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Brazing of Pure Aluminum by Aluminum Silicon Filler Metal Alloys

Abstract: *The aim of this work is to study the effect of clearance, on the metallurgical aspects of diffusion rate and mechanical properties of the brazing joint using two types of Silicon-Aluminum filler metal alloys on the commercially pure aluminum base metal. The brazing process experiments done by joining Al-alloys (1100) type by a brazing process using (4043, 4047) filler metals at 600-650°C. Two types of joint accomplished, inclined and curvature design. To indicate the brazing joint performance the specimens tested for single shear tensile test and metallurgical testing using optical and scanning electron microscope assisted with energy dispersive detector. Diffusion rate results according to joint clearance and brazing time accomplished using optical microscope images for joints cross sections and data gained with assisting of **ImageJ**® software. The joint sections analyzed using EDS detector and X-Ray analysis to observe the produced phases. The major phases of brazed joints using 4047 filler alloy gives (Al, Fe_3Si, Al 0.3Fe3Si0.7) and (Al 0.3Fe3Si0.7) for the 4043 filler alloy. The two filler alloys (5 and 12%Si) had equivalent tensile strength of 176 and 145MPa respectively, therefore the maximum joint efficiencies are 172% for AL5%Si filler alloy and 142% for AL12%Si filler alloy which mean that the tensile strength of the brazed joint had values greater than 100%.*

Keywords- *Aluminum brazing, eutectic aluminum filler metals, brazing clearance*

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1. Introduction

Brazing can be defined as the process of joining two pieces of material heated to appropriate temperatures in with filler metals or alloys with melting temperature higher than 427°C and lower than the base material [1]. The filler metal was located between the narrow close-fitted surfaces spread by the action of the capillary action [2].

Brazing joints are easy and fast to make and does not need high worker ability. Brazing was perfectly suitable for joining different materials. It could be simply join assemblages that joint ferrous by nonferrous metals, also metals by extensively different melting point or even metals to ceramic materials [3,4]. The brazing was a one-method process in most cases. There was rarely to need necessity for grinding, shaving or mechanical.

The joint clearance at brazing temperature can be evaluated with a simple model for thermal expansion of base materials. Due to the fundamental characteristic of thermal expansion, any joint configuration can be evaluated if the correct geometric relationships for the joint cross section are applied where in this work the joint clearance is calculated after brazing process.

There are many important processing ingredients for achieving a high quality-brazing joint. The ingredients in addition of proper fixturing, using the correct heating source, selection of the proper brazing alloy and cleanliness of the parts. Another important factor is the clearance or the gap between the surfaces to be joined [5].

For the, Copper-Phosphor and Aluminum-Silicon Nickel base brazing alloys wide-gap powders are available. There are two kinds: The first are alloys whose chemical makeup result in a sluggish spreading alloy that is able to bridge slightly wider than standard gaps. To help make this bridging possible, brazing at or below the liquids temperature or for shortened periods of time are suggested. This will help the braze alloy from becoming too liquid and spreading more than necessary. The goal is to keep the alloy more viscous so that it fills wider areas of the joint because the flow is retarded [5].

In this work flux used to clean the joint surface and remove oxide film where the experiments showed that, as commonly claimed, a flux brazing joints is superior compared to a flux less brazing joints from the viewpoint of reproducibility and stability in joint quality i.e.,

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a better joint filling property and better flow ability [6].

2. Experimental Work

The aim of this work is to evaluate the best and optimum clearance joint to give a high quality joint. For metallurgical analysis, inclined and cylindrical joints are used, Where all base metal used is a commercially pure aluminum (1100)) with a chemical composition showed in Table 1. Two types of aluminum-silicon filler metals selected, E4043 used as a filler rod with 3.2mm in diameter and 4047 as a cast.

Inclined specimen designed to make the clearance various with its length to facilities microstructure examination along different clearances values at the same test. Figure 1, showed a represented design for the joints combined of two parts, a rectangular aluminum plates with dimensions of (15x30x5 and 10x30x5mm) for inclined joint and (15x30x5 and sectioned part of a cylindrical shaft of 50mm in diameter and 5mm in thickness.

The flux used was [Al-Braze EC. 1070] product from HARRIS, which is compounds of fluorides and chlorides salt mixtures. Adding flux to joint done by mixing with water as a paste then a drop small quantity gently beside the joint clearance. After cover the joint by flux paste, the filler alloy rod placed parallel to the joint. After complete the flux and filler preparing on joint the assembly placed gently inside the vertical furnace chamber and the cover is closed. The furnace temperature set to 100°C for 10 minutes to evaporate the water from flux slowly preventing boiling and then it was set to 650°C for 5%Si filler and 600°C for 12%Si filler. The brazing time was varied from (30 to 120) minute.

Tensile shear test samples prepared as lap joints by putting two aluminum plates (80x20x5) mm and overlapped 5mm to achieve the shear area of 100 mm^2. The filler alloys and flux prepared in the same procedure of the microstructural varied clearance samples.

After complete the brazing cycle all samples extracted from furnace and cooled by tap water to remove flux immediately while the samples hot. Samples sliced normally to brazing line as shown in Figure 2, and then samples sliced face grinded using different grades of emery papers from (320 to200) PPI grades. Polishing was performed with diamond paste of 0.3 μm grain size on a polishing wheel covered with polishing cloth. Etching was done by immersion for 10 seconds in solution of 1% of hydrofluoric acid in distilled water. After etching, the specimens were washed by tap water and finally by distilled water. Specimen preparations were done according to the ASM Metals Handbook [8].

Seven inclined samples were done where two of them by using 5%Si filler alloy and the rest by using 12%Si filler alloy. For shear tensile samples, the 5%Si filler alloy all specimens failed from the base metal section and the joint stay without failure, which indicated that the joint is stronger than the base metal. Table 2 represent number of experiments done with different holding time in a brazing temperature for two-filler alloys.

Table 1: Base and filler aluminum alloys used

Alloy type	Chemical composition%								
	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ni	Al
1100	0.182	0.619	0.034	0.01	0.007	0.001	0.003	0.003	Rem
E4043	5.00	0.20	0.00	0.02	0.00	0.05	0.00	0.00	Rem
4047	11.63	0.872	0.88	0.24	0.153	0.51	0.013	0.03	Rem

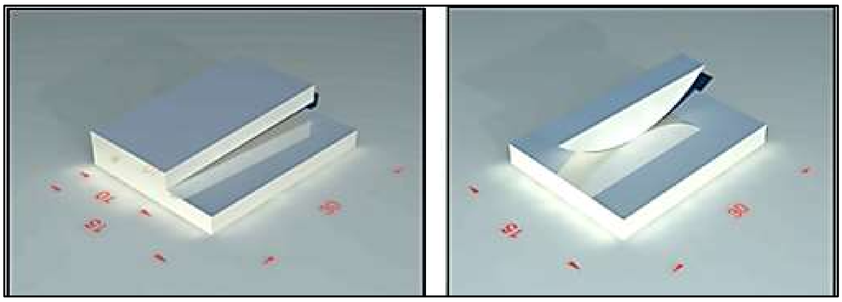


Figure 1: Design of inclined and curvature specimens of variable clearance

Figure 2: Prepared and brazed samples

Table 2: Experiments parameters for brazing inclined samples

No	Filler Metal	Specimen Design	Time (Minute)	T (C^o)	Maximum clearance (µm)
1	4043	inclined	30	650	800
2	4043	inclined	60	650	800
3	4047	inclined	30	600	800
4	4047	inclined	60	600	800
5	4047	inclined	90	600	700
6	4047	inclined	120	600	800
7	4047	inclined	150	600	800

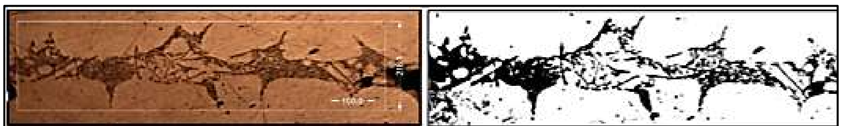
3. Results and Discussion

The results discuss the effect of clearance on the solubility and diffusion between filler and the base metal study the microstructure for the joints, tensile shear strength, and scanning electron microscopy, micro-hardness and X-ray analysis of the brazed joints.

To calculate the diffusion rate for joints with variable clearance and time a numerical equation of each case obtained using GraphPad Prism 6 and areas analyzed using **ImageJ** software's. The first filler alloy microstructure, which is Al + 12% Si, consist of eutectic (Al-Si) with a grain size about 225 □m. While the 5%Si filler alloy contain an eutectic structure of silicon-aluminum percentage of 40% according to level rule in the equilibrium transformation diagram of (Al-Si) [7].

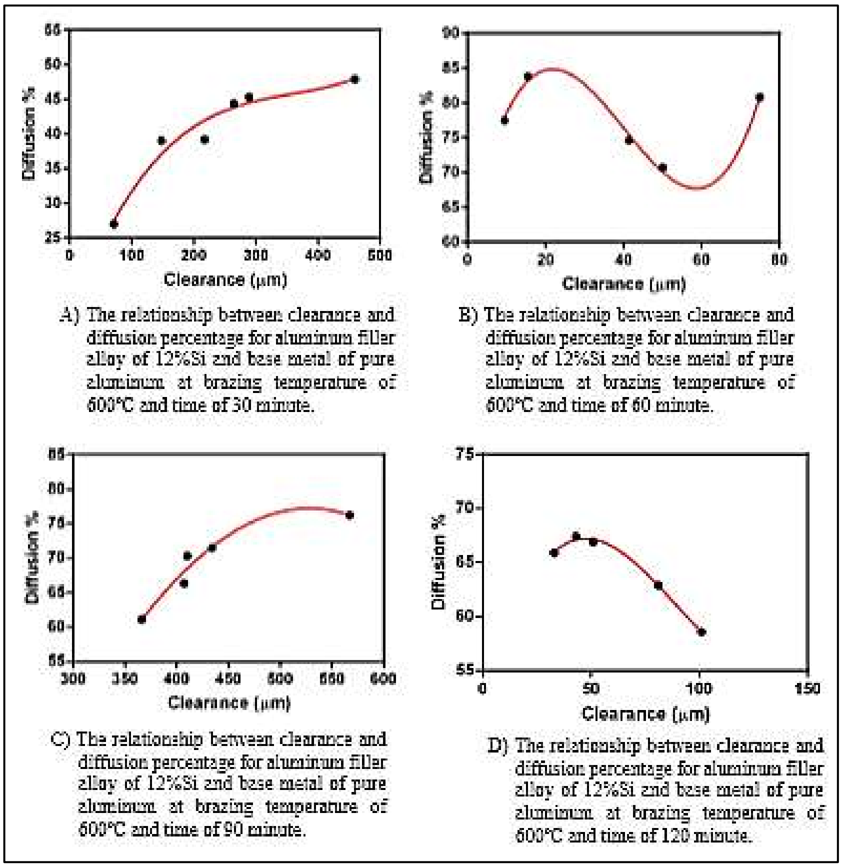
The calculations of diffusion rates done using optical microscope images of the sections joints and analyze the images using **ImageJ** software by converting the images to a binary colors where the program count the phases depending on the white and black pixels as it seen in Figure 3.

The analyzing done for all clearances and different brazing time and the results represented graphically in Figure 4.



75.1µm	Count	Total area	Average size	% Area	Mean
14-1.jpg	303	86226	284.574	19.156	255

Figure 3: ImageJ® software diffusion rate calculations sample



A) The relationship between clearance and diffusion percentage for aluminum filler alloy of 12%Si and base metal of pure aluminum at brazing temperature of 600°C and time of 30 minute.

B) The relationship between clearance and diffusion percentage for aluminum filler alloy of 12%Si and base metal of pure aluminum at brazing temperature of 600°C and time of 60 minute.

C) The relationship between clearance and diffusion percentage for aluminum filler alloy of 12%Si and base metal of pure aluminum at brazing temperature of 600°C and time of 90 minute.

D) The relationship between clearance and diffusion percentage for aluminum filler alloy of 12%Si and base metal of pure aluminum at brazing temperature of 600°C and time of 120 minute.

Figure 4: Effect of clearance value on diffusion rate for different brazing time

From Figure 4, it can be seen there are a direct relation between clearance and diffusion rate as shown in graph (A) and (C), but in graph, (B) the diffusion rate or the solubility fluctuated where the holding time at brazing temperature was one hour. For longer holding time the relation begin to be a reverse where the clearance lead to decrease the diffusion rate.

The important thing to be noticed that graph (A) and (C) deals with wide rage clearances while the rest deals with narrow clearance values. So that, in narrow clearances for long brazing time the diffusion tend to decreased which may be due to small amount of silicon in joint clearance, and with time the silicon drained from the core leading to low silicon concentration where the concentration difference is also important factor, with greater differences resulting in faster diffusion. In wide clearances, the joint core silicon concentration can supply more silicon atoms to neighboring base metal surface especially along the grain boundaries, and the process needs more time than narrow clearances to be depleted from silicon.

By curve fitting for four graphs in Figure 4, four equations can be driven as below:

$$D=13.3-0.2413C-0.0006315C^2+5.890e\text{-}7C^3 \quad (1)$$

$$D=59.78+2.628C-0.0827C^2-6.861e\text{-}4C^3 \quad (2)$$

$$D=-68.16+0.4786C-0.0002488C^2-2.58e\text{-}7C^3 \quad (3)$$

$$D=50.6+0.7977C-0.01149C^2-4.327e\text{-}5C^3 \quad (4)$$

Where:

D: is diffusion rate (%)

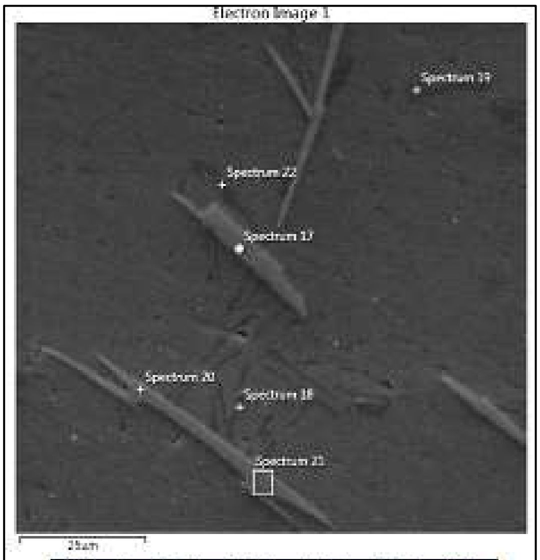
C: clearance in (µm)

The data of all cases can be represented by a general third order polynomial equation by graph the data and obtain the equation as shown in Figure 5. The equation formula can be derived from the plot in Figure 5 and it valid from 0 up to 800 µm of joint clearance as:

$$D=87.57-0.52C+0.001778C^2-1.57e\text{-}6C^3 \quad (5)$$

The joints of 5%Si filler alloy cannot analyzed by the software due to high diffusion rate and low phases of silicon concentration in joint core on the contrary of 12%Si filler alloy joints. As well as the same condition applies to shear tensile test, where the 5%Si filler alloy joints frailer occur in base metal instead of the joint. microstructural analysis using SEM assisted with EDS detector Figure 6 which represent the core of 4043 filler alloy and important structural phases and their chemical compositions. There are two phases shown clearly than in figure. The first phase represent the points 17, 20 and 21 which located in □□ region in Figure 7 as a small blue triangle and it appear as bright needles representing the major phase and the second phase appear like dark fine needles as minor phase where its chemical composition in points 18 and 22 and when these two points projected in ternary diagram it located in diamond silicon phase.

Figure 8 represent EDS points analysis for the SEM image, there are three main phases. Points 17 and 19 represents □ phase of aluminum-silicon when projected on ternary diagram shown in Figure 7, where this phase shaped as needle like and the diamond silicon irregular shape phase represents in points 20 and 22. Point 18 showing an aluminum 60% and copper composition which make □ phase on Al-Cu equilibrium phase diagram in Figure 9 [9].



No.	AL	Si	Fe	Cu	Mn
17	66.8	15.7	17.5	---	---
18	49.1	50.9	---	---	---
20	56.7	12.5	30.7	---	---
21	61.5	15.5	23.0	---	---
22	48.7	51	--	---	

Figure 6: Point chemical analysis for 5%Si filler alloy joint core with 30minute of brazing holding time at 600°C

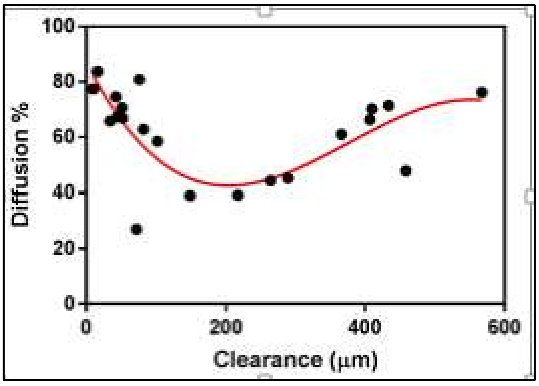


Figure 5: Diffusion rate change with a clearance value for time range from 30 to 120 minute

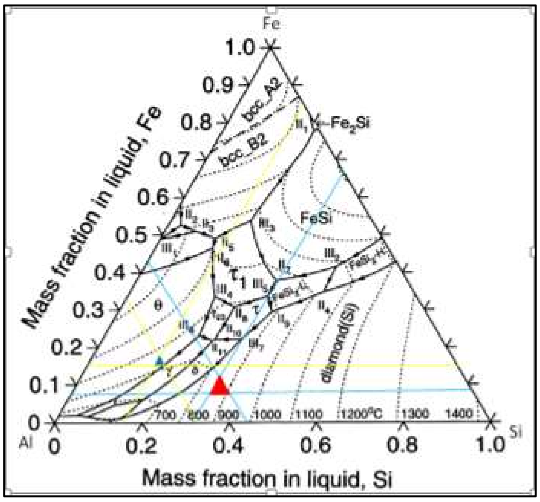
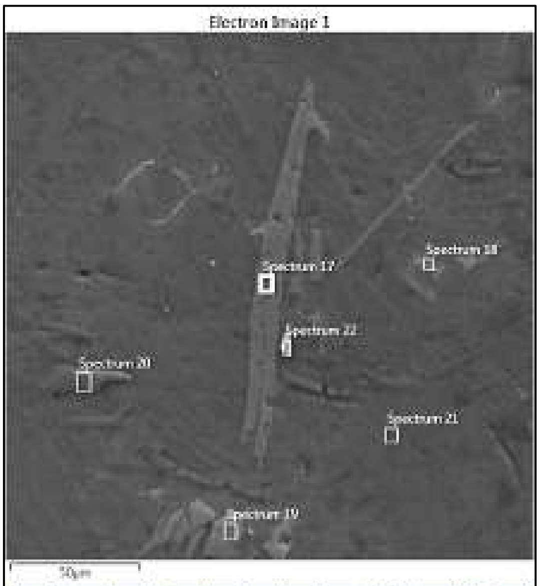


Figure 7: A-Si-Fe ternary phase diagram [9]



No.	AL	Si	Fe	Cu	Mn
17	56.3	17.2	24.0	---	2.5
18	60.0	---	---	40.0	---
19	66.6	8.8	18.2	---	6.5
20	37.9	61.3	---	---	---
21	97.3	2.1			
22	75.2	21.2			

Figure 8: Point chemical analysis for 12%Si filler alloy joint core with 30minute of brazing holding time at 650°C

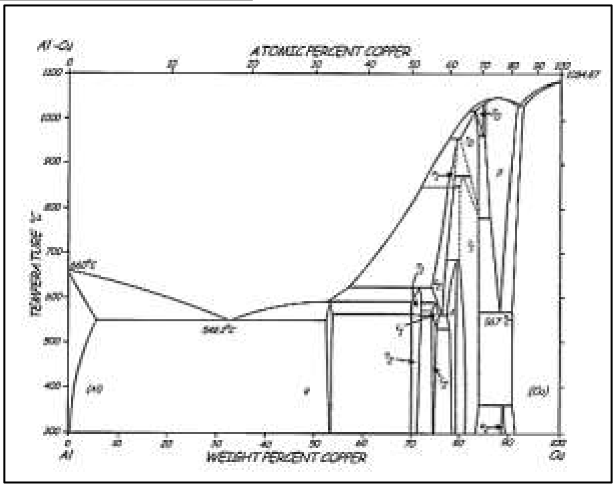


Figure 9: Al-Cu equilibrium phase diagrams [9]

4. Conclusion and Recommendations

The following can be concluded from the present work:

1. Al+5%Si gives quicker wetting of Al-alloy (1100) base metal in the starting of liquation than the filler alloy Al+12%Si which seen that it have higher surface tension than the other, but the two alloys completely spread and fill the joint at the first minutes of liquation.
2. The two filler alloys (5 & 12%Si) had equivalent tensile strength of 176 and 145MPa respectively, and the maximum joint efficiencies are 172% for AL-5%Si filler alloy and 142% for AL-12%Si filler alloy which mean that the tensile strength of the brazed joint higher than the base metal.
3. The formation of (AlSi, AlSiFe and eutectic phase) are responsible for joining process and gives the strength to the joint.

It can be recommended to future work of:

1. Trying to produce tension test specimens instead of shear-tensile specimens by controlling direction and clearance and the used flux.
2. Use flux less brazing by controlled atmospheres like argon or reduced atmospheres like hydrogen, which help to minimize the clearance, which is difficult to success the process with narrow clearances where the flux interrupted there.
3. Applying torch brazing with help of flux to braze Aluminum and compare results with furnace brazing to see the different in diffusion rate.

4. Braze light metals as Aluminum to heavy metals like copper by choosing the proper chemical formula of the used flux and the brazing route.
5. Study the possibility of another filler alloys instead of Aluminum-Silicon filler alloys.

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Authors' biography

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