Journal of Engineering and Applied Sciences 13 (Special Issue 1): 2364-2369, 2018
ISSN: 1816-949X

Enhancement Properties of Aluminum-Alumina Composite by Mechanical Mold Vibration

Rand A. Al-Shuraify, Haydar Al-Ethari and Saad H. Al-Shaafaie
Department of Metallurgical Engineering, Materials Engineering College,
University of Babylon, Hillah, Iraq

Abstract: This study is concerned with the influence of vibration during solidification on the mechanical properties of aluminum-alumina metal matrix composite. The main vibration effects include promotion of nucleation and thus reducing as-cast grain size; reduction of shrinkage porosities due to improved metal feeding and production of a more homogenous metal structure. Mechanical mold vibration was applied to pure aluminum reinforced with 5wt.% Al_2O_3 particles were prepared by two step stir casting. Mechanical mold vibrations were applied in amplitude and frequency range of 0-1 mm and 8-25 Hz, respectively. Experimental results show that keeping the amplitude constant at 0.5 mm and increasing the frequency give the best results. X-ray diffraction analyses, microstructure, grain size, hardness, porosity and tensile tests had been investigated. It was observed that brinell hardness, tensile strength, modules of elasticity and percentage elongation were improved by 38, 34, 6 and 33%, respectively porosity and grain size reduced by 83 and 43%, respectively as compared to that of stationary prepared sample.

Key words: Composite material, Al_2O_3, mechanical mold vibration, stir casting, amplitude, aluminum-alumina

INTRODUCTION

The Al_2O_3 reinforced aluminum alloys matrix composites have been progressively more used in the automotive, aircraft and aerospace industry because of their high strength-to-weight ratio, good castability and better tribological properties over the unreinforced alloys. Alumina particles have high melting temperature, high hardness, relatively good strength, chemically and thermally stable, high "hot" hardness which when reinforced with Al or its alloys, make it most promising material, possessing properties which can be tailored to meet the diverse demands of many engineering applications. The amount, size and distribution of reinforcing particles in the metal matrix play key role in controlling the overall properties of composites (Koli *et al*., 2015).

It is well accepted that microstructure is one of major factors that defines the mechanical properties of metallic materials. For general casting applications, refining to achieve equiaxed and fine grains will increase fluidity, reduces hot cracking and non-dendritic structures will be obtained. Semi-solid processing is an attractive process for obtaining globular structures and for minimizing the porosity and segregation problems of conventional casting (Limmaneevichitr *et al*., 2009), applying mechanical vibration into a molten alloy during solidification has been developed as an advantageous method to obtain fine grains because of low cost and simple system, compared with ultrasonic or electromagnetic vibration. Mechanical vibration is introduced into the solidifying has strong effects on grain refinement, degassing and mechanical properties (Guo *et al*., 2014).

Many papers focusing on such solidification behaviour of alloys under vibration had been published. Al-Ethari and Hasani (2013) studied the effect of solidification under mechanical vibration on (Al-13% Si) alloy. The study showed that solidification under vibration improves microhardness by 26%, tensile strength by 102% and modulus of elasticity by 20%. Kumar and Tewari (2015) studied the effect of mechanical vibration parameter frequency and amplitude range of 0-400 Hz and 0-15 μm on microstructure and mechanical properties of A356 aluminum alloy. Tensile strength, yield strength and percentage elongation were improved by 26.8, 17.7 and 52%, respectively as compared to that of stationary prepared specimens. Improvement in the properties is attributed to grain refinement of vibratory prepared cast which evident from microstructure photograph. Abu-Dheir *et al*. (2005) studied the effect of mechanical mold vibration on Al-Si eutectic (Al-12.5% Si) alloy at a frequency of 100 Hz and variable amplitudes in the range of 18-199 μm. It is shown that the silicon morphology was strongly influenced by the level of vibration amplitude. Generally, increasing the vibration amplitude tends to reduce the lamellar spacing and change the silicon morphology to become more

Corresponding Author: Rand A. Al-Shuraify, Department of Metallurgical Engineering, Materials Engineering College, University of Babylon, Hillah, Iraq

fibrous. However, exceeding a critical value of vibration amplitude tends to coarsen the silicon.

In the present research, mechanical mold vibration at different frequencies and amplitudes was introduced to Al-Al_2O_3 composite material, metallurgical, physical and mechanical properties as: microstructure, hardness, porosity and tensile properties were investigated.

MATERIALS AND METHODS

Materials used: High-purity aluminum was used as matrix phase in this composite. Chemical composition of pure aluminum wire used to prepare the Al base composite is shown in Table 1.

Magnesium was added during the preparation of the composite in order to improve the wettability of alumina particles by reducing its surface tension.

Aluminum oxide was used as reinforcement. Various percentages of aluminum oxide 1, 3, 5 and 7% were used in the present research to select the best out of them. Particle size analysis of Al_2O_3 was carried out using laser particle size analyzer type (Bettersize 2000). The average particle size of Al_2O_3 was 11.80 μm according to the report shown in Fig. 1.

Fabrication of Al-Al_2O_3 composite: Four samples coded in Table 2 were prepared by two-step stir casting method. The weighted alumina particles were divided into groups, covered with aluminum foil and preheated to 300°C for 2 h in dry oven. Pieces of Al-wire were charged in to graphite crucible and the furnace temperature was raised up to liquidus temperature 750°C. Slags were removed using alumina spoon and further the melt temperature was dropped to just below the liquidus temperature 620°C to attain the semi-solid state. The magnesium ribbon were rolled and covered by aluminum foil and then immersed inside the melt. The molten aluminum slurry was stirred with four-blade mild steel stirrer with a speed of 870 rpm for 10 min and the preheated, covered, alumina particles were slowly added to the molten metal. The stirring process was going under a shield of argon gas. The temperature during stirring was observed, using thermocouple type-K to be 610-620°C. Then, the temperature was raised above the liquidus temperature 750°C again. The melt was poured in preheated steel mold with a cavity of 20 mm in diameter and 150 mm in height. The prepared stir casting system is shown in Fig. 2.

Hardness and porosity of the cast samples were used as a criterion to choose one of them to study the effect of mechanical vibration. The chosen sample was recast by the same procedure but poured in a mold attached to a vibrating device. All prepared samples were put in an electrical furnace at 300°C for 3 h and cooled inside the furnace to remove all thermal stresses.

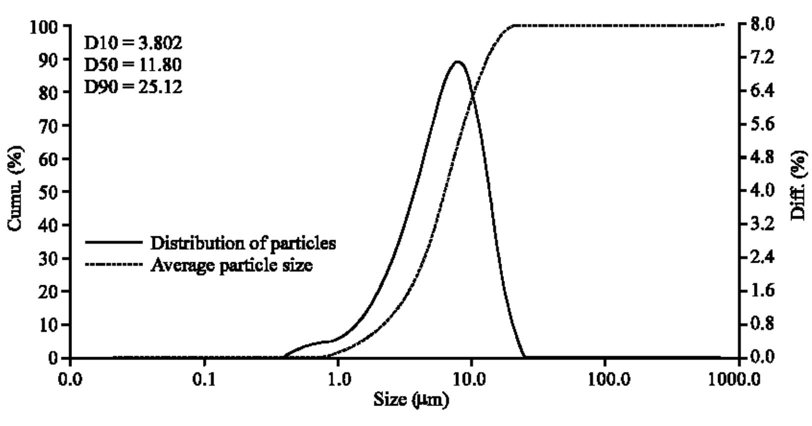
Mechanical vibration set up: The mechanical vibrations were provided using a vibrating device developed and

Table 1: Chemical composition of used aluminum wire

Chemical composition (%)	Values
I	0.036
Fe	0.219
Mn	0.003
Mg	0.001
Cr	0.003
Ti	0.002
V	0.007
Ni	0.001
Al	Bal

Table 2: Samples prepared in the present study

Sample code	Aluminum (wt.%)	Magnesium (wt.%)	Alumina (wt.%)
S0	98.5	1.5	0
S1	97.5	1.5	1
S2	95.5	1.5	3
S3	93.5	1.5	5
S4	91.5	1.5	7



Diameter μm	Percent
0.100	0.00
0.200	0.00
0.500	0.00
1.000	0.97
2.000	3.53
5.000	15.36
10.000	41.16
20.000	80.00
45.000	99.84
75.000	100.00

Fig. 1: Particle size analysis report of Al_2O_3

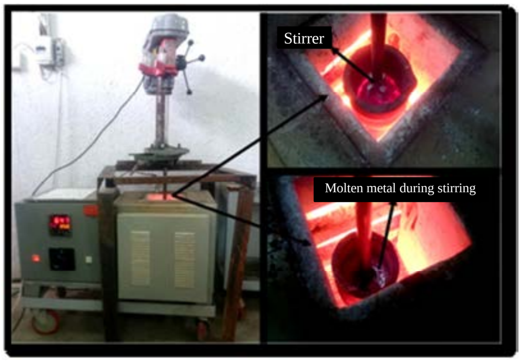


Fig. 2: Stir casting process

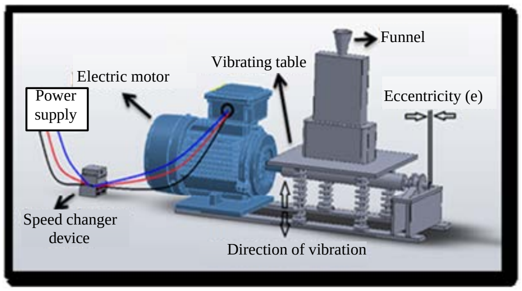


Fig. 3: Sketch of vibrating device

built specially for the present research. Figure 3 shows a sketch for this device. The device, provides four different amplitudes of vibration due to shaft with an eccentricity of values 0.25, 0.5, 0.75 and 1 mm. The shaft can be rotated with three rotating speed 500, 1000 and 1500 rpm to get the required frequency. Due to the eccentricity, a table where the die is attached to the device will vibrate vertically with the designed amplitude which is equal to the designed eccentricity.

Metallurgical, physical and mechanical tests

X-Ray Diffraction analysis (XRD): X-ray diffraction test was carried out for the cast to insure the existence of Al_2O_3 particles. The measurement conditions are Cu target of wave length of 1.5 A°, voltage and current are 30 kV and 15 mA, scanning speed 2 deg/min for scanning rang of 20°-90°.

Microstructure test: Specimens with 20 mm in diameter were cut from central portion of the cast sample to ensure homogeneous distribution of the reinforcement particles. The specimens were flattened using SiC grinding papers having different roughness 180, 220, 320, 400, 600, 800, 1000, 1200, 1500, 2000, 2500 grit size, then, polished using diamond paste to produce flat, scratch free, mirror like surface. The specimens were etched by (0.5% HF, 99.5% Distilled water) for 15 sec at room temperature, then specimens were washed with distilled water and dried by electric dryer. An optical microscope with suitable magnification was used to capture the microstructure of each samples.

Grain size measurement: Specimens with 20 mm in diameter and 10 mm in height were cut from samples solidified with and without vibration prepared for grain size measurement. The samples were prepared for testing in terms of grinding, polishing and etching operations. An optical microscope with magnification of 200X was used to capture the microstructure of each samples. The measuring of the grain size was carried by linear intercept technique. Through this technique, draw lines on a photomicrograph and the grain boundary intercepts number, "N" extension this line is calculated. The average linear intercept calculated through the Eq. 1 (Askela and Phule, 2006):

$$R = \frac{L}{NM} \tag{1}$$

Where:

L = The line length (μm)
M = Magnification
N = The intersection number

Brinell hardness test: This test was carried out according to ASTM (E10-15a) (Anonymous, 2015) with a ball indenter diameter of 2.5 mm and load of 31.25 g for 10 sec. The test was carried out for the samples cast without the effect of vibration and for samples solidified under the effect of vibration. The hardness was measured at top, center and bottom part of each sample cast with vibration. An average of three hardness measurements was recoded for each specimen.

Porosity test: Porosity of the final composite samples has been taken at top, center and bottom part of casting. It was determined according to the following Eq. 2 (Anonymous, 2003):

$$\text{Porosity (Apparent)(\%)} = \frac{W_w - W_d}{W_{sat} - W_s} \times 100 \tag{2}$$

Where:

W_w = Dry weight of the samples
W_w = Wet weight of the sample (the sample was weighted after immersing it for 24 h in distilled water)
W_{sat} = Saturated weight (the sample was weighted after immersing it for 5 h in pure water at 80°C)
W_s = Suspended weight (weighting the suspended sample in distilled water)

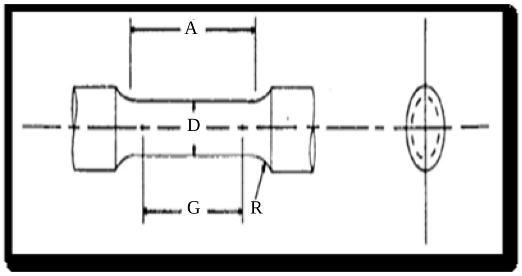


Fig. 4: Standard round tension test specimen; Gage length (G): (25.0+0.10) mm; Diameter (D): (6.25+0.12) mm; Radius of fillet (R): 5 mm; Length of reduced section (A): 32 mm

Tensile test: Standard specimens were prepared with dimensions shown in Fig. 4 for each sample, according to ASTM (B557m-15) (Anonymous, 2015a). The test was carried out via universal testing machine with tensile speed rate (0.1 mm/min) at room temperature.

RESULTS AND DISCUSSTION

Effect of Al_2O_3 on the hardness: Figure 5 shows that a largest Brinell's hardness number was recorded for the sample with 5 wt.% of the reinforcing particles (i.e., S3 sample). So, all samples used to study the effect of the mechanical vibration will prepared based on 5wt.% of alumina.

X-Ray Diffraction analysis (XRD): Figure 6 illustrates the X-ray diffraction of S3 sample. It is clear that there is four peaks of aluminum and three peaks of Al_2O_3 and other remaining minor peaks attributed to impurity. From XRD charts there is no solid state reaction between Al and Al_2O_3 during the casting process. This result are in agreement with Nagaral *et al.* (2013).

Microstructure test: Figure 7 shows the microstructures of Al-Al_2O_3 composite with and without vibration. It is clearly shown that the use of stir casting during preparation of these composites induced an acceptable distribution of the reinforcing particles in the matrix with very little segregation. It was also found that there was good bonding between matrix material and Al_2O_3 particles, It is noticeable that solidification with vibration causes refinement as a change in the size and distribution of Al-Al_2O_3 particle. Mechanical vibration can collapse dendrite arms during solidification and disperse them in the melt. Dispersed broken dendrite arms act as nuclei in the melt and produce finer grains and microstructure.

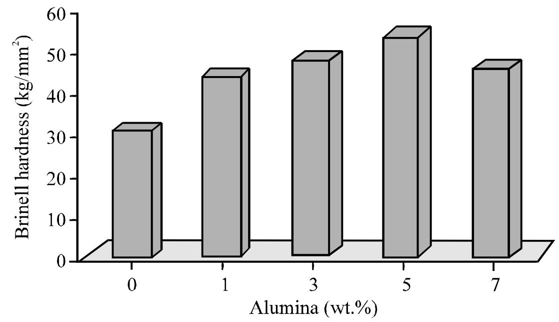


Fig. 5: Effect of Al_2O_3 on the hardness of Al-Al_2O_3 composite

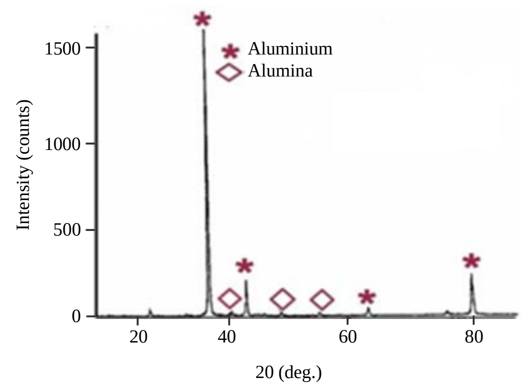


Fig. 6: XRD test for Al-Al_2O_3 composite

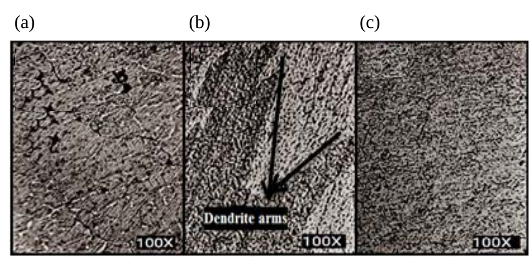


Fig. 7: Microstructures of: a) S0; b) S3 solidified without vibration and c) S3 solidified with vibration

Results of grain size measurement: Figure 8 shows the microstructure of grain size measurement for sample solidified with and without vibration. The result indicated that the average grain size of sample solidified without vibration was 56 μm while by applying mechanical vibration the average grain size reduced to 32 μm. It is clearly that the use of mechanical vibration led to increase in grain refinement due to high cooling rate which cases the grain refinement as a change in size and distribution of particle of composite material.

Effect of vibration on hardness and porosity: Table 3 demonstrates the results of the hardness and porosity

Table 3: Results of hardness and porosity tests

		Location of sample							
		Top		Center		Bottom		Average value	
Amplitude(mm)	Frequency (S^{-1})	BHN(kg/mm^2)	Porosity (%)	BHN (kg/mm^2)	Porosity (%)	BHN (kg/mm^2)	Porosity (%)	BHN (kg/mm^2)	Porosity (%)
0	0	53	4.00	53	4.00	53	4.00	53	4.00
0.25	8	54	3.00	55	2.90	56	2.80	55	2.90
	17	55	2.90	56	2.80	58	2.50	56	2.70
	25	55	2.40	58	2.30	62	2.00	58	2.20
0.5	8	63	0.92	64	0.98	65	1.00	64	0.96
	17	66	1.00	68	0.90	70	0.70	68	0.86
	25	72	0.90	73	0.80	74	0.40	73	0.70
0.75	8	59	1.90	60	1.80	63	1.20	61	1.61
	17	63	1.50	64	1.30	66	1.00	64	1.16
	25	65	1.20	66	1.00	68	0.90	66	1.03
1	8	58	2.00	59	1.90	62	1.80	60	1.90
	17	59	2.30	62	2.00	64	1.30	62	1.70
	25	63	1.30	65	1.00	67	0.92	65	1.07

(a)

(b)

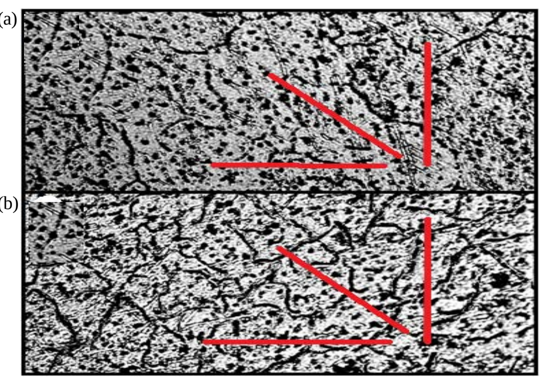


Fig. 8: Grain size measurement of: a) S3 solidified without vibration and b) S3 solidified with vibration

test for samples with 5 wt.% of Al_2O_3 solidified under the effect of mechanical vibration with wide ranges of amplitude and frequency. The results show that the bottom, the center and the top part record nearly the same value of the hardness number for all samples. The largest value of hardness was recorded for the sample prepared under a vibration of 25/S frequency and an amplitude of 0.5 mm. Porosity results indicate that the test specimens solidified without the effect of vibration have more porosities than that solidified under vibration. It is conspicuously revealed that the porosity decreases with the frequency of vibration, reaches the minimum value at amplitude of 0.5 mm and frequency of 25 Hz.

Result of tensile test: The tensile properties are demonstrated in Table 4. It is shown that mechanical results depend on metallurgical features which itself depends on the solidification behaviour. It is clear that the ultimate tensile strength and elastic modulus of sample solidified under mechanical vibration is more than that of sample solidified without mechanical vibration and

Table 4: Results of tensile test

Sample code	Amplitude (mm)	Frequency (S^{-1})	UTS (MPa)	E (GPa)	El (%)
S0	0.0	0	98	71	3.5
S3	0.0	0	113	80	2.1
S3	0.5	25	151	85	2.8

Table 5: Variation in mechanical and physical properties of vibrated and un vibrated sample

Tests	S3 solidified with vibration	S3 solidified without vibration	Change (%)
Brinell hardness (kg/mm^2)	53	73	38 ⇧
Tensile strength (MPa)	113	151	34 ⇧
Elastic modulus (GPa)	80	85	6 ⇧
Elongation (%)	2.1	2.8	33 ⇧
Grain size (µm)	56	32	43 ⇩
Porosity (%)	4	0.7	83 ⇩

increased with increasing vibration condition. Contrary to ductility which is reduced by increasing these conditions. This is due to the fact that vibration induces a higher heat transfer to the mold (higher cooling rate) due to the alternated movement of the liquid. Furthermore, this movement may also provide displacement of the heterogeneous solidification sites providing a higher solidification rate. The consequence is that fine and no dendritic microstructure as well as less porosity in casting.

Abbreviation of mechanical and physical properties results: Table 5 demonstrates the mechanical and physical properties of S3 sample solidified with and without vibration and change percentage.

CONCLUSION

The amplitude and frequency of the vibration have significant effects on metallurgical, physical and mechanical properties of cast Al-Al_2O_3 composite.

Keeping the amplitude constant at 0.5 mm and increasing the frequency resulted in an improvement of hardness and porosity, this effect was reduced when the amplitude was increased.

Mechanical properties significantly enhanced under the effect of mold vibration. Brinell hardness, elastic modulus, percentage of elongation and ultimate tensile strength were increased by 38, 6, 33 and 34%, respectively. By mechanical vibration, grain size of particles and porosity reduced by 43 and 83%, respectively.

Applying vibration to the solidifying Al-Al_2O_3 composite material leads to microstructural changes to dendritic structure of aluminum. Vibration successfully broke the dendritic structure into small islands of aluminum.

ACKNOWLEDGEMENT

The researchers are thankful to the staff of the workshop materials lab. in Babylon University.

REFERENCES

Abu-Dheir, N., M. Khraisheh, K. Saito and A. Male, 2005. Silicon morphology modification in the eutectic Al-Si alloy using mechanical MOLD vibration. Mater. Sci. Eng. A, 393: 109-117.

Al-Ethari, H. and E.A. Hasani, 2013. Influence of graphite and solidification under vibration on mechanical and machining properties of hypereutectic (AL-SI) alloy. Iraqi J. Mech. Mater. Eng., 13: 241-253.

Anonymous, 2003. 328, Standard test method for density, oil content and interconnected porosity of sintered metal structural parts and oil-impregnated bearing. ASTM International, West Conshohocken, Pennsylvania, USA.

Anonymous, 2015a. Standard test method for brinell hardness of metallic materials. ASTM International E10-15a, West Conshohocken, Pennsylvania, USA.

Anonymous, 2015b. Standard test methods for tension testing wrought and cast Aluminum- and Magnesium-Alloy products (Metric). ASTM B557M-15, West Conshohocken, Pennsylvania.

Askel, D.R. and P.P. Phule, 2006. The Science and Engineering of Materials. 5th Edn., Thomson, Canada, pp: 79-85.

Guo, H.M., A.S. Zhang, X.J. Yang and M.M. Yan, 2014. Grain refinement of Al-5% Cu Aluminum alloy under mechanical vibration using meltable vibrating probe. Trans. Nonferrous Metals Soc. China, 24: 2489-2496.

Koli, D.K., G. Agnihotri and R. Purohit, 2015. Influence of ultrasonic assisted stir casting on mechanical properties of Al6061-nano Al2O3 composites. Mater. Today Proc., 2: 3017-3026.

Kumar, S. and S.P. Tewari, 2015. Effect of vibration on mechanical properties of A356 Aluminum alloy casting. Intl. J. Mech. Prod. Eng. Res. Dev., 5: 75-80.

Limmaneevichitr, C., S. Pongananpanya and J. Kajornchaiyakul, 2009. Metallurgical structure of A356 Aluminum alloy solidified under mechanical vibration: An investigation of alternative semi-solid casting routes. Mater. Des., 30: 3925-3930.

Nagaral, M., V. Bharath and V. Auradi, 2013. Effect of Al_2O_3 particles on mechanical and wear properties of 6061al alloy metal matrix composites. Mater. Sci. Eng., 2: 120-124.