The Effect of Alumina (Al_2O_3) Volume Fraction and Stir casting Conditions on Porosity and Fatigue Life of Aluminum Matrix Composites

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Abstract: Aluminum matrix composites (AMCs) have gained research attention because of their excellent strength to weight ratio. The current paper is focused on mechanical and microstructural characterization of stir cast aluminum (AA6063) matrix composites reinforced with three volume fractions of 150 µm Al_2O_3 particles. The samples under investigation were created by stir casting at various melting temperatures and stirring speed. Different produced composites were evaluated using tensile strength, porosity, fatigue life, and microscopic examination. The tensile and fatigue tests indicated that the mechanical properties of produced composites are improved as the volume fraction of alumina particles increased. Additionally, porosity levels increased with higher Al_2O_3 volume fractions but decreased at elevated temperatures. variations in porosity were observed when mixing speed were varied. Microstructural study exposed that Micro- Al_2O_3 particles were distributed uniformly throughout the matrix.

Keywords: Volume fraction, stir casting, fatigue life, porosity, alumina, aluminum (AA6063), composite material

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تأثير جزء الحجم للألومينا وظروف الصب بالتحريك على المسامية وعمر الكلال لمركبات الألمنيوم

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المستخلص: اكتسبت مركبات مصفوفة الألمنيوم (**AMCs**) اهتمامًا بحثيًا بسبب قوتها الممتازة إلى نسبة الوزن. تركز الورقة الحالية على التوصيف الميكانيكي والميكرو للمركبات الأساسية للألمنيوم المصبوب (**AA6063**) المقواة بثلاثة أجزاء حجمية من 150 ميكرومتر من جزيئات $\mathbf{Al_2O_3}$. تم إنشاء العينات قيد الدراسة عن طريق الصب بالتقليب في درجات حرارة ذوبان مختلفة وسرعة التقليب. تم تقييم المركبات المنتجة المختلفة باستخدام قوة الشد والمسامية وعمر الكلال والفحص المجهري. أوضحت نتائج الاختبار أن مقاومة الشد وعمر التعب للمركب تزداد مع زيادة جزء الحجم لمحتوى جسيمات الألومينا. زادت المسامية مع زيادة نسبة حجم $\mathbf{Al_2O_3}$ وانخفضت عند درجات الحرارة المرتفعة. لوحظت اختلافات في المسامية عندما اختلفت سرعة الخلط. كشفت دراسة البنية المجهرية أن جزيئات **Micro–** $\mathbf{Al_2O_3}$ موزعة بشكل موحد في جميع أنحاء الألمنيوم.

كلمات مفتاحيه: جزء الحجم، الصب بالتحريك، عمر الكلال، المسامية، الألومينا، الألمنيوم، المادة المركبة.

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Introduction:

Reinforced aluminum matrix composites are widely employed in the maritime, transportation, and military industries due to their high strength-to-weight ratio, outstanding thermal conductivity, and increased wear resistance. It is primarily employed in the production of automobile parts such cylinder liners, drive shafts, and connecting rods [1]. Centrifugal, vacuum, stir, in situ, compo, and squeeze casting are among the several casting processes and technologies that are often used in the production of aluminum matrix composites (AMCs) [2]. However, stir casting approach is often preferred due to its cost-effectiveness and simplicity. Stir casting offers notable advantages as it is a flexible and straightforward method compared to others. It is particularly well-suited for producing near net shape components and is applicable for large volume production [3-4]. AMCs can be reinforced with various micro-sized ceramic particles, including B4C [5], SiC [6], ZrB_2 [7], Al_2O_3 [8], and AlN [9]. Fatigue strength of produced composite are the most crucial consideration where its prediction in advance can help prevent catastrophic events in operating machines [10]. Metal matrix composites fatigue has been the subject of numerous studies [11–15]. However, the effects of stir casting conditions and matrix composition ratios on fatigue strength of such composite are still not fully identified. Many factors control the AMC strength including type of reinforcements material, particle size, and its quantity as well as stir casting conditions including stir speed, process time and temperature [16]. However, volume fraction is the most parameter influences the interstice composite structure and fatigue performance accordingly. A few studies [17–22] have examined the effects of particle size and reinforcement volume percent on the fatigue life of particle-reinforced metal matrix composites. Although these researches come to the overall conclusion that decreasing particle size and increasing volume fraction improve fatigue life, the optimum process conditions are still coarse. Further studies focused on porosity issues have revealed a rise in overall fatigue life and strength regardless porosity raise [23]. It is usually difficult to create AMCs with alumina particles by casting procedures due to their extremely low wettability and agglomeration problems, which cause non-uniform distribution and weak mechanical characteristics. This makes understanding the effects of volume fraction and stir casting conditions on porosity and fatigue behavior particularly important. [24]. The aim of this paper is to characterize 6063/Al_2O_3 composites with several selected volume fractions of alumina using the stir casting method with different conditions. Subsequently, the study seeks to analyze the impact of these variables on porosity, fatigue life, and tensile strength.

Experimental Procedure:

a) Composites samples preparation

Commercial AA6063 as matrix and micro-alumina particles as the reinforcements were used to produce the composite material under the study. Alumina powder particles have nominal size of 150 µm. The AA6063 alloy has a nominal composition of 0.47 Mg, 0.42 Si, 0.16 Fe, 0.03 Mn, Cu0.01, 0.01 Cr, 0.01 Zn, and 0.014 Ti, and the remaining is aluminum.

The AA6063 alloy scraps put in a steel container and heated in a lab electric resistive furnace till 800 °C. mixing processes were carried out by an impeller rotating at a speed of about 500 rpm. The impeller design allows it to exert centrifugal radial force on the melt. Before being added to the melt in the presence of air, the ceramic particles were preheated at 400 °C to increase wettability. The powder injection process took about 4-8 minutes depending for volume fraction. Then, the slurry was stirred for ten minutes after particle injection. In order to investigate how stir casting conditions affected the distribution of reinforcement particles, the melting temperature and mixing rate were changed. In order to determine the appropriate speed, 200, 300, 400, and 500 rpm were used. The melt mix was poured into a heated split cylindrical steel die until the solidification process was complete at room temperature while the **casting** temperature was varied at 800, 850, 900, and 1000 °C. In order to minimize surface oxidation during the solidification process and minimize surface exposure to air, the diameter-to-height ratio of the cylindrical steel die was kept as low as possible.

b) Composite Characterization

1) Density and Porosity

The Archimedes principle was used to estimate the densities of the aluminum matrix and reinforced samples. In this approach, the sample must first be weighed in both air and water, or in any fluid with a known density. The measured density (ρ_{mmc}) of the composites may then be represented using Archimedes' principle as follows:

$$\rho mmc = \rho w * m /(m-m1) \qquad (1)$$

where m and m_1 are the masses of the composite sample in air and water, respectively. Furthermore, the density of water ρ_w at 20 °C is 1000 kg/m^3.

The porosity percentage can be calculated using the following expression:

$$\text{porosity } \% = (\rho th - \rho m) / \ \rho th \qquad (2)$$

where ρ_{th} and ρ_m are the theoretical and measured densities.

The rule of mixtures can be used to determine ρ_{th} for a single ingredient:

$$\rho th = vm\, \rho m \ + vr\, \rho r \qquad (3)$$

Where ρ_m is the matrix's density for AA6063 = 2.69 g/cm^3[25], v_m is the matrix's volume fraction, ρ_r is the reinforcement's density for Al_2O_3 = 4 g/cm^3, and v_r is the reinforcement's volume fraction.

2) Tensile Tests

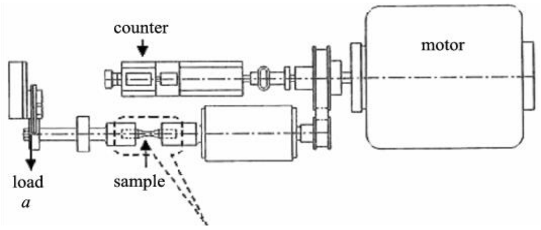
A universal tensile machine was used to measure the yield strength (YS) and ultimate tensile strength (UTS) of the original alloy and the produced composites. Circular specimens with gauge diameters of 9 mm and lengths of 120 mm were machined in accordance with ASTM E-8 standards were used for the tensile tests. Tensile tests were performed in an atmosphere with a strain rate of 0.001/sec.

3) Fatigue Tests

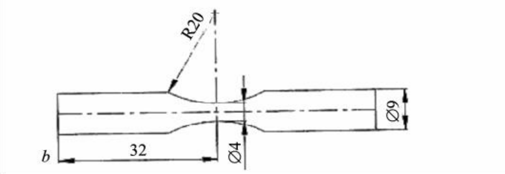
Cantilever rotating bending machine with constant amplitude was used to perform all fatigue tests. The fatigue specimen dimensions is shown in Fig. 1(b); it has a round cross section and is subjected a bending moment as result of transverse load acting at the end of shaft of the machine as shown in Fig.1 (a). Therefore, cyclic bending stresses are applied at each point on the specimen's surface according to the following expression :

$$\sigma = MC / I \qquad (4)$$

where σ is the bending stress, M is the bending moment, C and I are geometry factors.



(a)



(b)

Fig. 1 (a) Fatigue test rig. (b) fatigue sample geometry (dimensions in mm)

The fatigue life curves of each aluminum composite were measured at five **stresses**. The fatigue life curves of each composite were specifically tested for a range of 30, 40, 50, 60, and 70 MPa applied stress. Three samples were used for each test in order to reduce the possibility of error, and the average value was used for the study.

4) Microstructure

Optical microstructure studies were carried out to evaluate the distribution of particles, pores, and phases found in the composite samples. Standard metallographic techniques were used to prepare specimens for metallography, including grinding with silicon carbide emery papers with grits of 800 and 1200 followed by polishing with alumina paste. They were then etched with a mixture of: 190 ml water +5 ml nitric acid +3 ml hydrochloric acid +2 ml hydrofluoric acid;. A digital camera-equipped optical microscope was used to examine the various prepared samples.

Result and Dissection

1) *Influence of Al_2O_3 on porosity*

Table 1 displays the density and porosity content of the manufactured composites. The presence of porosity in the structure is what causes the measured density (ρ_m), which was determined using the chemical composition of the composites, and the theoretical density (ρ_{th}) to differ. The table shows how increasing alumina weight fraction resulted in an increase in porosity volume percent. This is caused by an interaction of limited wettability, agglomeration when there is high additives , and pore nucleation at matrix-Al_2O_3 interfaces. Also, the reduction in liquid metal flow coupled to the particle clusters causes the formation of porosity. A report of such an observation can be found in the literature [26-27].

Table 2 shows the effect of increasing the stirring temperature on the porosity and density of aluminum alloy without reinforcement materials. The porosity clearly decreases with increasing mixing temperature as a result of increased mixture liquidity, and thus the possibility of trapped air bubbles decreases. Furthermore, at higher temperatures (1000ºC), the solidification process will be slower, allowing more time for grain size to grow and fewer dislocations to form, resulting in denser materials.

Table 3 shows that the porosity was reduced when the aluminum matrix is **casted** at higher **temperatures**. The porosity of the composite reduces with stirring speed up to 300 rpm.

The mechanical and fatigue characteristics were improved by Al_2O_3 uniform dispersion. However, maintaining a minimum amount of porosity is advisable [28].

Table 1 variations in density and porosity with micro- Al_2O_3 particle content At 800 °C, a mixing speed of 500 rpm and stirred for 10 min.

Reinforcement (%)	**ρ_m (g/cm^3)**	**ρ_{th} (g/cm^3)**	**Porosity %**
0	2.636	2.69	2
5	2.604	2.756	5.5
10	2.624	2.821	7

Table 2 variations in porosity and densities of unreinforced alloy with alteration of casting temperature at a mixing speed of 500 rpm and stirred for 10 min.

Temperature °c	ρ_m (g/cm^3)	ρ_{th}(g/cm^3)	Porosity %
800	2.636	2.69	2
850	2.639	2.69	1.89
900	2.644	2.69	1.71
1000	2.651	2.69	1.45

Table 3 Variation in densities and porosity of unreinforced alloy versus stirring speed at 900 °C and stirred for 10 min.

Speed (rpm)	ρ_m(g/cm^3)	ρ_{th}(g/cm^3)	Porosity %
200	2.613	2.69	2.86
300	2.618	2.69	2.68
400	2.612	2.69	2.89
500	2.603	2.69	3.23

2) Influence of Al_2O_3 on strength:

Variations in the YS and UTS of synthetic alumina-aluminum alloy composites are shown in Figure 2 along with a standard error bar. The addition of Al_2O_3 particles improves the composites' UTS and YS. When 10% alumina particles were added to an aluminum alloy, UTS climbed to a maximum of 7.6% and yield strength improved to around 7%.

Tensile strength is often increased because to strong interfacial adhesion between the aluminum matrix and Al_2O_3. Despite the existence of porosity, the tensile test showed a minor improvement when compared to the literature evaluations. Researchers [29, 30] showed an increase in tensile strength when particles such as B_4C, B_4CHfB_2, and Al_3Ti were added. However, when $ZrSiO_4$ was added to aluminum alloy, the tensile strength of the composites was reduced [31]. By putting ceramic reinforcements inside aluminum foils before adding the liquid, an enhanced dispersion of those reinforcements in the molten aluminum was confirmed. Composites can strengthen and increase tensile strength by multiple directions thermal stress and refinement of grains at the matrix-reinforcement interface [32]. The dissimilarity in thermal extension between Al_2O_3 particles and the base alloy results in dense dislocation structure and high local residual stresses, both of which boost composite tensile strength [33]. The strength, which is dependent on the processing temperature, is enhanced at the Al_2O_3/Al contact by thermodynamically unstable reinforcement particles [34]. In summary, the main elements impacting the tensile strength of composites are the presence of dimples, microcracks, and micro voids produced by deboning [35].

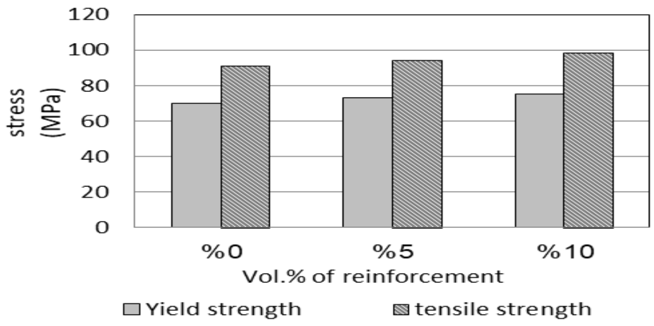


Fig 2: Influence of Al_2O_3 on Tensile Strength

3) Influence of Al_2O_3 on fatigue life

The results of fatigue life using the rotating bending machine fatigue–testing for different alumina volume fractions additives are illustrated in Figure (3). Overall, analysis of the fatigue life of MMCs and metal matrix showed that MMCs have superior fatigue resistance. The experimental data provided in figure (3) were curve fitted using the Basquin formula which can be stated in the form,

$$\sigma f = aNb \qquad (5)$$

Where N represents the number of cycles, with ***10^7*** cycles utilized, σ_f denotes the reference value of fatigue strength (in simulation, this corresponds to the stress range, typically taken as twice the alternating stress), b stands for the slope of the log s – log N fatigue strength curve, and a represents the stress value at one cycle.

The improvement in fatigue conduct is evidently attributed to the presence of hard Al_2O_3 particles, which reinforce the soft aluminum matrix, consequently increasing the strength of the composite. Initially, the inclusion of 5% Al_2O_3 micro-particles led to a fatigue strength increase of approximately 2.58% compared to that of the metal matrix, which rose to 6.32% at 10% weight. This increase in fatigue strength with reinforcement percentage occurs due to a significant fraction of the load backed by the stiffer particle reinforcement, resulting in lower overall stresses for a given fatigue stress [36]. Furthermore, the dispersion of hard micro-particles within the base metal restricts plastic flow, thereby enhancing the strength of the composite [37].

However, as observed in previous sections, the inclusion of Al_2O_3 particles increases porosity. These consistently distributed holes in the composite material matrix may also aid to control plastic flow under dynamic load conditions, increasing fatigue strength. However, fatigue strength can be increased more for the same reinforcement percentage with smaller particle size [38]. This is also confirmed in [39-40] that decreasing the size of particles reinforced 6061 Al composite stretched the fatigue life by lowering the breaking of larger particles in the distribution. Also, the surfaces condition of the test specimens have a significant impact on the final fatigue strength test results. Because of the limited time, the effect of this parameter is beyond of this study scope. Finally, melting temperature during stir casting process play another role in the final product properties. According to [41], at high temperatures, voids form at the particle-matrix interface, considerably shortening the fatigue life of particle-reinforced materials.

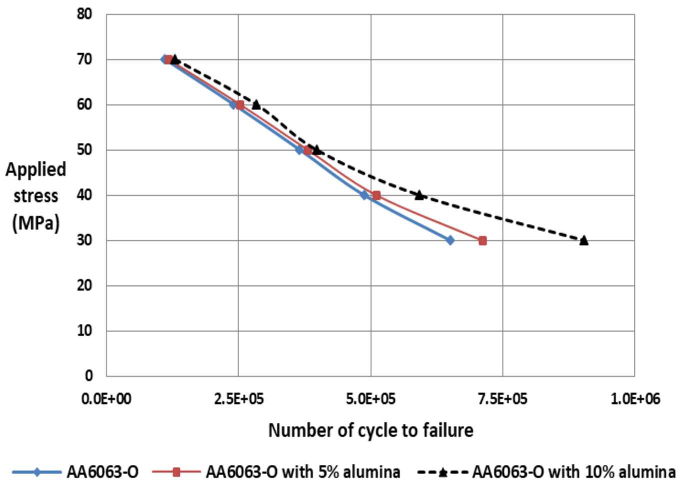


Fig 3: Influence of (Al_2O_3) on fatigue life

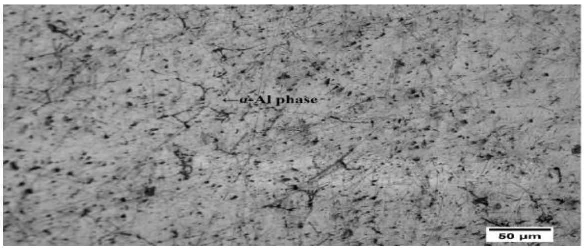
4) Influence of Al_2O_3 on microstructure

Figure 4 depicts the microstructure of composite samples with several reinforcement levels fabricated through stir-casting processes. During the solidification of AA6063/Al_2O_3 composites, the Al_2O_3 particles have extremely different thermal properties compared to the metal matrix. Consequently, Al_2O_3 particles looses heat more slowly than the molten matrix, resulting in their temperature being fairly higher than that of the liquid alloy. This higher temperature of the particles can elevate the temperature of the surrounding melt, thereby delaying the solidification of the adjacent liquid alloy.

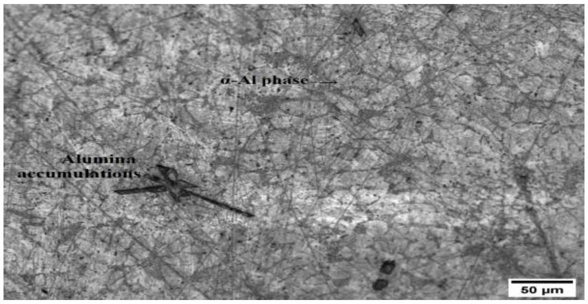
Consequently, nucleation of the α-Al phase begins in the liquid at colder points surrounded the hotter Al_2O_3 particles where the temperature is higher. Thus, the microstructure of the composites comprises primary α-Al dendrites. Various studies have reported the presence of intermetallic phases such as "Chinese script" shaped α-Al15 $(Mn,Fe)_3Si_2$ precipitating in the interdendritic and intergranular substructures. Meanwhile, the Al_2O_3 particles appear as isolated entities in an inter-dendritic configuration.

Figure 8 (b, c) illustrates that stirring the melt has three chief impact on the microstructure. Firstly, it disrupts the dendritic structure, leaving it in an equiaxed form. Secondly, it enhances the wettability and incorporation of particles within the melt. Lastly, it promotes a more uniform dispersion of particles throughout the matrix. Consequently, the stirring process leads to the refinement of α-Al grains and improves the diffusion of alumina particles inside the melt. The optical micrographs in Figure 8 indicate that the range of grain size in reinforced composites is smaller than in the original alloy, owing to particles serving as nucleation sites and their good wettability with the melt.

Furthermore, an observation from these paragraphs is that black spots appear with an increase in reinforcement percentage, which may be clumps resulting from the presence of pores. According to literature [44], porosities are visible the micro level specifically at interfaces between the matrix and the added particle. As a result, there is less adhesive strength between the reinforcements and matrix.



(a)



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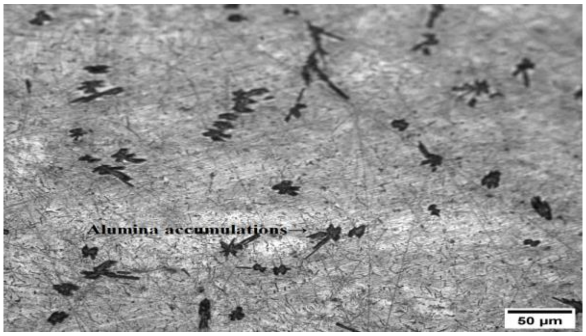

(c)

Fig.4 Optical photos of micro-composites at different reinforcement wt.% Al_2O_3 (a) zero wt.% (b) 5 wt.% (c) 10 wt.%.

Conclusions:

In the current study, stir-casting micro-composites of AA6063/Al_2O_3 were prepared at different parameters. Studies have been done on how different manufacturing factors affect the microstructure and a few mechanical and physical characteristics of composites. The following findings were drawn:

1. The following conditions were optimal for producing the composites: 400°C particle preheating before injection; 500 rpm stirring speed; and 800 °C casting temperature.
2. Tensile strength is increased 7% with the alumina particles volume fraction 10%.
3. A rise in the volume fraction of Al_2O_3 particles leads to a small increase in sample porosity.
4. Raising the volume fraction of Al_2O_3 particles leads to an increase in fatigue failure cycles for composites.
5. The microstructure study showed that composites reinforced with up to 5% wt.% Al_2O_3 particles had uniform dispersion. However, particles clustered at 10 wt.% Al_2O_3 particles.

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