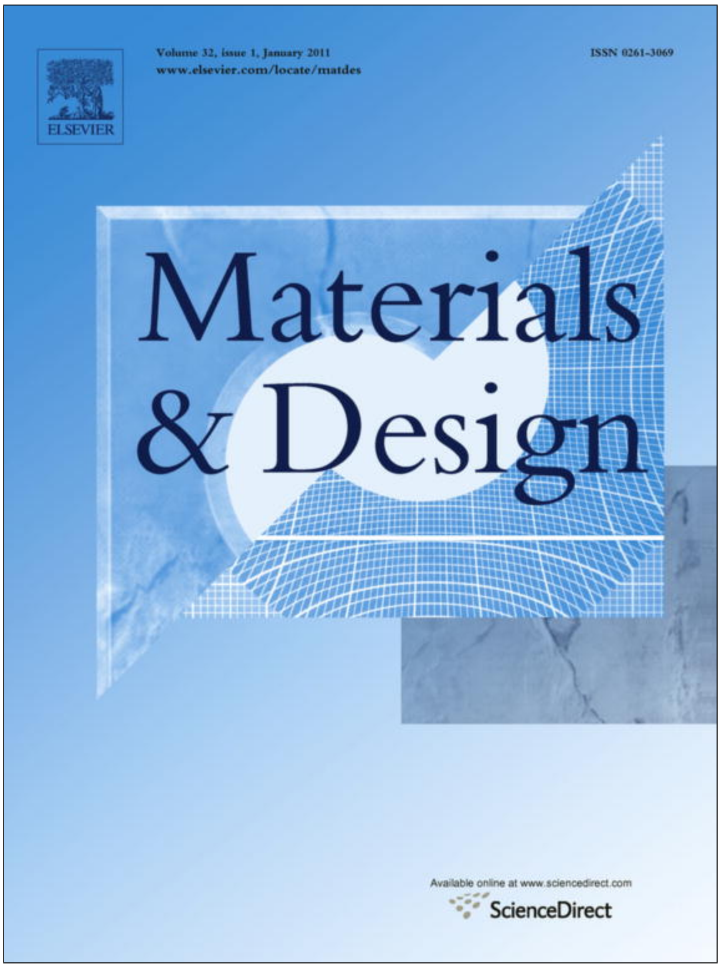
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Materials and Design 34 (2012) 106–111

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al_2O_3 composites fabricated by stir and compo-casting processes

S.A. Sajjadi [a,*], H.R. Ezatpour [a], M. Torabi Parizi [b]

[a] Department of Materials Science and Metallurgical Engineering, Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Materials Science and Metallurgical Engineering, Engineering Faculty, Azad University of Saveh, Saveh, Iran

A R T I C L E I N F O

Article history:
Received 29 May 2011
Accepted 15 July 2011
Available online 3 August 2011

Keywords:
A356/Al_2O_3 composite
Mechanical properties
Microstructure
Stir-casting
Compo-casting

A B S T R A C T

Metal–matrix composites (MMCs), as light and strong materials, are very attractive for application in different industries. In the present work, nano and micro-composites (A356/Al_2O_3) with different weight percent of particles were fabricated by two melt techniques such as stir-casting and compo-casting. Microstructural characterization was investigated by optical (OP) and scanning electron microscopy (SEM). Tensile, hardness and compression tests were carried out in order to identify mechanical properties of the composites. The results of microstructural study revealed uniform distribution, grain refinement and low porosity in micro and nano-composite specimens. The mechanical results showed that the addition of alumina (micro and nano) led to the improvement in yield strength, ultimate tensile strength, compression strength and hardness. It was indicated that type of fabrication process and particle size were the effective factors influencing on the mechanical properties. Decreasing alumina particle size and using compo-casting process obtained the best mechanical properties.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Metal–matrix composites (MMCs) are most promising in achieving enhanced mechanical properties such as: hardness, Young's modulus, 0.2% yield strength and ultimate tensile strength due to the presence of nano and micro-sized reinforcement particles into the matrix. Generally, regards to the mechanical properties, the reinforcements result in higher strength and hardness, often at the expense of some ductility [1].

Aluminum-matrix composites (AMCs) reinforced with particles and whiskers are widely used for high performance applications such as in automotive, military, aerospace and electricity industries because of their improved physical and mechanical properties [2]. In the composites relatively soft alloy like aluminum can be made highly resistant by introducing predominantly hard but brittle particles such as Al_2O_3 and SiC.

A356 aluminum alloy is a very commonly Si-containing Al-alloy used as the matrix in MMCs. It is characterized by: low cost, ease of handling, good strength and ductility and resistance to atmospheric corrosion. Hard particles such as Al_2O_3 and SiC are commonly used as reinforcement phases in the composites. The application of Al_2O_3 or SiC particle reinforced aluminum alloy matrix composites in the automotive and aircraft industries is gradually increasing for pistons, cylinder heads, connecting rods etc. where the tribological properties of the materials are very important [1–4].

Mechanical properties of composites such as strength and ductility may be improved, simultaneously if the dispersed particles are of nano-size. The enhancement of mechanical properties in the novel nano-particle reinforced MMCs has been reviewed recently [4].

In addition, the mechanical properties of MMCs are sensitive to the processing technique used to fabricate the materials. Considerable improvements may be achieved by applying science-based modeling techniques to optimize the processing procedure. Several techniques have been employed to prepare the composites including powder metallurgy, melt techniques and squeeze casting [2,3]. However, powder metallurgy appears to be the preferred process in view of its ability to give more uniform dispersions. Hot extrusion is generally used as post-treatment to take the advantages of applying compressive forces and high temperatures, simultaneously [5].

There are two types of melting methods to fabricate composites, depending on the temperature at which the particles are introduced into the melt. In the liquid metallurgy process, the particles are incorporated above the liquid temperature of the molten alloy, while in compo-casting method the particles are incorporated at the semi-solid slurry temperature of the alloy. In the both processes, the vortex occurs and the composites have high porosity. However, the melting process has two major problems firstly, the ceramic particles are generally not wetted by the liquid metal

* Corresponding author. Fax: +98 511 8763305.
E-mail address: sajjadi@um.ac.ir (S.A. Sajjadi).

0261-3069/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2011.07.037

Author's personal copy

matrix, and secondly, the particles tend to sink or float according to their density relative to the liquid metal. Consequently, the dispersion of the ceramic particles is not uniform. In order to decrease the porosity in the composite material, the pressure casting such as die and squeeze casting methods is needed [6].

Although powder metallurgy produces better mechanical properties in MMCs, melt processing has some important advantages. They are as: better matrix-particle bonding, easier control of matrix structure, simplicity, low cost of processing, nearer net shape and the wide selection of materials [1–4].

Investigation of mechanical behavior of aluminum alloys reinforced by nano and micro hard particles such as Al_2O_3 and SiC is an interesting area of research. Therefore, the aim of this study is to investigate the effects of different factors such as: (i) particle size (micro and nano Al_2O_3 particles) (ii) weight percentage of the particles (iii) type of fabrication process (stir and compo casting) on the microstructure and mechanical properties of the composites.

2. Experimental procedure

In the current research, A356 alloy and particulate alumina powder with size of 50 nm and 20 μm were used as the matrix and reinforcement phases.

Composite specimens were manufactured by compo- and stir-casting methods using mechanical mixing of the molten alloy. Micro and nano-particles were injected into the melt by argon gas in a graphite crucible inserted in a resistance heating furnace. The magnitude of alumina powder injected into the composites were chosen 1, 3, 5 and 7.5 wt.% micro-alumina and 1, 2, 3 and 4 wt.% nano-alumina. The crucible was equipped with a bottom pouring system. In the case of stir-casting injection temperature was chosen 700 °C and for compo-casting it was 610 °C. Depending on the quantity of the particles added, the injection time was 7 to 15 min. The stirring was continued for 30 min to produce homogenous mixture. The pouring temperature for the two processes was selected 650 °C. The speed of impeller was 300 rpm.

To study the microstructure of the specimens they were cut by an automatic cutter device. The specimen surfaces were prepared by grinding through 600 and 1200 grit papers and then by polishing with 3 μm diamond paste. Microscopic examination of the composites was carried out by optical and scanning electron microscopy.

The porosity volume percent of the composites was determined by comparing the measured density with that of their theoretical density. The Brinell hardness values of the samples were measured on the polished samples using a ball with 2.5 mm diameter at a load of 10 kg.

To investigate the mechanical behavior of the composites the tensile and compression tests were carried out using Zwick 760 testing machine according to ASTM.B 557 and ASTM E9-89a, respectively. The crosshead speed was set at 3 mm/min on the round specimens. Each test was repeated three times to obtain a precise average value for each property.

3. Results and discussion

Fabrication of metal–matrix composites with alumina particles by casting processes is usually difficult because of the very low wettability of alumina particles and agglomeration phenomena which results in non-uniform distribution and weak mechanical properties. In the current work, A356 aluminum alloy matrix composites with micro and nano-size alumina particles were produced by two casting methods (stir- and compo-casing). The chemical composition of A356 aluminum alloy is shown in Table 1. The magnitude of alumina powder used in the composites were 1, 3, 5 and 7.5 wt.% micro-alumina and 1, 2, 3 and 4 wt.% nano-alumina. The optical micrographs of the nanocomposites with 1 wt.% alumina fabricated by stir and compo-casting processes are shown in Fig. 1. The micrographs show that grain size of the reinforced composite (Fig. 1b and c) is smaller than the alloy without alumina particles (Fig. 1a) because, particles act as nucleation sites. In addition, due to the good wettability of particles with melt, the grain size of composite fabricated by compo-cast was smaller than that of fabricated by stir-casting process. The SEM micrographs shown in Fig. 2 indicate distribution of alumina particles in different specimens. Fig. 2a reveal good distribution of particles and very low agglomeration in the nano-composite reinforced with 1 wt.% Al_2O_3, fabricated by compo-casting process. Moreover, the figure indicates that the Al_2O_3 nano-particles have tendency to segregate and cluster at inter-dendritic regions which are surrounded by eutectic silicon (Fig. 2b–d).

The porosity content of micro and nano-composites is shown in Table 2. The volume percent of porosity was measured by comparing the theoretical and experimental densities determined by the Archimedean method [2,3]. The results show that the amount of porosity increases with increasing micro and nano alumina because of pore nucleation at the Al_2O_3 particulate surfaces and decreasing liquid metal flow. Also, in a constant Al_2O_3 percent, the porosity percent of nano-composite is more than micro composite because of the low wettability and more agglomeration and particle clustering of nano-particles. Additionally, the porosity content in composites fabricated by compo-cast process was lower than that of fabricated by stir-casting because of good wettability of particles in compo-cast process.

The stress–strain curves of the nanocomposites are shown in Fig. 3. The main feature of these curves is that the yield stress and tensile strength increase while fracture strain decreases with increasing nano-particle content.

To investigate the strengthening effects of nano and micro-particles on the hardness, tensile and compression properties of the composites such as yield and ultimate strength a model has been proposed which is summarized as bellows [7–9]:

$$\Delta\sigma = \Delta\sigma_{load} + \Delta\sigma_{Hall-Petch} + ((\Delta\sigma_{Orowan})^2 + (\Delta\sigma_{CTE})^2)^{1/2} \quad (1)$$

The shear transfer of load from the soft matrix to the hard ceramic nano or micro reinforcements during tensile and indentation tests, especially when there is a good interfacial integrity between the two phases, is called the load bearing effect, σ_{load} which is represented as [7–9]:

$$\sigma_{load} = 0.5V_p\sigma_{ym} \quad (2)$$

where V_p is the volume fraction of reinforcement nano or micro-particles and σ_{ym} is the matrix yield stress.

The contribution of grain refinement to the strength levels could be discussed on the basis of the classical Hall–Petch equation [10,11]:

$$\Delta\sigma_{Hall-Petch} = K(d)^{-1/2} \quad (3)$$

in which, K is the Hall–Petch coefficient and d is the matrix grain diameter.

The interaction of dislocations with the non-shear-able nano-particles increases the strength of composite samples according to the Orowan mechanism. Due to the presence of the dispersed nano-sized particles in the matrix, dislocation loops form when dislocations pass the particles. σ_{Orowan} can be calculated as [12]:

$$\Delta\sigma_{Orowan} = \frac{0.13Gb}{\delta}\ln\frac{r}{b} \quad (4)$$

Table 1
Chemical composition of A356 aluminum alloy (wt.%).

Composition	Al	Si	Mn	Mg	Zn	Fe	Ti	Ni	P	Pb	Ca
wt.%	93.275	6.104	0.013	0.425	0.063	0.180	0.009	0.006	0.002	0.002	0.005

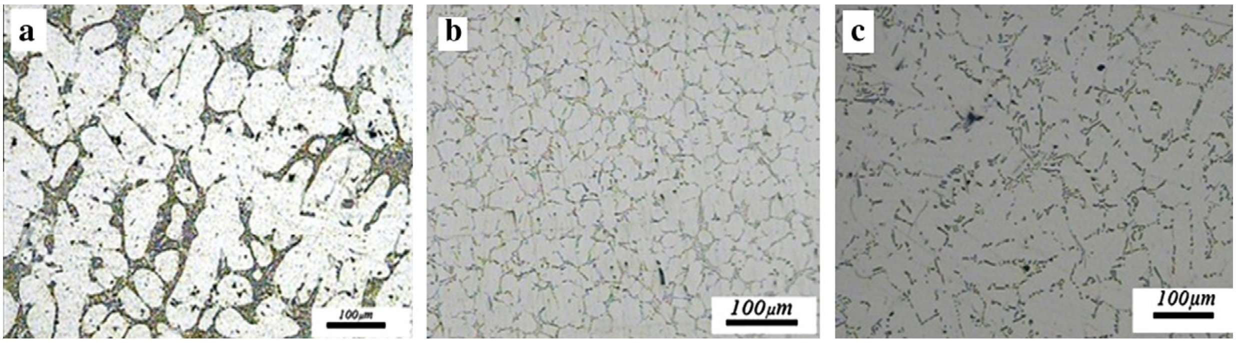


Fig. 1. Optical micrographs of (a) A356 Alloy; (b) A356 reinforced with 1 wt.% nano alumina particles fabricated by compo-casting; and (c) A356 reinforced with 1 wt.% nano alumina particles fabricated by stir-casting process.

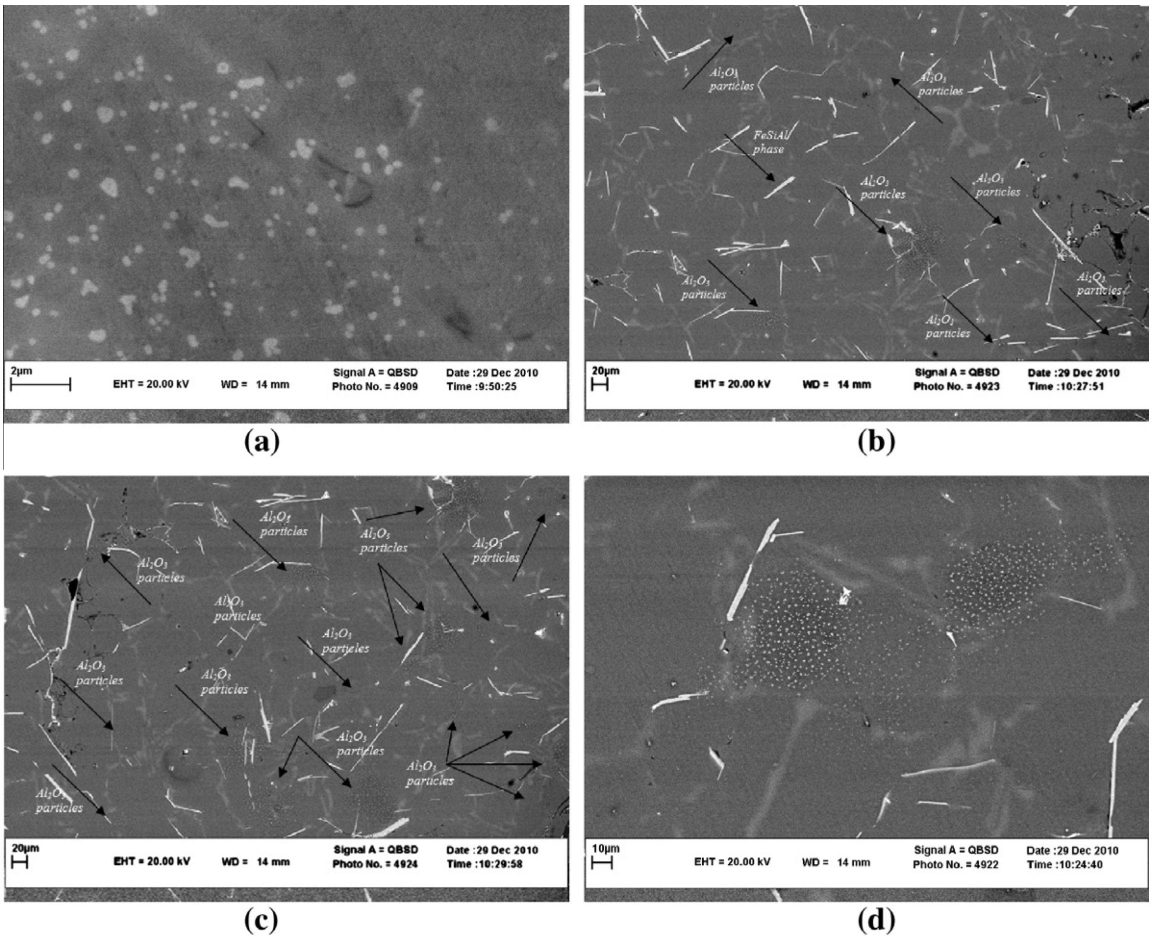


Fig. 2. SEM micrographs of nano-composites reinforced with: (a) 1 wt.% Al_2O_3; (b) 2 wt.% Al_2O_3; (c) 3 wt.% Al_2O_3; fabricated by compo-casting process; and (d) 1 wt.% Al_2O_3; fabricated by stir-casting process.

where *G* is the shear modulus of matrix, *b* is the Burgers vector, δ is the inter-particle spacing, and *r* is the particle radius.

The difference between the coefficient thermal expansion (CTE) values of reinforcement (Al_2O_3) and Matrix (A356 aluminum alloy) generates geometrically necessary dislocations and thermally induced residual stresses. The thermal stresses in the interface of the particles and matrix make the plastic deformation more difficult, and thus enhance the level of hardness and flow stress. The effect of mismatch strain due to the difference between the CTE values of particles and that of the matrix is given by [9]:

Author's personal copy

Table 2
The porosity percent of micro and nano-composite fabricated by compo and stir-casting process.

Micro/nano-composite	Porosity (%) (stir casting)	Porosity (%) (compo casting)
A356	1.11	1.11
A356–1 wt.% micro-Al_2O_3	1.18	1.15
A356–3 wt.% micro-Al_2O_3	2.05	2.05
A356–5 wt.% micro-Al_2O_3	2.90	2.85
A356–7.5 wt.% micro-Al_2O_3	5.6	5
A356–1 wt.% nano-Al_2O_3	1.18	1.12
A356–2 wt.% nano-Al_2O_3	1.62	1.5
A356–3 wt.% nano-Al_2O_3	2.41	2.25
A356–4 wt.% nano-Al_2O_3	–	3.5

Table 3
Ductility of the micro and nano-composites fabricated by compo- and stir-casting process.

Micro/nano-composite	Ductility (%) (stir casting)	Ductility (%) (compo casting)
A356	1.55	1.55
A356–1 wt.% micro-Al_2O_3	1.45	1.48
A356–3 wt.% micro-Al_2O_3	0.94	1
A356–5 wt.% micro-Al_2O_3	0.83	0.87
A356–7.5 wt.% micro-Al_2O_3	0.65	0.7
A356–1 wt.% nano-Al_2O_3	1.31	1.37
A356–2 wt.% nano-Al_2O_3	1.21	1.29
A356–3 wt.% nano-Al_2O_3	1.12	1.19
A356–4 wt.% nano-Al_2O_3	–	0.74

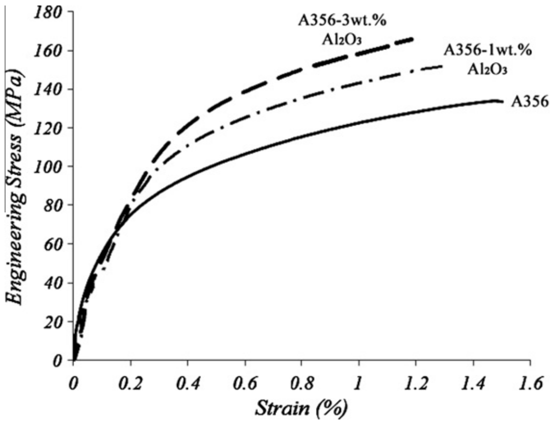


Fig. 3. The tensile stress–strain curves of the nanocomposites, fabricated by compo-casting process.

$$\Delta\sigma_{\mathrm{CTE}} = \sqrt{3}\beta G_m b\sqrt{\frac{24V_{\mathrm{p}}\Delta\alpha\Delta T}{(1-V_{\mathrm{p}})br_{\mathrm{p}}}} \quad (5)$$

where β is the strengthening coefficient, $\Delta\alpha$ is the difference between CTE of reinforcement and that of matrix and ΔT is the difference between the processing and test temperature.

Fig. 4 shows the variation of 0.2% yield strength and ultimate strength of the composites with different nano and micro-Al_2O_3 volume fractions. At first, the yield and ultimate strength of the composite increase with increasing Al_2O_3 content because of increase in load stress (Eq. (2)). The enhancement in tensile strength is partly due to the higher work hardening rate of the particle containing materials [4]. In addition to the grain refinement and particle strengthening, the enhancement of strength is affected by the higher load bearing and mismatch strengthening caused by nano-particles. It is expected that due to the thermal mismatch stress, there is a possibility of increased dislocation density within the matrix during cooling from solidification temperature. The dislocations might lead to making local stress and also to increase in the strength of the matrix and in turn, in the strength of the composite. This stress depends on the temperature from which the composite is cooled. Higher temperature leads to more local stress and to the further increase in the strength of the composite [9].

The great enhancement in the values observed in the composites in comparison to the base aluminum is due to grain refinement according to the Hall–Petch theory (Fig. 1) and the presence of the particles as obstacles that restrict the motion of dislocations in the matrix (Orowan mechanism). In addition, uniform distribution of Al_2O_3 particles confirmed by SEM micrographs (Fig. 2) and low degree of porosity (Table 2) affect the strength of the composites. The parameters cause to the effective transfer of applied tensile load to the uniformly distributed strong Al_2O_3 particulates.

The type of used processes for fabrication of composite in this research (stir- and compo-casting) is an effective factor on the mechanical properties of the composites. The results of the porosity and microstructure study show that the porosity volume percent and grain size in compo-casting is lower than those in stir process because of good wettability of particles in compo-casting

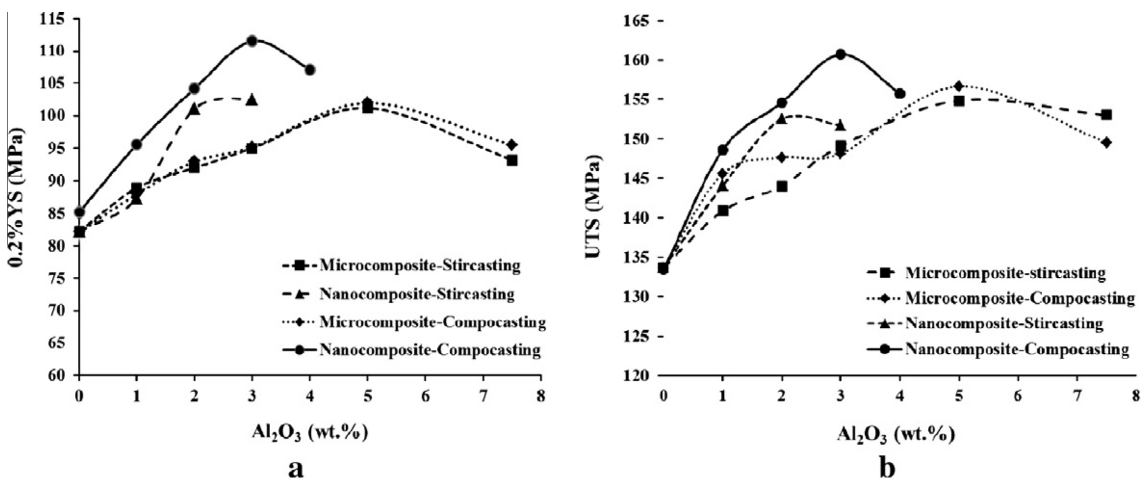


Fig. 4. The variation of (a) 0.2% yield strength; and (b) ultimate strength of the composites with different nano and micro-Al_2O_3 weight fractions fabricated by compo and stir-casting processes.

Author's personal copy

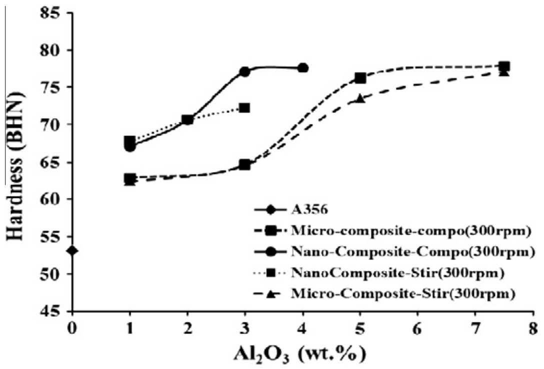


Fig. 5. The hardness variation of the composites fabricated by compo and stir-casting with nano and micro-Al_2O_3 content.

(Table 2 and Fig. 1). The fact has been confirmed by other researchers [2,3]. Consequently, the yield and ultimate strength in compo-casting is greater than stir process.

Moreover, the particle size is one of the important factors in strengthening mechanism. Nano-particles play an important role in the high strength, hardness and ductility of the composites in comparison to micro-particles because of the good interface between nano-particles and matrix [7,8]. They also act as hard obstacles to the motion of dislocation (Eq. (4)). Consequently important point is that the improvement in the yield and ultimate strength of the MMCs increases with decreasing particle size (Fig. 4). This is in agreement with the other researches [7,8]. Thus, nanoparticulate-reinforced MMNCs produce excellent mechanical properties, compared to the counterpart of micro particulate-reinforced MMCs due to a strong cohesion at the atomic level between the matrix and particles. In other words, the nano-sized particles are directly bonded to the matrix [8].

Table 3 shows the results of ductility (elongation percent in stress–strain curves) of the composites. According to the table, ductility increases with decreasing particle size and weight percent. Also, ductility of compo-cast specimens is greater than that of stir-cast samples. The increment of ductility can be attributed to the effects of increase in grain boundary area due to grain refinement (Fig. 1), the strong multidirectional thermal stress at the Al/Al_2O_3 interface, and the effective transfer of applied tensile load to the uniformly distributed enormous number of well-bonded strong nano-Al_2O_3 particulates [1].

The influence of nano and micro particle content on the hardness is depicted in Fig. 5. The observed increase in the hardness levels with increasing weight percent of nano and micro-particles is mainly due to the grain refinement and Hall–Petch mechanism (Eq. (3)) and particle strengthening effects which act as obstacles to the motion of dislocations (Eq. (4)). Also, the results show that the hardness of the composite fabricated by compo-casting process is more than the composite fabricated by stir-casting because of the grain refinement produced during compo-casting, as shown in Fig. 1.

The strength (yield and ultimate) and the hardness also increase with increase in the reinforcement content. However, according to the results of this research, quite significant improvement in strength and hardness is noted when 3 wt.% nano-Al_2O_3 and 5 wt.% micro-Al_2O_3 particles in the case of compo-casting and 2 wt.% nano-Al_2O_3 and 5 wt.% micro-Al_2O_3 particles for stir-casting is added. Further increase in Al_2O_3 content leads to the reduction in strength values. This might be the result of more agglomeration of particles and higher degree of defects and micro-porosity present in the composite at higher Al_2O_3 content. The results are consistent with the trends reported by other investigators [1–4]. It should be mentioned that alumina particles act as potent sites for nucleation of porosities so, with increasing Al_2O_3 content the micro-porosities increase which might lead to the lower flow stress in composite. On the other hand, increasing dislocations and other defects around Al_2O_3 particles due to the difference in thermal expansion coefficients of Al356 and Al_2O_3 (Eq. (5)), might result in debonding of the interface and decrease in UTS in the composites with more Al_2O_3 volume fraction [1,9]. However, different factors could neutralize the effect of each other and thus, the nano-composites

Table 4
Compression strength of nano and micro-composites fabricated by compo- and stir-casting process.

Micro/nano-composite	Compression strength (MPa) (compo casting)	Compression strength (MPa) (stir casting)
A356	234.26	234.26
A356–1 wt.% micro-Al_2O_3	250.65	272.50
A356–3 wt.% micro-Al_2O_3	310.5	348.23
A356–5 wt.% micro-Al_2O_3	390.55	423.45
A356–7.5 wt.% micro-Al_2O_3	437.54	450.12
A356–1 wt.% nano-Al_2O_3	550.80	579.35
A356–2 wt.% nano-Al_2O_3	586.39	601.78
A356–3 wt.% nano-Al_2O_3	595.30	624.78
A356–4 wt.% nano-Al_2O_3	–	630.50

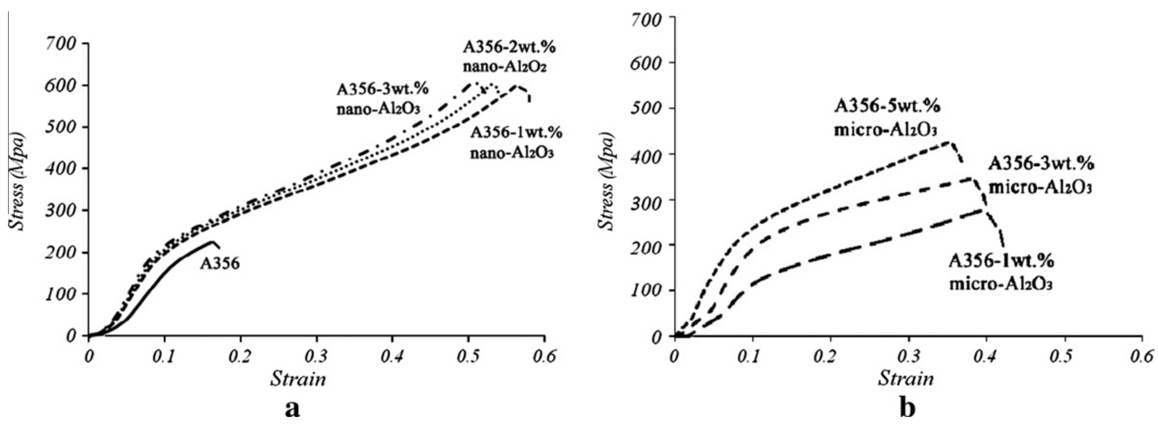


Fig. 6. The compression stress–strain curves of (a) nano and (b) micro-composites fabricated by compo-casting process.

Author's personal copy

containing 4 wt.% Al_2O_3 in the case of compo-casting and 3 wt.% in the case of stir-casting exhibit less UTS than that of the 3 wt.% and 2 wt.%, respectively.

The compression stress–strain curves of the composites are shown in Fig. 6. The compressive strength of a composite can primarily be attributed to: the significant grain refinement, the presence of reasonably distributed hard particulates, dislocation generation due to elastic modulus mismatch and coefficient of thermal expansion mismatch between the matrix and reinforcement phase, load transfer from matrix to reinforcement phase and Orowan strengthening mechanism [13–15].

According to the results obtained from Fig. 6 and Table 4 it can be concluded that the effect of Al_2O_3 content on the compressive strength is considerable. Although increasing the content of Al_2O_3 increases the content of porosity (Table 2), the compressive strength shows an increasing trend. This confirms the obvious effect of Al_2O_3 particles on strengthening of the composites.

The results presented in Table 4 show that the compression strength of nano-composites is greater than that of micro-composites because, nano-particles are more effective in strengthening of the composites. Moreover, compression strength of composites fabricated by compo-casting is more than that of composites fabricated by stir-casting because of the effect of grain size.

4. Conclusions

In the current research, micro- and nano-composites were fabricated using stir- and compo-casting processes and effects of different fabrication parameters on microstructure and mechanical properties were investigated. The following results were obtained:

1. The SEM micrographs show good distribution of particles and very low agglomeration of alumina produced by compo-casting method.
2. The stress–strain curves show that the yield strength and tensile strength increase while fracture strain decreases with increasing nano-particle content.
3. The yield, ultimate and compression strength of the composite increase with increasing Al_2O_3 content because of increase in load stress.
4. The type of used processes for fabrication of composites in this research (stir- and compo-casting) was an effective factor on the mechanical properties. The porosity and microstructure results showed that the porosity percent and grain size in compo-casting was lower than stir-casting process because wettability of particles in compo-casting was better than stir-casting process.
5. Increasing of hardness with increasing weight percent of nano and micro-particles is mainly due to grain refinement and particle strengthening effects.
6. The significant improvement in strength and hardness is noted when 3 wt.% nano-Al_2O_3 and 5 wt.% micro-Al_2O_3 particles for compo- and 2 wt.% nano-Al_2O_3 and 5 wt.% micro-Al_2O_3 particles for stir-casting is added; further increase in Al_2O_3 content leads to the reduction in strength values.
7. Ductility increased with decreasing particle size and particle percent. Also, ductility of compo-casting was greater than stir-casting samples.

Acknowledgments

The authors wish to express appreciation to Research deputy of Ferdowsi University of Mashhad for supporting this project by Grant No.: 10449-10/9/88. Also, we acknowledge the careful assistant work of H. Beygi and H. Sadeghi who participated in the process.

References

[1] Vencl A, Bobic I, Arostegui S, Bobic B. Structural, mechanical and tribological properties of A356 aluminium alloy reinforced with Al_2O_3, SiC and SiC + graphite particles. J Alloys Compd 2010;506:631–9.
[2] Sajjadi SA, Ezatpour HR, Beygi H. Microstructure and mechanical properties of Al–Al_2O_3 micro and nano composites fabricated by stir casting. In: Proceedings of 14th national conference on Materials Science and Engineering, Tehran, Iran; 2010. p.325–32.
[3] Sajjadi SA, Torabi Parizi M, Ezatpour HR, Sedghi A. Fabrication of A356 composites reinforced with micro and nano Al_2O_3 particles by a developed compocasting method and study of their properties. J Alloys Compd 2011, accepted for publication.
[4] Mazahery A, Abdizadeh H, Baharvandi HR. Development of high-performance A356/nano-Al_2O_3 composites. Mater Sci Eng A 2009;518:61–4.
[5] Kok M. Production and mechanical properties of Al_2O_3 particle-reinforced 2024 aluminum alloy composites. J Mater Process Technol 2005;161:381–7.
[6] Sevik H, Can Kurnaz S. Properties of alumina particulate reinforced aluminum alloy produced by pressure die casting. Mater Des 2006;27:676–83.
[7] Zhang Z, Chen DL. Contribution of Orowan strengthening effect in particulate reinforced metal matrix nanocomposites. Mater Sci Eng A 2008;483–484:148–52.
[8] Zhang Z, Chen DL. Consideration of Orowan strengthening effect in particulate reinforced metal matrix nanocomposites: a model for predicting their yield strength. Scr Mater 2006;54:1321–6.
[9] Habibnejad-Korayem, Mahmudi R, Poole WJ. Enhanced properties of Mg-based nano composites reinforced with Al_2O_3 nano-particles. Mater Sci Eng A 2009;519:198–203.
[10] Hertzberg Richard W. Deformation and fracture mechanics of engineering materials. John Wiley & Sons, Inc.; 1996.
[11] Hall EO. Proc Phys Soc Lond 1951;64B:747–53.
[12] Ashby MF. Proceedings of the second bolton landing conference on oxide dispersion strengthening. New York: Gordon and Breach, Science Publishers Inc.; 1968.
[13] Ansary Yar A, Montazerian M, Abdizadeh H, Baharvandi HR. Microstructure and mechanical properties of aluminum alloy matrix composite reinforced with nano-particle MgO. J Alloys Compd 2009;484:400–4.
[14] Nguyen QB, Gupta M. Enhancing compressive response of AZ31B using nano-Al_2O_3 and copper additions. J Alloys Compd 2010;490:382–7.
[15] Sastry S, Krishnab M, Uchil J. A study on damping behaviour of aluminite particulate reinforced ZA-27 alloy metal matrix composites. J Alloys Compd 2001;314:268–74.