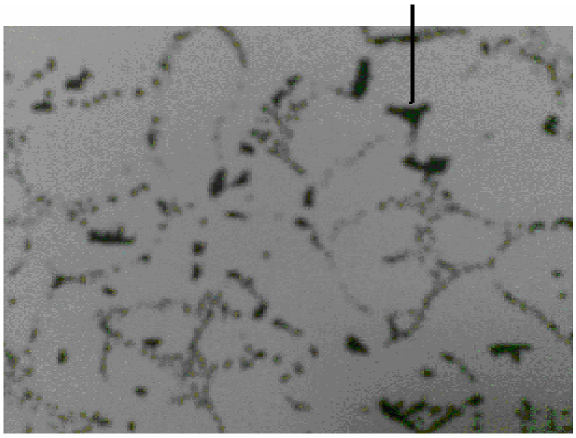


Fig. (15) The microstructure for cast Al-7%Si with cooling rate 4ºC/sec Magnification (300X), shows the formed porosity.

Porosity (Gas and Shrinkage)

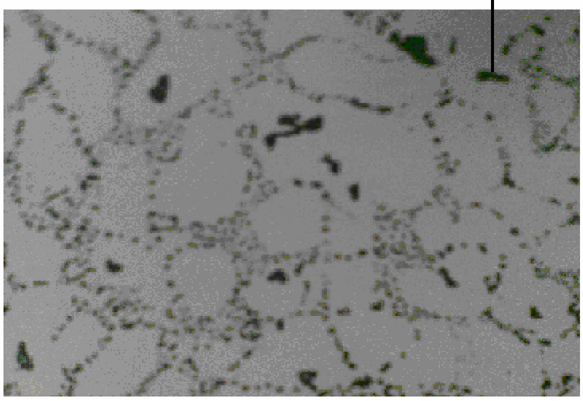


Fig. (16) The microstructure for cast Al-7%Si with cooling rate 7ºC/sec Magnification (300X), shows the formed porosity.

4-Conclusions

Investigating the mechanical properties of eutectic and hypoeutectic Al-Si alloys with different cooling rates yielded the following conclusions:-

1- It has been found that the following mechanical properties; ultimate tensile strength, hardness and the impact energy for the eutectic and hypoeutectic Al-Si alloys increases with increasing the cooling rates.

2- The values of ultimate tensile strength, hardness and the impact energy for the eutectic alloy (Al-12.6%Si) are greater than that for the hypoeutectic alloy (Al-7%Si) at the same cooling rates.

3-The percentage of the formed porosity increases with decreasing the cooling rate.

5- References

1- I. J. Polmear "Light Metals", Second edition, P(147-152), 1989. Routledge, chpman and Hall, Inc.

2- M. F. Hafiz and T. Kobayashi "Fracture toughness of eutectic Al-Si casting alloy with different microstructural features", J. Materials Science, V 31 p(6195-6200),1996.

3- J. P. Anson and J. E. Gruzleski " The Quantitive Discrimination between shrinkage and gas microporosity in cast aluminum alloys using spatial data analysis", Materials Characterization 43, p(319-335), 1999.

4- J. P. Anson and J. E. Gruzleski "Effect of Hydrogen content on relative shrinkage and gas microporosity in Al-7%Si casting", AFS Transactions, p(135-141),2000.

5- Mark E. Seniw, James G. Conley and Morris E. Fine "The effect of microscopic inclusion locations and silicon segregation on fatigue lifetimes of aluminum alloy A356 castings", Materials Science and Engineering, A285 (43–48), 2000.

6- Haizhi Ya "An Overview of the Development of Al-Si alloy based material for engine applications",J. Materials Engineering and Performance,V12, P(288-297),2003.

7- John A. Taylor "The effect of iron in Al-Si casting alloys", Cooperative Research Centre for Cast Metals Manufacturing (CAST), 2004.

8- J. Kajornchaiyakul,R. Sirichaivejakul, n. Moonrin "Solidification characteristics and mechanical properties of hypoeutectic aluminum – silicon alloy containing sulfur", la metallurgia italiana, V10,p(47-50),2005.

9- L.A. Dobrzański , R. Maniara , J.H. Sokolowski "The effect of cast Al-Si-Cu alloy solidification rate on alloy thermal characteristics", J. of Achievements in Materials and Manufacturing Engineering 17 p(217-220),2006.

10- Abdulwahab, M., Shehu, U. and Bello.K.A "Comparative Study of the Hardness and Impact Energy of As-cast and Age-hardened Al-Si-Fe-MnCr Alloy", J. of Applied Sciences Research, 3(9): p(823-827), 2007.

11- Kyuhong Lee , Yong Nam Kwon , Sunghak Lee "Effects of eutectic silicon particles on tensile properties and fracture toughness of A356 aluminum alloys fabricated by low-pressure-casting, casting-forging, and squeeze-casting processes", J. of Alloys and Compounds 461 p(532–541), 2008.

12- Abhishek Sharma "Strength and Fracture studies of as-cast Al-Si-Cu alloys", Ms.c. Thesis, School of physics and materials science, Thapar University, patiala, India, 2008.

13- F. Grosselle, G. Timelli, F. Bonollo, A. Tiziani, E. Della Corte "Correlation between microstructure and mechanical properties of Al-Si cast alloys", la metallurgia italiana, Alluminio e leghe, p (25-32) 2009.

14- Mathew Philip and Bill Bolton "Technology of Engineering Materials", first edition, P (46), 2002.

15-T.Uddin, PhD Thesis, University of Birmingham, UK, 1991.