



Effect of Spheroidization Treatment on Friction Stir Processing of Al- 14 wt.% Si Alloy

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Abstract

Three different rotational speeds (800, 1000 and 1250 rpm) and traverse speeds of (0.42 mm/sec) at a constant taped pin have been employed to produce the stir zones generated from friction stir processing (FSP) of near eutectic Al- 14 wt.% Si alloy. The processed samples were thoroughly analyzed macroscopically and microscopically. The as-cast microstructure of eutectic (α Al+ Si) and primary Si were fragmented to produce spheroidization of small size of Si and deformed matrix. The stir zones showed an increase in hardness from around 45-50 Hv for as-cast to 40-65 depending on the variables applied. All the processed samples were characterized by advanced and retreated regions with large single piping defects formed mainly at the retreated region. High temperature spheroidization at 500 °C with two soaking times of 10 and 20 hrs was applied for the processed sample of 1000 rpm to investigate the effect of heat treatment on the silicon fragmentation and hardness. Growth and fragmentation of Si have taken place at soaking time of 10 hrs. At soaking time of 20 hrs noticeable microvoids and macrovoids were formed at the stir zones. Microhardness of both the advancing and the retreating regions decreased with increasing soaking time.

Keywords: Friction stir processing (FSP), spheroidization treatment, Al- Si Alloy.

تأثير المعاملة الحرارية على عملية الخلط الاحتكاكي لسبيكة الألمنيوم- 14 نسبة وزنية سليكون

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الخلاصة

تم استخدام ثلاث سرعات دورانية (800 و 1000 و 1250 دورة/دقيقة) و سرعة انتقال ثابتة مقدارها (0.42 ملم/ثانية) مع شكل هندسي ثابت للأداة (اداة ذات راس مخروطي) للحصول على مناطق الخلط الاحتكاكي في سبيكة الألمنيوم-14 نسبة وزنية سليكون. ان تحليل العينات التي عُرضت لعملية الخلط الاحتكاكي قد تم بصورة ماكروسكوبية و ميكروسكوبية. كشف البحث الحالي التطور الحاصل في كل من البنية المجهرية و الصلادة لسبيكة الألمنيوم-14 نسبة وزنية سليكون نتيجة لعملية الخلط الاحتكاكي. ادت هذه العملية الى تشطي السيليكون وتحواله الى حجم كروي صغير مُنتشر في ارضية مجهدة. مناطق الخلط الاحتكاكي اظهرت زيادة في قيم الصلادة تتراوح من 60 الى 80 فيكرز مقارنة بالسبيكة الاساس التي تتراوح قيم الصلادة فيها من 55 الى 60 فيكرز اعتمادا على المتغيرات المُطبقة. ان هذه العملية حدثت بسبب تكون طاقة احتكاكية تحولت بصورة اساسية الى حرارة قبل المعاملة الحرارية مما ادى الى تشطي و تشوه جزئي.

تميزت جميع العينات التي تمت معاملتها باحتوائها على المناطق المتقدمة و المناطق المتأخرة مع ظهور عيب انبوبي الشكل في المناطق المتأخرة. ان العينة التي تعرضت لعملية الخلط الاحتكاكي , عند سرعة دوران 1000 دورة/ دقيقة, تمت معاملتها حراريا عند درجة حرارة التكوين (500 درجة سليزية) عند زمن تثبيت 10 و 20 ساعة. النمو البلوري للسليكون المتشضي بفعل المعاملة الحرارية حدث عند زمن الابقاء 10 ساعات. عند زمن ابقاء لمدة 20 ساعة تشكلت الفجوات الماكروسكوبية والمايكروسكوبية في منطقة الخلط الاحتكاكي. العينة التي تم معاملتها حراريا اظهرت انخفاض في قيم الصلادة مع زيادة زمن التثبيت.

1. Introduction

Cast Al–Si alloys are used in military, automobile and general engineering industry. Aluminum–silicon eutectic and near-eutectic alloys are casted to produce majority of pistons and for this, the alloy is known as the piston alloy. The addition of silicon to aluminum, as an alloying element, can improve the mechanical properties of aluminum [1]. Friction stir processing (FSP) is a surface engineering process developed from friction stir welding (FSW). The welding process was invented at the Welding Institute, UK in 1991 [2]. It may be considered as a novel technique for surface engineering to enhance the microstructure of the upper surface of products [3]. It is simply a solid-state transformation based on high energy produced during the process [4]. The process may be advanced more to obtain complex composite or alloyed surfaces by adding new elements during the process. The FSP is achieved by forcing a rotating small pin with a large shoulder through a desired thickness of the bulk material. A combination of heating and deformation takes place causing plastic deformation by the pin constrained by the shoulder through the traverse of the rotated tool. Successful FSP has been obtained for different ferrous and nonferrous alloys such as Al, Cu, Mg, Fe, and Ni-based alloys with high improvements [5] [6]. Many advantages, such as ductility, fatigue life and corrosion resistance improvement, have been obtained depending on the type of materials processed. As the process of FSP deals with the surface, the process may be used effectively to improve the surface, such as casting defects, inhomogeneity and phase coarsening, by eliminating the defects taking place during manufacturing processes [7]. It has emerged as a surface welding process producing grain refinement for the treated localized region [8]. The factor responsible for these fine grains at the stirring zone is believed to be due to dynamic recrystallization [9]. Many detailed studies emphasize that the formation of fine grains represents a promising technique to develop superplastic materials; especially for Al-based alloys [10]. Detailed studies showed FSP of Al- alloys as a promising and attractive surface engineering technique with many advantages and it has been used widely during the last decade [11]. In this article, the effect of friction stir processes and spheroidization treatment on the silicon morphology and the microhardness of Al- 14 wt.% Si alloy is studied.

2. Experimental details:

The chemical composition of the plates, with dimensions of (35 mm x 35 mm x 8 mm), used in the present work is shown in Table 1. The plates were produced by sand casting method. The melt was poured into a sand mold. For smooth and finished surfaces with equal dimensions, the plates were machined. AISI H13 steel tool was fabricated with a lathe machine to obtain the desired design of shoulder and pin, as illustrated schematically in Figure1. Shoulder diameter was 18 mm and the end of the shoulder had a taper pin of 3 mm height. The taper pin profile was 4 mm at root (the contact region between shoulder and pin) and 2 mm at end, as shown in Figure 2. Friction stir processing (FSP) was carried out with a milling machine at various rotational speeds and at a constant traversed speed. Table 2 lists the values of variables used. Primary test was performed to select the traversed speed. Because the milling machine is not prepared directly for FSP, a fixture system was designed. The vise was prepared

Table 1-Chemical composition of the base materials

Wt.% Si	Wt.% Fe	Wt.% Cu	Wt.% Mn	Wt.% Mg	Wt.% Cr	Wt.% Ni	Wt.% Pb	Wt.% Zn	Wt.% Al
14.4	0.85	1.68	0.150	0.869	0.037	0.97	0.026	0.39	Bal.

Table 2-Summarizes the tool and friction stir process parameters.

Process parameters	Values	Notes
Tool rotational speed	800, 1000, 1250 rpm	
Processing speed	0.42 mm/s	

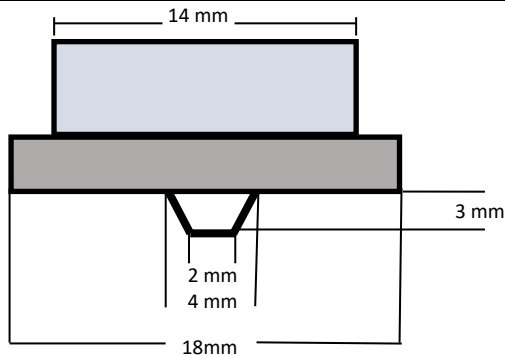


Figure 1- illustration of FSP tool used in the present work.



Figure 2- milling machine used to carry out FSP region.

Axial Force	Not measured	Nonstandard machine
Shoulder diameter	18 mm	
Pin diameter	2-4 mm	Tapered
Pin length	3 mm	
Tool geometry	Smooth (probe and shoulder)	
Tool material	AISI H13 Tool steel	

in such a way as to be suitable for the milling machine table. three samples consisting of FSP regions were sectioned perpendicularly to the traverse direction with an abrasive cutting machine with the dimensions (15 x10 x 8) mm, and grinded with ASTM grit of (220, 320, 500, 1000 and 1200) SiC emery paper. The samples were cleaned with water after each grinding step. Polishing of the samples was made with 1 μ m alumina and finally etched by a mixture of 99% distilled water and 1% HF acid for 20 second. Detailed microstructure of the processed samples before and after heat treatments was obtained using optical microscopy. Images of each sample were taken on the advance side, retreat side, bottom of stir zone (Sz) and center of Sz. Microhardness tester was used to determine the hardness on a small area on the surface of base metal, advancing side, stir zone and retreating side to indicate the variation in hardness of each place. The value of hardness (Hv) was represented by the average of three readings. A load of 100 g was applied for 15 sec. In order to investigate the effect of homogenization temperature as a function of soaking time on the friction stir processed sample with rotational speed of 1000 rpm, the samples were heated to 500 °C. The effect of soaking time of 10 and 20 hrs was studied to investigate the process of spheroidization or growth of fragmented Si particles.

3. Results and discussion

3.1. General observations of friction stir zones

Before investigating the effect of stir processing parameters on Al-14 wt.% Si, the typical microstructure of the bulk material was investigated. Figure 3 shows the microstructure without etching. It shows the presence of some casting porosities; the microstructure consists of eutectic structure of α -Al and Si needle plus a small amount of primary silicon. The average sizes of the dendritic arm spacing (DAS) of Al and length of Si needle are in the range of 4.8-5.2 and 80-120 μm , respectively. Figure 4 shows typical optical macrographs magnification obtained

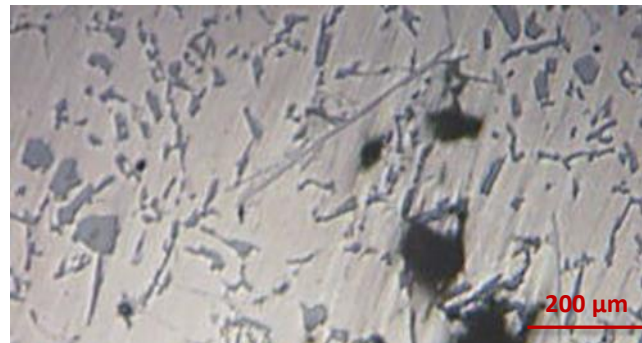


Figure 3- Typical microstructure of as-cast Al-14 wt.% Si alloy.

from friction stir processing regions showing the features of the advanced side (same directions of both tool rotation and tool traverse) and retreating side (opposite directions of both tool rotation and tool traverse). The low magnification micrographs show the general features of friction stir processing regions namely the presence of casting defects, interface between Sz/substrate and the symmetry of stir zone (Sz) shape (Figure 4 a and b). The three features are strongly dependent on rotational speed and traverse speed. The most important feature which was observed is the presence of multi, but small numbers, defects at each sample subjected to friction stir processing (Figure 4 c). It was found that rotational speed has an important effect on the location of defects formed. It is worth noting that in spite of the presence of many small casting defects in the substrate; only one relatively large defect was produced either on the advanced or the retreating sides. The casting defects provided insufficient material flow (dynamic volume) during the pin rotation. As a result of accumulation of casting defects through processing, a large defect is produced and located at both Sz side in all the variables that were applied. Samples processed at 800 and 1000 rpm produced defects on the retreating side. On the other hand, increasing the rotational speed to 1250 rpm resulted in changing the location of defect from retreating side to advance side (Figure 4 c).

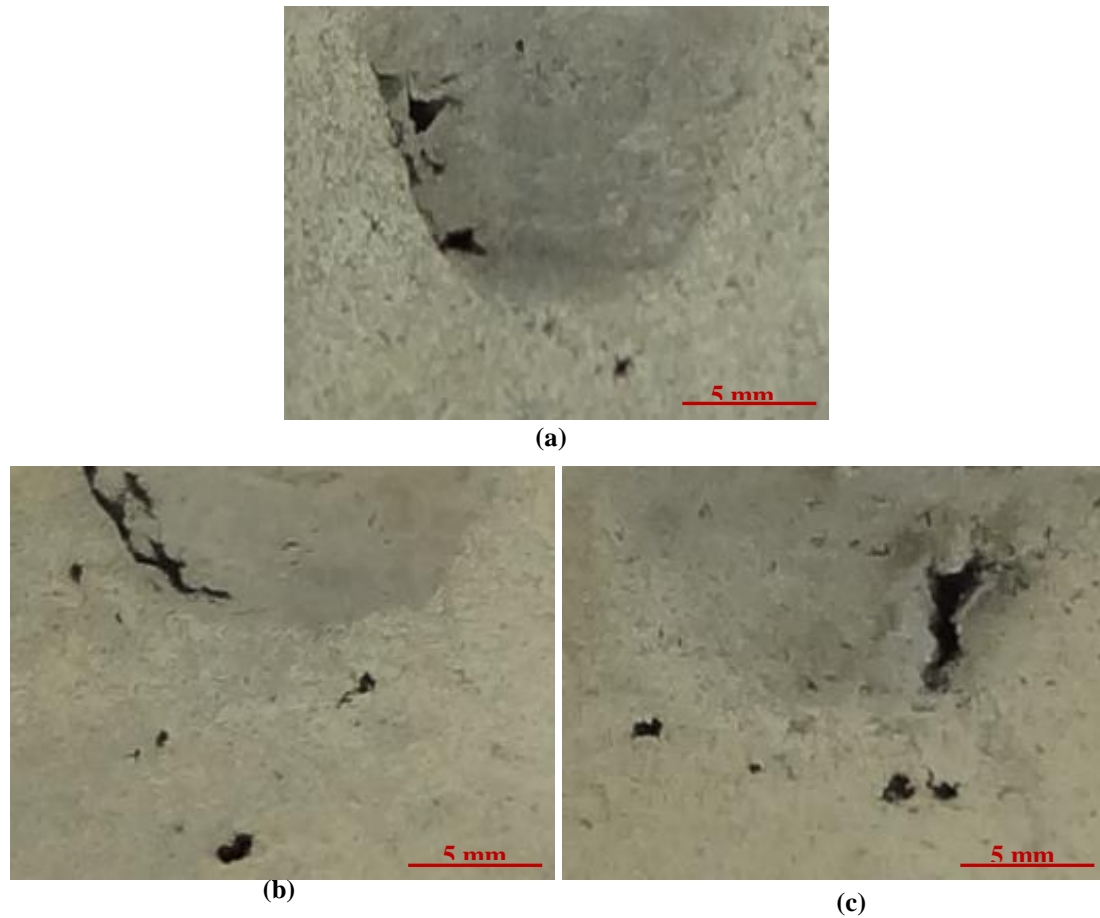


Figure 4-Influence of rotational speed on appearance of friction stir processing of Al-14 wt.% Si at 0.42 mm/s traverse speed: (a) 800 rpm, (b) 1000 rpm and (c) 1250 rpm.

3.2 Effect of rotational speed

It was observed from the detailed microstructural analysis of stir zones and interfaces between advanced/substrate and retreating/substrate that the rotational speed plays an important role in the fragmentation of Si phase. This behavior is believed to be due to temperature rise as a function of rotational speed. At lower rotational speed of 800 rpm and 0.42 mm/s traverse speed, the temperature rise was relatively slow and did not reach a high value. This is related to incomplete fragmentation of Si phase especially of primary Si. The average size was approximately 5 μm (Figure 5). The fragmented particles showed approximately smooth spherical shape (Figure 5, 6). The decreasing size of Si fragments in the processed basin shaped stir zone (Sz) is related to the complex interrelationship between the temperature rise and the recrystallization temperature of Al matrix. Presence of texture effect on Si distribution and Al matrix aligned with traverse speed direction was also observed. This behavior of the Al matrix may be explained as being due to incomplete recrystallization. At a specific region at the processed Sz especially at low rotational speed, higher fragmented Si particles were observed. This may be related to the non-uniform plastic deformation at these regions (Figure 5). The interesting point to be observed from this study is that there was a relatively specific size of fragmentation produced at the processed parameters; both fine Si needles and primary Si particles fragmented of similar sizes. This size was approximately 1 μm . A most important observation from this study was that the axial load is a very important parameter which should be considered during friction stir processing of Al-14 wt.% Si. This was very important at high Si content since it behaves as a

tentative composite due to the large size of Si particles. This was observed under all processing parameters regardless of the improvement in the hardness and microstructure. The formation of single large defects along the processing zone was noticed, which highly believed to be due to insufficient applied axial force. Detailed study for this variable is strongly advised. Figure 7 shows these defects for all samples processed. Different sections along the traverse track demonstrated this effect.

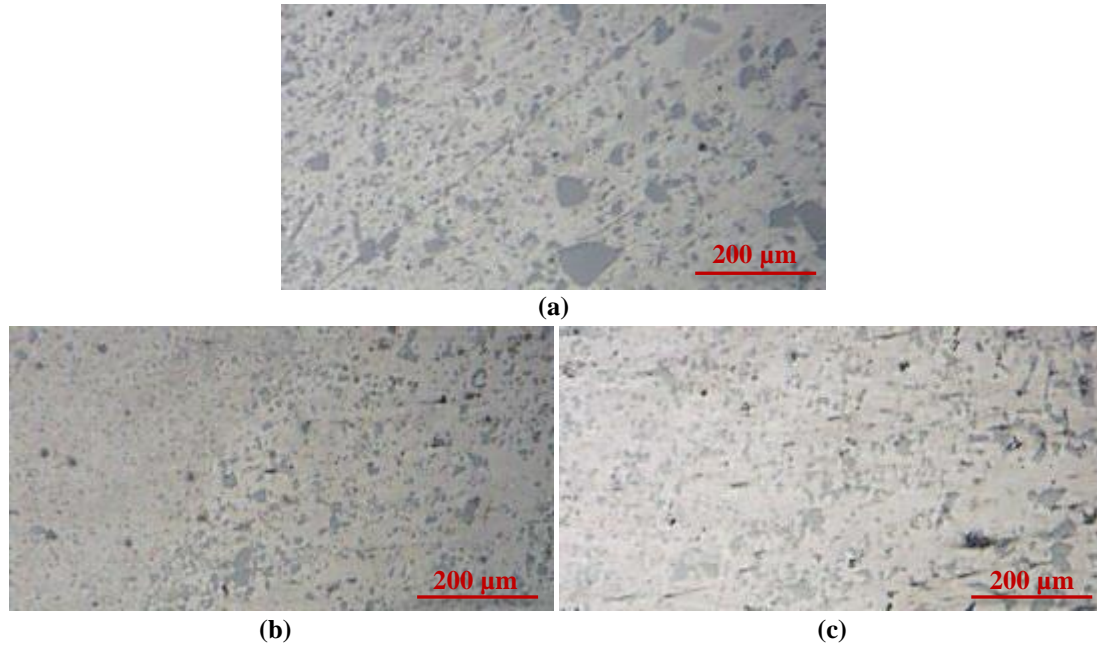


Figure 5. Optical micrographs of the microstructure of the advanced region of Al-14 wt.% Si friction stir processed at different rotational speeds and at 0.42 mm/s traverse speed showing the degree of Si fragmentation: (a) 800 rpm, (b) 1000 rpm and (c) 1250 rpm.

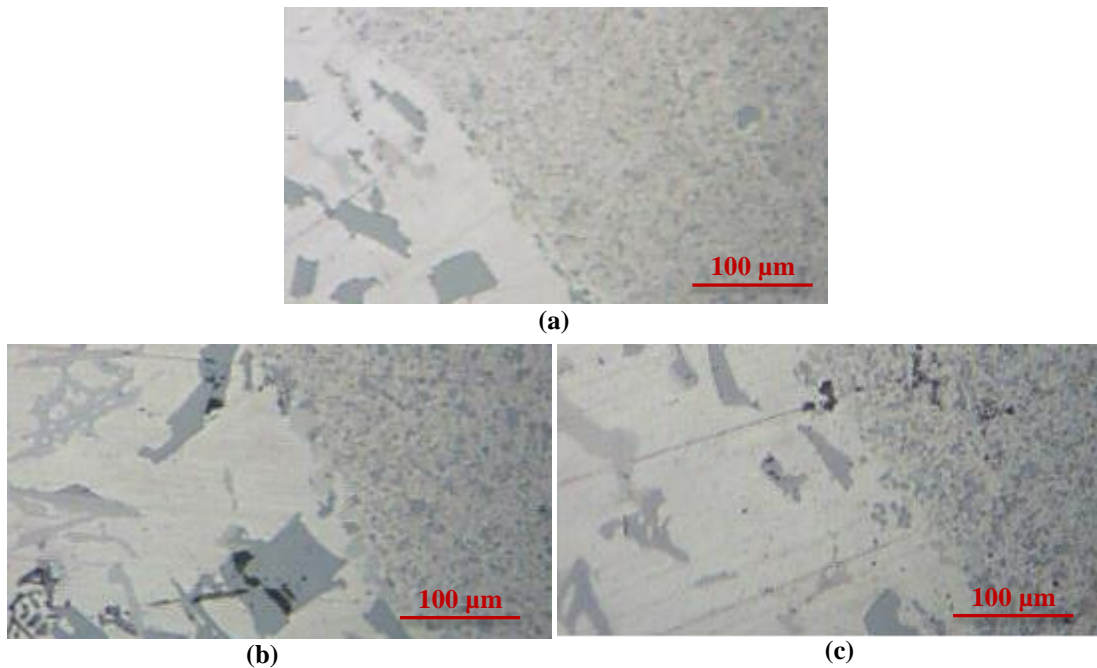


Figure 6- Optical micrographs of the microstructure of the retreated region of Al-14 wt. % Si friction stir processed at different rotational speeds and at 0.42 mm/s traverse speed showing the degree of Si fragmentation: (a) 800 rpm, (b) 1000 rpm and (c) 1250 rpm.

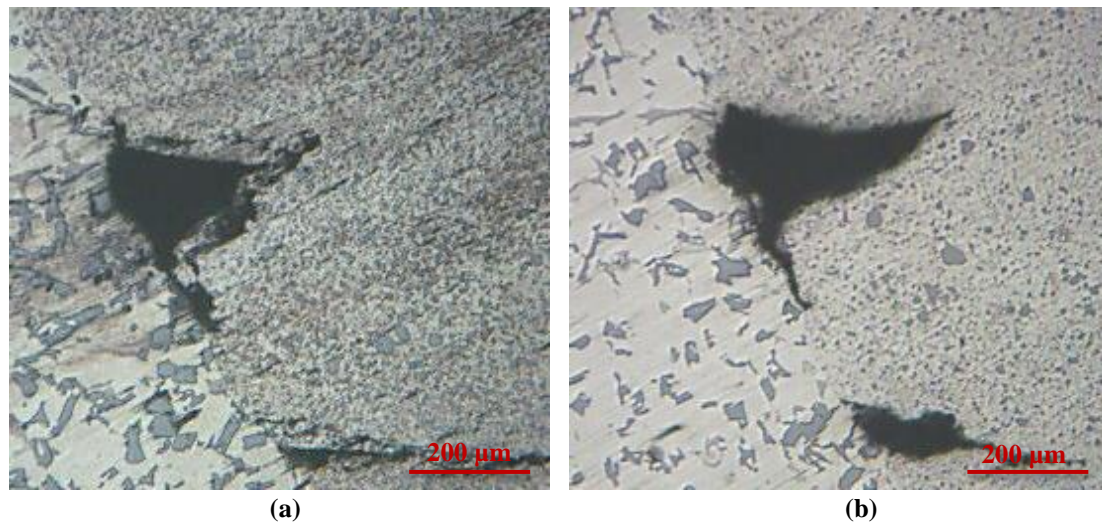


Figure 7-Typical defects formed after friction stir processing at (a) 800 rpm, (b) 1250 rpm.

3.3 Microhardness

It is well known that there are different strengthening mechanisms having low or high impact on hardness and strength. The alloy studied is a simple near eutectic Al-Si alloy having an average hardness of 44 Hv (± 4 Hv). This scatter in hardness for as-cast Al-14 wt.% Si alloy is due to heterogeneous distribution of the eutectic and primary Si. There is a restricted mechanism to improve the strength and hardness to higher values of Al-14 wt.% Si alloys. The percentage of hardness increased by friction stir processing for the system studied, which was affected by the absence of small defects, fragmentation of Si phase and fragmentation of Al matrix. Table 3 shows that hardness decreased with increasing the rotational speed. Under all rotational speeds employed, the temperature increased continuously and the fragmentation increased. The continuous decrease of hardness with increasing rotational speed suggests that the temperature rise led to complete spheroidization and the residual stresses decreased with both rotational speed and traverse speed; partial recrystallization may take place at higher rotational speed. This relatively low decrease in hardness suggests that the range of rotational speed studied is in the acceptable limit for friction stir processing (except the axial force). The continuous decrease of hardness also confirms that no large deformation was maintained.

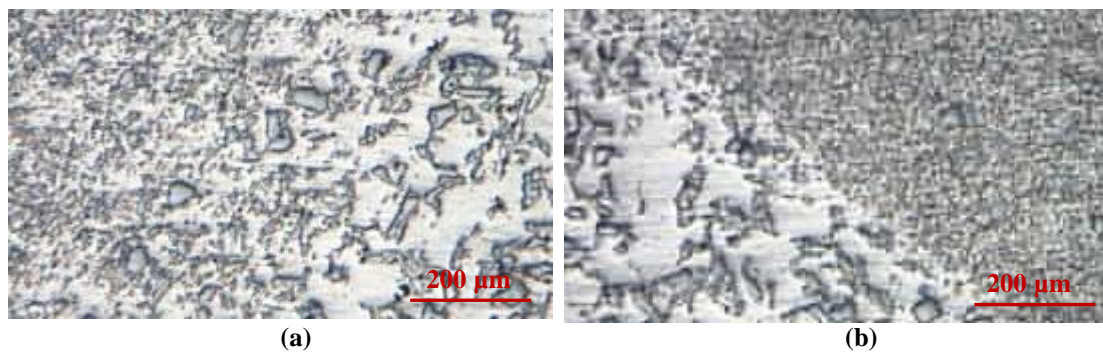
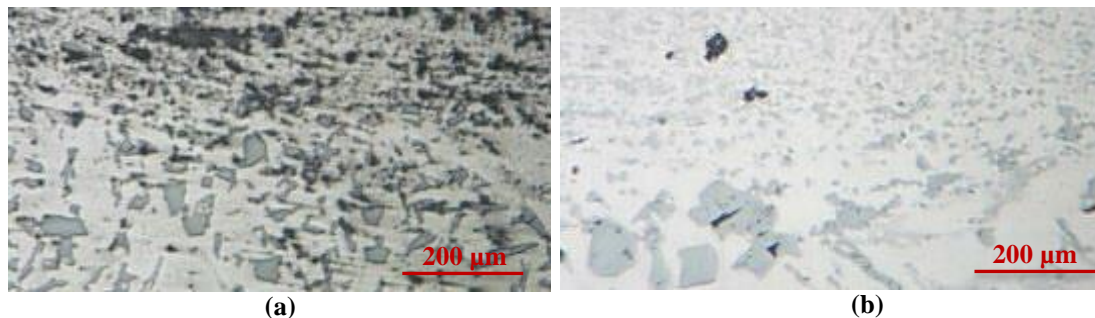
3.4 Effect of homogenization on friction stir processing

Detailed microstructural analysis of friction stir sample of 1000 rpm heated to 500 °C for 10 and 20 hrs demonstrates many noticeable points as follows:

At 10 hrs, clear evidence of a noticeable growth of Si was observed (Figure 8). The interfaces between advanced/ substrate and retreating/ substrate became smoother. Grain growth of matrix with maintaining the rough appearance was also observed. At 20 hrs, noticeable microvoids and macrovoids were formed at the stir region (Figure 9) corresponding to hardness reduction (Table 3). Fragmentation of Si phase in the substrate took place but without any defect formation. This phenomenon of defect formation at both advanced and retreated side of stir zone was not clear. The interfaces between advanced/substrate and retreating/substrate were also still smoother. The large defects present in the processed sample were not removed.

Table 3- Average values of hardness for as-cast and homogenized Al-14 wt.% Si alloy at 500 oC and different interval time.

Rotational speed rpm	Traverse speed mm/s		Interval time (Hrs)	Hardness Hv
As cast				45
800	0.42			55
1000	0.42			47
1250	0.42			47
1000	0.42		10	40
1000	0.42		20	38

**Figure 8.** Optical micrographs of the microstructure of Al-14 wt.% Si friction stir processed at rotational speeds of 1000 rpm and at 0.42 mm/s traverse speed showing the degree of Si fragmentation after homogenized at 500 °C for 10 hrs: (a) the advancing region, (b) the retreating region.**Figure 9-** Optical micrographs of the microstructure of Al-14 wt.% Si friction stir processed at rotational speeds of 1000 rpm and at 0.42 mm/s traverse speed showing the degree of Si fragmentation after homogenized at 500 °C for 20 hrs: (a) the advancing region, (b) the retreating region.

Conclusion

Two types of defects were observed by this work namely, pinhole and tunnel. Pinhole is mainly found on the advanced side, while tunnel defect was recognized at retreating side because of insufficient material at specific region. The silicon morphology in all the stir zones was highly different from the Si structure in the as cast structure. All the Si needles in the eutectic and the primary Si particles were fragmented to small sizes. Shape and sizes of fragmentation depended on the variables (which are 800, 1000, 1250 rpm). The rotational speed plays an important rule on the fragmentation of Si phase. Hardness of stir zones were

increased by the absence of small defects, fragmentation of Si phase and the fragmentation of Al matrix. Hardness decreased noticeably with increasing the soaking time at 500 °C.

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