MECHANICAL AND THERMOMECHANICAL TREATMENTS OF STIR-CAST ALUMINUM BASED COMPOSITES

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ABSTRACT: Composites were prepared by stir casting using matrix of AA 4032 aluminum alloy. The reinforcing materials were varied to include particles of Al_2O_3, SiC, and graphite. In each case 10 vol. % reinforcing particles were used. Specimens of the cast composites were subjected to two schemes of thermo-mechanical treatments, the first scheme involves hot pressing the specimen whereas the second scheme involves hot pressing followed by solution treatment. After thermomechanical treatments some specimens were cold worked. The constituents of the matrix showed considerable refining effect by the additives as compared to the matrix without additives. The microstructures show a distinctive arrayed distribution of the reinforcing particles For the other additives, the microstructures show clustering of reinforcing particles which is more pronounced in AA 4032 10 vol. % Al_2O_3 MMC.

After hot working, microscopic observations manifests closure of pores and other volumetric casting defects and more uniform distribution of reinforcing particles Solution treatment of the hot worked AA 4032- based composites proved to induce spherodization of eutectic silicon.

The application of hot working to the cast AA 4032 alloy and AA 4032/10 vol. % SiC composite results in a decrease of their hardness. The application of cold working increases the hardness of AA 4032 alloy and AA 4032/10 vol. % SiC composite. The application of solution treatment after hot working increases the effectiveness of cold working in hardening of materials.

KEYWORDS: Composites, Particulate Composites, Thermo-mechanical Treatments.

1- Introduction

Composite materials are continuously displacing traditional engineering materials because of their advantages of high stiffness and strength over homogeneous materials formulations. The high values of stiffness and strength of composites are at the expense of tensile ductility and fracture toughness [1, 2, 3] . The low values of strain to failure and fracture toughness are the main cause of limited applications of composites [4]. As reviewed by Durand et al. [5], particle- reinforced materials offer low cost and ease of fabrication. Aluminium- based matrices are the most widely reported in the literature [5&6], while other alloys such as Mg- and Ti- based, as well as high speed steels are receiving increased attention [5]. Aluminium and some of its alloys are inexpensive in comparison with other light metals, such as titanium and magnesium [6]. Due to the low weight, high strength and stiffness, and enhanced wear resistance of particulate- reinforced aluminium- based metal matrix composites, the automotive and aerospace industries have identified a number of applications for these materials [7&8]. The weight reduction achieved by the use of these MMCs results in superior fuel economy and higher engine performance [5].

There are several routes (e.g. molten metal routes, powder metallurgy) by which the reinforcing material may be introduced into the matrix, and the microstructure and hence the properties of the resulting composite will depend on the type and quantity of the ceramic [8]. The SiC particles are the most common reinforcements in Al matrix composites although the density of SiC is slightly higher than that of Al [6]. This is because it is inexpensive and readily available but still gives the composite high strength and elastic modulus. The improved wear resistance is often the primary feature as well. In the same way as in the case of continuous SiC fibres the possibility of chemical reactions limits the high temperature applications and may cause problems in production [6]. Excess Si reduces the reactivity of SiC in Al remarkably [6]. In these types of composites, microstructural effects such as distribution of silicon carbide particles, grain size, and intermetallic inclusions all play an important role in controlling the mechanical behavior.

An important and widely used particulate reinforcement in Al matrix composites is Al_2O_3 [6]. In comparison to SiC it is much inert in Al and it is also oxidation resistant. Accordingly, it is much more suitable for high temperature fabrication and use [6]. The wettability of Al_2O_3 by Al is poor and disturbs especially in the case of liquid stirring production routes [8]. In order to overcome this problem, the matrix is alloyed or the reinforcement is surface coated [8]. The volume fraction of Al_2O_3 affect the properties of composites.

Graphite gives the composite specific tribological properties [6]. Aluminium- graphite particle composites have been successfully developed in recent years [9]. The addition of graphite has improved the wear resistance, machinability, damping capacity and decreased the coefficient of thermal expansion [9]. However, as the amount of graphite particles increases, the strength of composites decreases [9]. This limits their application on high load components. The production methods of graphite- containing aluminium alloys have not been optimized [10].

As reported in the above paragraphs and reviewed by Zhou and Xu [11], the casting methods and associated techniques used to fabricate composites based on aluminium alloys have been amply studied. The major problem in this technology is to obtain sufficient wetting of dispersoid by the liquid metal and to get a homogeneous dispersion of the ceramic particles. Several structural defects such as porosity, particle clusters, oxide inclusions and interfacial reactions were found to arise from the unsatisfactory casting technology. Particulate reinforced metal matrix composites (PMMCs) produced by casting are usually low on ductility and [12&13]. The lack of toughness, ductility and formability of particle reinforced materials (produced either by casting or powder metallurgy) limits the industrial applications of these materials [13].

One of the prime advantages of particulate MMCs is that billets of the composites can be mechanically processed using the technologies developed for monolithic alloys

[8,14,15]. Also, the composites reinforced with discontinuous fibres having random orientation may possess isotropic properties and offer the possibility of being shaped using standard methods such as extrusion, forging, rolling…etc. [4]. Much research has been carried out recently on particle reinforced metal matrix composites (PMMCs) due to the combination of high strength to weight ratio, high stiffness, and the ability to be formed by conventional metal processing techniques [16]. The successful large scale production of particulate reinforced aluminium alloy composites by liquid metal mixing and continuous casting has opened to automotive applications if the secondary processing by traditional metal forming can be adapted [17]. Because of the high strength, limited ductility, and tendency for particle degradation in deformation at room temperature, hot working processes have the most promise [8&17].

It is well known that the microstructure of a material can be refined and homogenized through thermomechanical processing e.g. extrusion, forging, and/or rolling [18]. This has been demonstrated in several aluminium based composites [18]. Mukai et al. [18] demonstrated a dramatic improvement in tensile ductility (from 2% to 10%) at room temperature in a magnesium based composite (ZK60/SiC/17p) through additional extrusion. In order to widen the application of traditional forming processes to the composites, the present study has been designed. The study aims to prepare groupes of particulate aluminium alloy- based composites and to investigate the combined effect of different types of reinforcing particles and application of a thermomechanical treatment on microstructural features, hardness of the resulting composites. AA 4032 aluminum alloy was used as matrix and SiC, Al_2O_3, and graphite were used as reinforcing materials.

2- Experimental work

In this work, different aluminium alloy- based composites were prepared by stir-casting technique. Matrix alloy namely AA 4032 was reinforced using different additives including particles of Al_2O_3, SiC and graphite. Tables (1) lists the chemical composition of AA 4032 alloy.

Table (1) Chemical composition of alloy AA 4032

Element, wt. %			
Si	Mg	Cu	Ni
12.0	1.0	1.0	1.0

The AA 4032 alloy is used in applications where good forgeability and low coefficient of thermal expansion are required; forged pistons are typical [19]. The hot working temperature range of this alloy is 260 to 480 °C [19]. The solution treatment is carried out by heating the alloy at 504 to 516 °C for a minimum holding time of 4 hr. followed by quenching in water [19].

<u>Preparation of composites</u>

The matrix was melted using induction furnace at a temperature of 740 °C. The melt was then poured inside a preheated crucible. The temperature of the crucible is controlled to within ± 5 °C using a temperature controller. The melt is stirred by a metallic stirrer to develop a vortex. This vortex allows incorporation of the additives which would be otherwise segregate due to low wettability with aluminum melt [20]. Wetting is enhanced by application of a special chemical treatment to the additive. In this treatment , the particles were immersed in a solution containing Na+ions for a few hours, then the solution was decanted and the particles were dried. The treated particles are then added gradually by charging them inside the vortex. After complete incorporation the stirring is stopped and the aggregate is poured inside a steel mold to produce specimens for further investigations.

Mechanical and thermo-mechanical treatments:

Samples having rectangular cross- section of 5 mm × 10mm and height of 15 mm were prepared for thermomechanical treatment. Two schemes of thermomechanical treatment were proposed. These procedures involve hot deformation (hot pressing) and solution treatments. In these procedures, the cast samples of AA 4032 - based composites were heated at 480 °C for 18 minutes inside a specially constructed furnace attached to a hydraulic press. The specimens were then pressed at a ram speed of 3 mm/s up to 33.3% reduction in height. The deformation temperature was controlled to within ± 5 °C using a thermocouple and a temperature controller. The hot pressed samples were cooled in air. Samples of deformed composites were solution treated by heating the specimens at 510 °C for 5 hours and then quenched in water. Samples of the matrix were subjected to the same thermomechanical treatments for comparison.

In order to study the effect of cold deformation, some specimens of both cast and thermo-mechanically treated materials were cold pressed using hydraulic press at ram speed of 3 mm/s.

Testing and Investigations

Samples were prepared for microstructural investigations and hardness measurements. Microstructure of the materials has been investigated using optical microscope.

3- Results and discussion

Microstructures of cast matrix alloy and composites

The microstructures of cast AA 4032 alloy alloy is shown in Figure (1). α- aluminium dendrites dispersed in eutectic matrix are evident in the figure.

The microstructures of AA 4032/10 vol. % graphite, AA 4032/10 vol. % Al_2O_3, and AA 4032/10 vol. % SiC composites are shown in Figures (2),(3)&(4) respectively. In all micrographs, the structure consists mainly of reinforcing particles dispersed in the matrix material. Generally, it is observed that the presence of reinforcing particles resulted in refinement of the matrix material constituents.

The size of primary aluminium (α- dendrites) in the composite was found to be smaller compared with that present in the unreinforced alloy. A similar phenomenon of grain refinement is also observed with silicin phase in the composite. Similar results have been obtained by Pollard and Stevens in the case of A 356- SiC particle

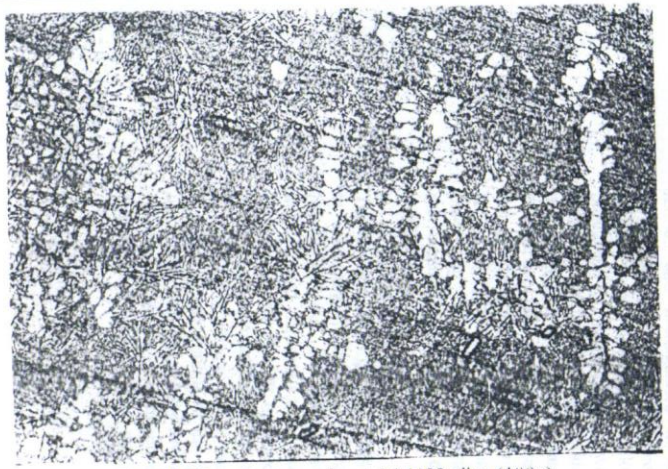


Fig. (1) Microstructure of cast AA4032 alloy (100x)

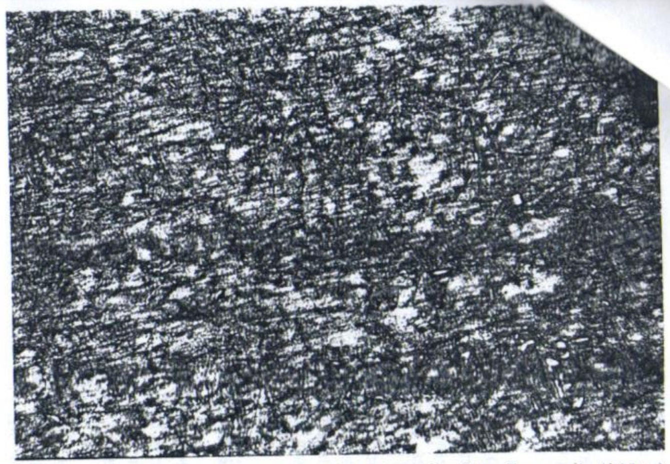
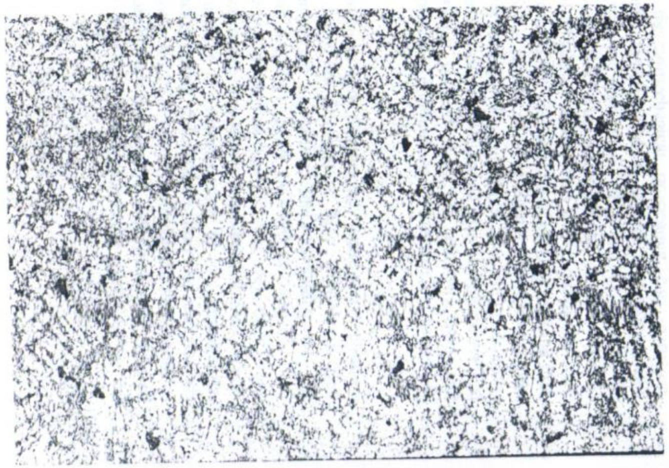


Fig. (2) Microstructure of cast AA4032/10 vol. % Graphite Composite (100 x)



(3) Microstructure of cast AA 4032/10 vol. % Al_2O_3 composite (100X)

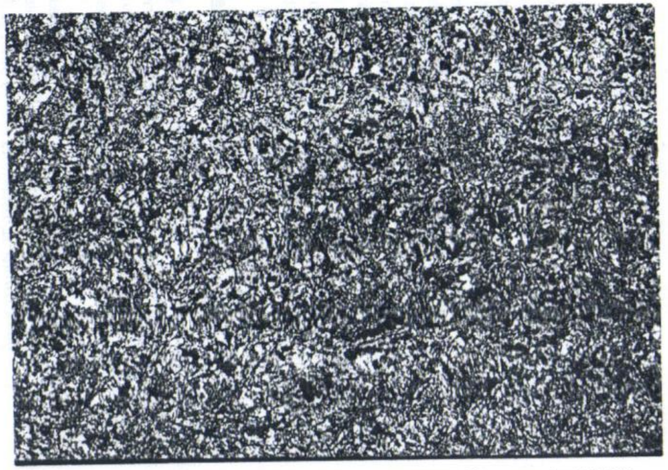
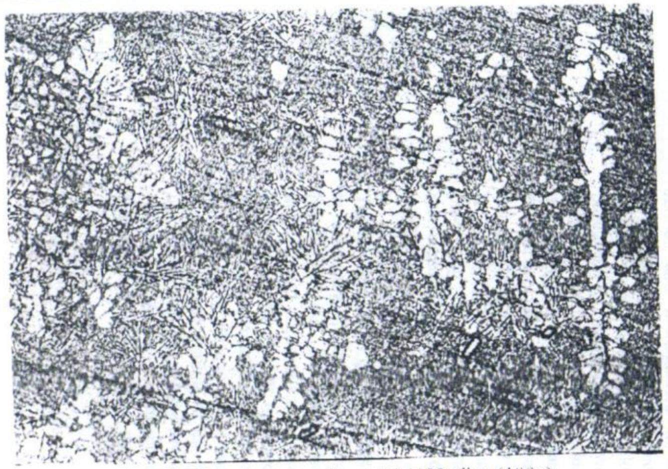


Fig. (4) Microstructure of cast AA 4032/10 vol. % SiC composite(100X)



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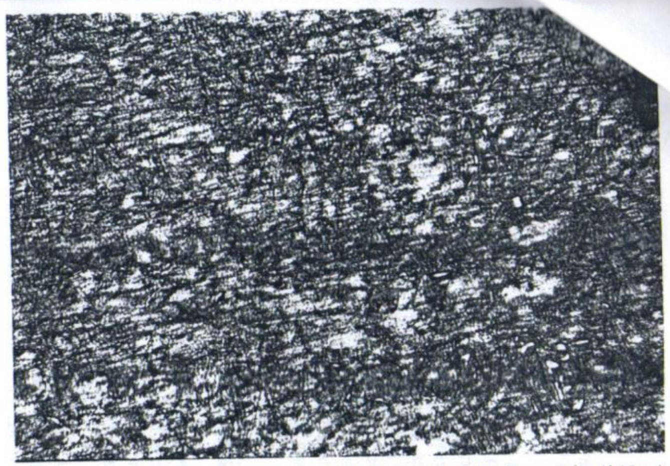
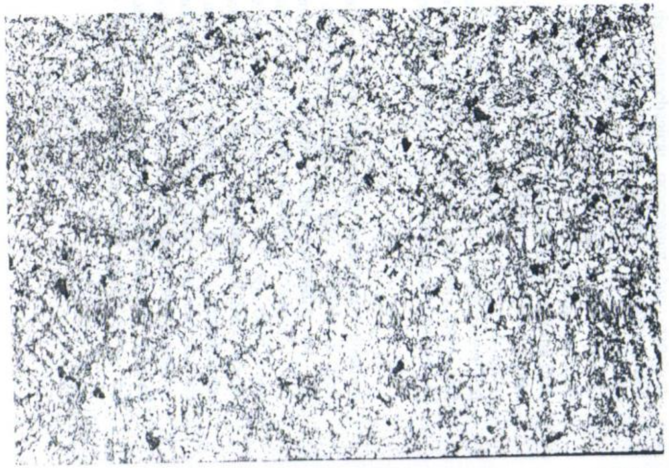


Fig. (2) Microstructure of cast AA4032/10 vol. % Graphite Composite (100 x)



(3) Microstructure of cast AA 4032/10 vol. % Al_2O_3 composite (100X)

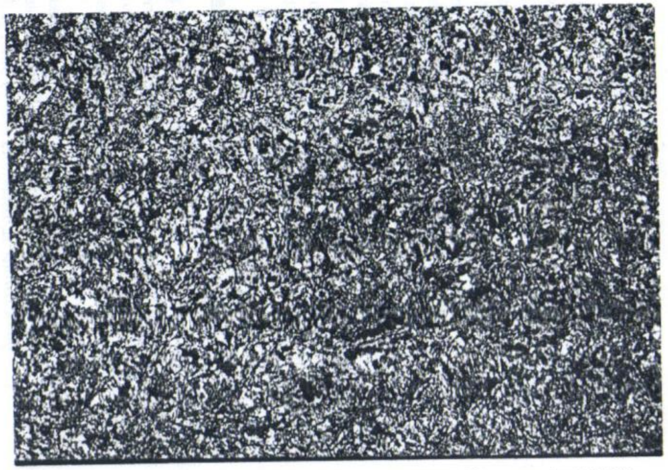


Fig. (4) Microstructure of cast AA 4032/10 vol. % SiC composite(100X)

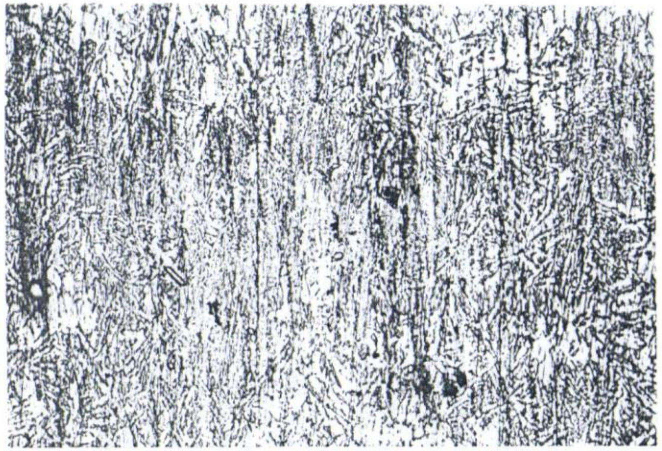


Fig. (5) Microstructure of hot worked AA4032 alloy (100x)

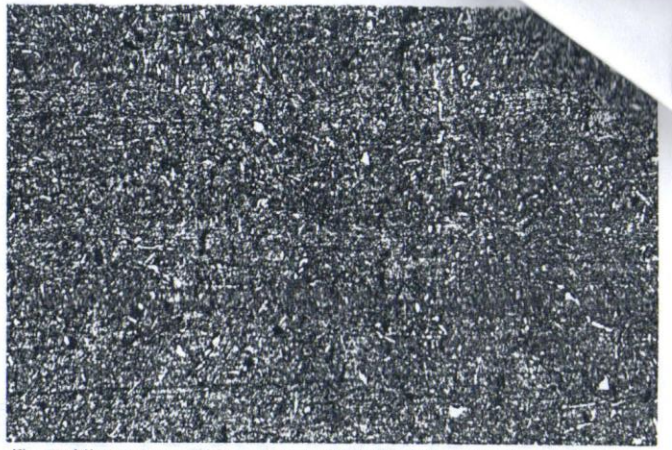


Fig. (6) Microstructure of hot worked AA4032/10 vol.%Graphite Composite (100 x)

(7) Microstructure of hot worked AA 4032/10 vol.% SiC composite (100X)

Fig.(8) Microstructure of hot worked AA4032/10vol.% Al_2O_3 composite(100X) accumulation of dislocations will occur. In this case, no deformation zones will be formed (and the dislocation structure is expected to be rather similar to that of the unreinforced alloy) and PSN of recrystallisation will occur on subsequent annealing [8].

The microstructures developed and the characteristics during hot working of a liquid mixed composite (MMC, A 356-15 vol. % SiC_p) and its matrix alloy (Al-7.0 Si-0.35 Mg-0.2 Cu) were determined over the range 300-500 °C and 0.1-5.0 S^{-1} [17]. From examination by TEM in both bright and dark field, it was established that dynamic recovery gives rise to some regions of subgrains in the matrix of the MMC but they are smaller and less polygonised than those in the alloy. In other regions, very high dislocation densities were observed and in some cases gave rise to dynamic recrystallisation (DRX) nuclei [17]. However, the DRX did not progress into the growth stage, thus no rapid work softening was noted in the flow curves. However, as reviewed by Ferry and Munroe [24], dynamic recrystallisation can occur in aluminium based particulate reinforced MMCs during hot deformation. The recovery, recrystallisation, and fracture behaviour of particle and whisker reinforced metal matrix composites are found to differ from the matrix alloys [25&26]. The recrystallized structure is not clear in the present micrographs.

As reported by Humphreys et al [8], the ceramic may undergo fracture or realignment during the deformation. It has been established from fracture studies that particles in the larger size range (>10 μm dia.) are more likely to fracture than are smaller particles. Non- equiaxed ceramic reinforcements tend to rotate during mechanical processing and become aligned in the working direction [8]. The investigation of microstructure of A 357 aluminium alloy reinforced with Ni and Nip coated SiC particles; produced via addition of particles into liquid and extrusion of solid, [20] indicated that extrusion leads to the alignment of the particles in the extrusion direction and also to the breakage of some particles. Even particulate ceramic particles are seldom equiaxed, and some realignment can be detected after working. The fracture and realignment of reinforcing particles is the case in the present study.

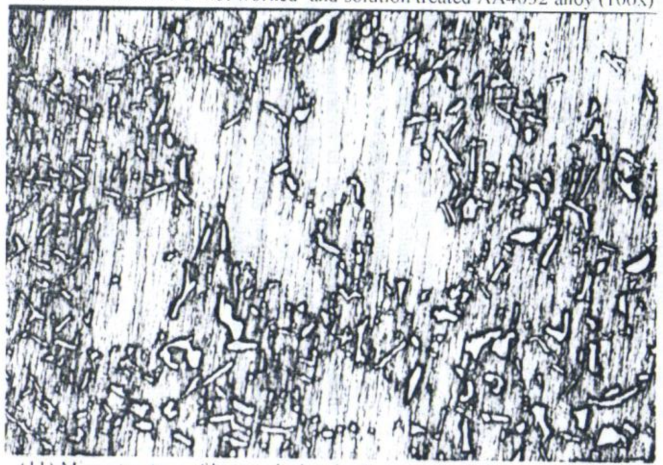
Solution treatment of hot worked microstructure

Figure (9) shows micrograph of the microstructure of hot worked and solution treated aluminium alloy AA 4032 comparison between the microstructure of hot worked AA 4032 base alloy and that of hot worked followed by solution treatment shows that, solution treatment renders the microstructure more homogeneous than the hot worked structure. The eutectic silicon particles are shorter and widely spaced after solution treatment.

The microstructures of AA 4032/10 vol. graphite, AA 4032/10 vol. % Al_2O_3, and AA 4032/10 vol. % SiC, composites after hot working and solution treatment are shown in Figures (10),(11), & (12) respectively. On the macroscale, the graphite, Al_2O_3 and SiC particles are well distributed within the aluminium matrix. From these figures, it can be seen that the reinforcing particles occur mostly at primary aluminium boundaries although some of the SiC particles are observed within the aluminium phase. Similar results have been obtained by Han et al. [21] in the case of sand cast aluminium alloy A 356- SiC particle metal matrix composite. As reported by Warner et al. [27], the reinforcing particles are pushed to the intergranular regions. The review

(9) Microstructure of hot worked and solution treated AA4032 alloy (100x)

Fig.(10) Microstructure of hot worked and solution treated AA4032/10 vol. %



(11) Microstructure of hot worked and solution treated AA 4032/10 vol. % Al_2O_3 composite (100X)

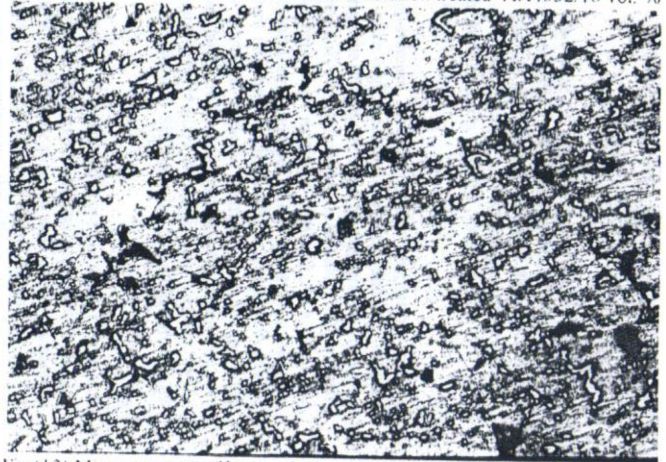


Fig.(12) Microstructure of hot worked and solution treated AA 4032/10 vol. % SiC composite (100X) of Ko et al. [25], showed that, the clustering of reinforcing particles is commonly observed in the extruded metal matrix composite reinforced with SiC_w. Bayoumi et al. [22] reported that, the reinforcing particle distribution through the interdendritic regions can be attributed to the very small dendrite arm spacing compared to the reinforcing particle size. The high solidification cooling rate resulted in more homogeneous of SiC particle distribution [22].

Hu et al. [28] reported that, the aluminium has low energy absorption and the ceramics (such as SiC and Al_2O_3) have high energy absorption and low thermal conductivity. Hence, it can be said that, the energy received by the ceramic cannot be transferred efficiently to the aluminium alloys (matrix materials) before well-distributed ceramic particulate in the material of matrix is obtained. As a result, the ceramic particulates will agglomerate and form a number of bulk phase in some areas in the matrix [28]. Hence, in the present investigation and based on these analyses, the agglomeration of some reinforcing particles and the clustering of the particles through the interdendritic regions can be attributed to the very small dendrite arm spacing and low transformation of energy (received by the reinforcing particles) to the matrix alloys. Better distribution of graphite and SiC particles are evident in Figures (10) and (12).

From Fig. (11), it can be seen that the extent of clustering is greater in the case of AA 4032/ Al_2O_3 composite as a consequence of the large α-Al dendrites. Han et al. [21] reported that, silicon phases are present outlining the primary aluminium (aluminium grains), located at the grain boundaries and can also be found isolated from or adjacent to SiC particles. In the present investigation, the silicon particles can be found adjacent to the reinforcing particles. The silicon particles can also occur within the reinforcing particle clusters as reported by Han et al. [21] in their case. These authors [21] reported also that, the fibrous morphology of the silicon phase in the alloys is modified in the composite to that of a spheroidised particle. As reviewed by Siaminwe and Clegg [29], the effect of solution heat treatment on the eutectic silicon morphology has been studied extensively in unmodified and modified A- Si- Mg alloys. Solution heat trearment changes the morphology of the eutectic silicon through the processes of spheroidisation and coarsening [29].

In the present investigation the morphology of silicon particles is mainly changed due to the combined effect of composite preparation and the solution treatment. The silicon particles which refined in the composites can easily spheroidised.

Voids are evident in the micrograph. Preparation of the composites and eutectic melting when solidus is exceeded during solution heat treatment cause voids in the microstructure of composites. In some cases, particles are torn out during mechanical polishing [1] and as a result porosity adjacent to reinforcing particles (or at interface between matrix and particles) is presented. Most pores surrounded the particles can be resulted from poor wetting.

Effect of cold working on microstructure after solution treatment of hot worked AA 4032 alloy

Figures (13),(14) and (15) show the microstructures of cast, hot worked, and hot worked and solution treated AA 4032 alloy after cold working. α-Al dendrites in the cast structure is elongated and aligned in the working direction; Fig. (13). The micrograph in Fig. (14) shows the microstructure of hot worked alloy is not significantly changed after application of cold working. Banded structure is shown in Fig. (15).

Hardness of matrix material and composites

The mechanical properties are governed by the composite microstructure, i.e. reinforcing phase, volume fraction of forcing phase, matrix alloy composition, and fibre/matrix interfacial strength [4]. As reviewed by Zhou Zhao et al. [30], the mechanical properties of the composites are affected strongly by the high dislocation density and the pronounced thermal stress generated by thermal expansion mismatch during heat treatment processing. Hardness measurements have long been recognised as a simple, reliable means of assessing the mechanical behaviour of materials [31].

Hardness of alloy (AA 4032) and their composites were evaluated. Fig. (16) shows the values of hardness (HV 10) of cast AA 4032 alloy and their cast composites. The hardness values of composites are higher than the hardness value of alloy. As a strengthening mechanism of the particle reinforced composite, two main causes are considered [14]. The one is increasing in the load carrying capacity by including hard particles, and the another is increasing in the work-hardening capacity of a matrix by dispersing fine particles [14&17]. As reviewed by Karnezis et al. [15], a high rate of work hardening is caused by a high initial dislocation density in the matrix and to the generation [8,15,30] and inhibited motion of dislocations around the SiC particles during plastic deformation. The generally agreed explanation for the high dislocation densities, (commonly found in composites), is that they develop as the result of the difference in the thermal expansion coefficients between the reinforcing particles and the metal matrix components of the composite [16&21]. The ceramic particles in the composite force the matrix to undergo additional strain hardening during deformation [24].

As reported by karnezis et al. [15] the increase in hardness with reinforcing material content is due to the generation of matrix dislocations during cooling from the fabrication temp. and to the plastic constraint with the non-deformable reinforcing particles. Also, the refinement of matrix constituents plays an important role in the increase of hardness of composites.

Figure (17) shows the hardness values (HV 10) of hot worked AA 4032 alloy and their hot worked composites. Hot working (hot pressing) decreases the hardness of the matrix alloy and their composites. Similar results have been obtained by Xu et al. [12]. The values of hardness of composites are higher than those of the matrix alloy. The improvement in hardness of the composites can be attributed to the hardening resulted from the reinforcement and the refinement of matrix constituents. The most hardened composite after hot pressing is AA 4032/10 vol. % graphite.

Fig. (13) Microstructure of cast and cold worked AA4032 alloy (100x)

Fig.(14) Microstructure of hot worked and cold worked AA4032alloy (100 x)

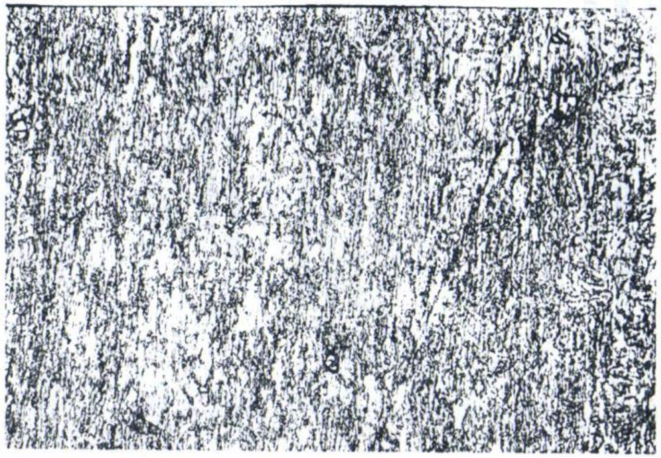


Fig. (15) Microstructure of hot worked, solution treated and cold worked AA 4032 alloy (100X)

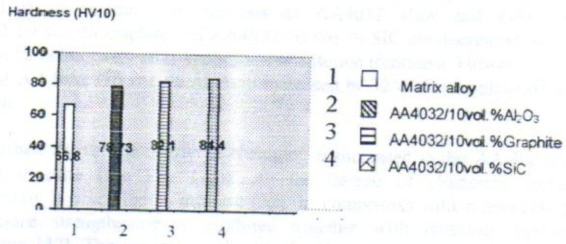


Fig. (16) Hardness of cast materials (AA4032 alloy and their composites)

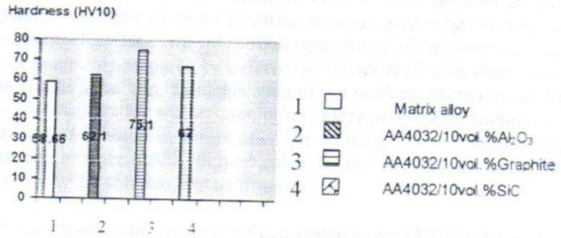


Fig. (17) Hardness of hot worked materials (AA4032 alloy and their composites)

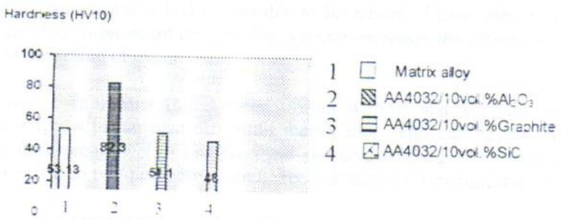


Fig. (18) Hardness of hot worked and solution treated materials (AA4032 alloy and their composites)

The hardness values of AA 4032 and their composites after application of hot working and solution treatment are shown in figure (18). Comparison with the hardness values of only hot worked materials (AA4032 alloy and their composites; (Fig. (17)) shows that, the hardness of AA4032 alloy and their composites; AA4032/10 vol. % graphite and AA4032/10 vol. % SiC are decreased by 10% , 47% and 45.6 % respectively after application of solution treatment. However, the hardness values of AA4032 /10 vol. % Al_2O_3 in increased by 32% after application of solution treatment

As described above, the degree of clustering is increased in the AA 4032/10 vol. % Al_2O_3 composite (see Fig. (11)). As the degree of clustering increases, the strengthening is predicted to increase [32]. In composites with a networking cluster, much more strengthening is exhibited together with relatively uniform strain distribution [32]. The primary mechanism leading to additional strengthening due to clustering derives from an optimum ratio in deformation resistance between a matrix and a reinforcing phase [32].

Figures (19) and (20) show the effect of cold working on hardness values (HV 10) of AA 4032 alloy and AA 4032/10 vol. % SiC composite (after the different treatments) respectively. In all cases, the application of cold working resulted in a remarkable improvement in hardness of materials owing to strain hardening. Similar results have been obtained by Kanetake et al. [33]. After application of cold working, the values of hardness of composite prepared by different processes are higher than those of matrix alloy. The results show that, the application of hot working decreases the hardness of the materials (matrix alloy and its composite). More decrease in hardness is obtained by application of solution treatment after hot working. These results mean that, the composite can be successfully formed either by hot working or application of hot working followed by solution heat treatment.

Cold working improves the hardness of cast materials by 13% for AA 4032 alloy and 10% for AA 4032/10 vol. % SiC composite. Cold working applied after hot working improves the hardness by 26% for AA 4032 alloy and 28% for AA 4032/10 vol. % SiC composite. Cold working when conducted on hot worked solution treated AA4032/10 vol. % SiC composite improves the hardness by 82% whereas, it increases the hardness of the matrix alloy by only 39% . The effectiveness of cold working in hardening of cast composite is lower than that in hardening of cast matrix alloy. The effectiveness of cold working in hardening of hot worked materials (matrix alloy and its composite) is higher than that in hardening of cast ones. However, the application of solution treatment after hot working increases the effectiveness of cold working in hardening of materials.

In the case of composite (hot worked or hot worked and solution treated) the hardening effect is higher than that in the matrix alloy. This can be attributed to the combined hardening effect of reinforcement and cold working. The main conclusion to be drawn is that, two procedures can be recommended for manufacturing of MMC. These are:

1- hot working followed by cold working.
2- hot working and solution treatment followed by cold working.

Improvement in hardness (%) due to the application of cold working

13	26	39

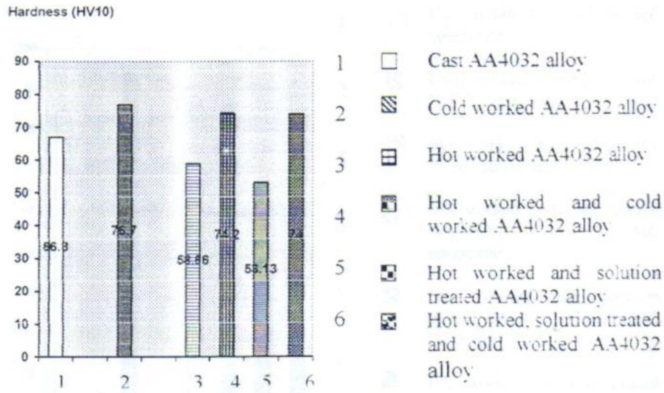
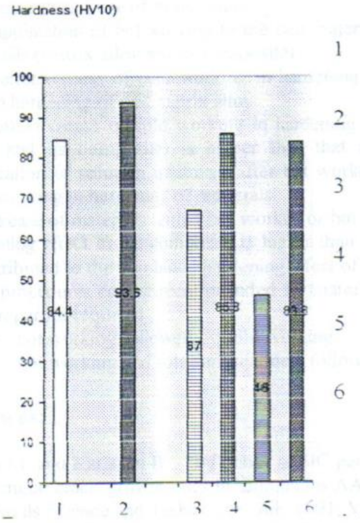


Fig. (19) Hardness of AA4032 alloy after different treatments

Improvement in hardness (%) due to the application of cold working

▧	◘	⊠
10	28	82



1 □ Cast AA4032/10 vol. % SiC composite

2 ▧ Cold worked AA4032/10 vol. % SiC composite

3 ⊞ Hot worked AA4032/10 vol. % SiC composite

4 ◘ Hot worked and cold worked AA4032/10 vol. % SiC composite

5 ▪ Hot worked and solution treated AA4032/10 vol. % SiC composite

6 ⊠ Hot worked, solution treated and cold worked AA4032/10 vol. % SiC composite

Fig. (20) Hardness of AA4032/10 vol. % SiC composite after different treatments

4- Conclusions:

The results of present work lead to the following conclusions:

1- Particulate metal matrix composites can be readily fabricated (prepared) via liquid processing route using AA 4032 alloy as matrix and reinforcing particles such as graphite, SiC, and Al_2O_3

2- Clustering of reinforcing particles occurs in the eutectic constituent region. Clustering is more pronouuced for AA 4032/10 vol. % Al_2O_3 MMC.

3- The features of matrix constituents and reinforcing particles play important roles in hardening of composites. Refined matrix constituents increase the hardness of the composites. Moreover, the clustering of reinforcing particles affect the hardness of the composite, as the degree of clustering increases, the strengthening is predicted to increase.

4- After application of cold working to the materials (AA 4032 alloy and AA 4032/10 vol. % SiC composite) prepared by different processes (casting, hot working, hot working and solution treatment), the values of hardness of composite are higher than those of matrix alloy.

5- The application of hot working to the cast materials decreases the hardness of the materials (matrix alloy and its composite).

6- The effectiveness of cold working in hardening of cast composite is lower than that in hardening of cast matrix alloy.

7- The effectiveness of cold working in hardening of hot worked materials (matrix alloy and its composite) is higher than that in hardening of cast ones. The application of solution treatment after hot working increases the effectiveness of cold working in hardening of materials.

8- In the case of materials (either hot worked or hot worked and solution treated), the hardening effect in the composite is higher than that in the matrix alloy. This can be attributed to the combined hardening effect of reinforcement and cold working.

9- Two procedures can be recommended for manufacturing of MMC, depending on the properties required :
   1- hot working followed by cold working.
   2- hot working and solution treatment followed by cold working.

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