ScienceDirect

Journal of Alloys and Compounds
Volume 784, 5 May 2019, Pages 1047-1061

Production of aluminum alloy-based metal matrix composites using scrap aluminum alloy and waste materials: Influence on microstructure and mechanical properties

Pradeep Kumar Krishnan [a], John Victor Christy [b], Ramanathan Arunachalam [c], Abdel-Hamid I. Mourad [b], Rajaraman Muraliraja [d], Majid Al-Maharbi [c], Venkatraman Murali [a], Majumder Manik Chandra [e]

Show more

Share Cite

https://doi.org/10.1016/j.jallcom.2019.01.115
Get rights and content

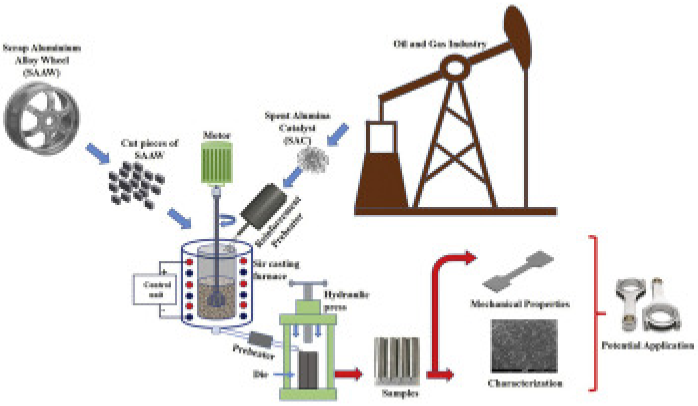
Highlights

- A novel approach used to produce metal matrix composites from waste materials.
- The alumina reinforcement combines with the eutectic silicon to form a mixture.
- Acicular, blunted, needle-like mixture morphology improves mechanical properties.
- Enhanced ultimate tensile (125 MPa) and compressive strength (312 MPa) obtained.

Abstract

In the present study, aluminium metal matrix composites (AMCs) were successfully produced through stir-squeeze casting using a novel approach. The feasibility of using car scrap aluminium alloy wheels (SAAWs) as the matrix material and spent alumina catalyst (SAC) from oil refineries as reinforcement material was investigated. For the purpose of comparision, composites were also produced using AlSi7Mg (LM25 grade) aluminium alloy as a matrix and alumina as reinforcement particles through the stir-squeeze casting process. In total, four different combinations of composites (AlSi7Mg+alumina; scrap aluminium alloy+alumina; AlSi7Mg+spent alumina catalyst; scrap aluminium alloy+spent alumina catalyst) were produced and characterized. Microstructural investigations using an optical microscope and a scanning electron microscope (SEM) as well as energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) revealed that in all four composites the reinforcement formed a mixture in the eutectic silicon phase of the matrix alloy. The alumina particles' size and content ratio greatly influenced this mixture's formation and morphology. The composites produced using alumina exhibited smaller pore sizes and lower porosity as compared to the composites produced with a spent alumina catalyst. Superior mechanical properties were also obtained when using alumina as reinforcement, and better mechanical properties can mainly be attributed to the morphology of the reinforcement and silicon eutectic phase mixture. The scrap aluminium alloy+alumina exhibited the lowest porosity (7.3%) and abrasive wear loss (0.11 mg for the finest abrasive), highest hardness (58.5 BHN), and second highest ultimate tensile strength (UTS) (125 MPa) and ultimate compressive strength (UCS) (312 MPa) among the four composites.

Graphical abstract



Download: Download high-res image (204KB)

Download: Download full-size image

Introduction

Aluminum is widely available in the Earth's crust and accounts for about 8% by weight of the Earth's stable surface. Its properties, such as high strength-to-weight ratio, ductility, durability, etc., and abundant availability have attracted researchers and caused industries to prefer it. For these reasons, global aluminum demand has increased [1]. By 2020, worldwide consumption of aluminum products is expected to double, driven by the growth and industrialization in China, India, Russia, and Brazil according to Alcoa's 2005 Annual Report. Fuel savings of 5–7% can be realized for every 10% weight reduction by substituting aluminum for heavier steel through appropriate design [2]. Although aluminum exhibits a high strength-to-weight ratio, it can be further improved by adding reinforcements such as ceramic particles resulting in a metal matrix composite (MMC). The synthesis of cast aluminum metal matrix composite with ceramic particles reinforcement dates back to 1965 when Pradeep Rohatgi discovered it [3]. Since then, many researchers have investigated the development and characterization of metal matrix composites. Over the past three decades, metal matrix composites have moved from research to commercial applications. The worldwide metal matrix composite markets as of 2004 required more than 3500 metric tons and are increasing rapidly, with an annual growth rate exceeding 6% [3]. Metal matrix composites' functional properties, including high structural efficiency, excellent wear resistance, and attractive thermal and electrical characteristics, have enabled their application in ground transportation, including auto and rail; thermal management; and the aerospace, recreational, and infrastructure industries [4]. Metal matrix composites have also been commercialized in a large number of high-performance applications [3]. Currently, metal matrix composites are used in automotive applications, including in cylinder liners, pistons, connecting rods, camshafts, tappets, brake calipers and rotors, and much more. However, the cost of these high-performance components is still high, and they are not widely used. Several approaches could be taken to reduce the cost of composites such as single-step mixing, opting for selective reinforcements, and using cheaper reinforcements [5]. A few researchers in Oman have investigated using spent catalyst waste for producing building materials, but the added value of such applications is quite low when compared to using the waste in high-performance applications such as in components for automotive industries [6,7]. Spent alumina catalyst, for example, mainly consists of alumina (71.38 wt %) so could be easily used as a reinforcement for producing aluminum metal matrix composite reinforced with alumina [6]. Around 200–500 kg of waste spent alumina catalyst is produced daily in oil refineries in Oman and pose an environmental threat [6].

Aluminium production involves very high energy consumption because its production is based on an electrolytic reduction process involving very high current [8]. It has been estimated that 20–40% of the cost of production can be accounted for by the electric power consumed during production [9]. Hence, the present approach is environmentally friendly because scrap aluminium alloy wheels were used as the matrix material for producing aluminum metal matrix composite. It has been suggested that recycling aluminum could eliminate more than 94% of the impact of global warming and fossil fuel depletion as compared to producing aluminium as a primary processes [8]. Also, transmuting waste materials into value-added composite materials to be used for different applications results in the conservation of natural resources. Economic benefits also result from the reduced cost associated with using scrap materials.

Aluminum metal matrix composites are normally produced by the established route of stir casting [10]. Although stir casting is an economical process for producing casted components, they suffer from porosity issues, which prevents their use for producing high-strength components. To overcome this issue, researchers have adopted squeeze casting. Among the metal matrix composites produced, aluminum and silicon carbide (SiC) are the most commonly investigated matrix and reinforcement materials, respectively [11,12]. Although alumina (Al_2O_3) exhibits similar properties, researchers have made relatively few attempts to develop metal matrix composites using alumina as compared to SiC. Two different metal matrix composites with the matrix-reinforcement combinations of Al6061-SiC (20 μm) and Al7075- alumina (20 μm) have been produced through stir casting [12]. The researchers recommended particle reinforced composites over fiber reinforced ones for the advantages of lower cost and better plastic forming capability as well as excellent heat and wear resistance. The Al7075- alumina composite was found to exhibit better mechanical properties than Al6061-SiC because the Al7075 matrix was found to possess better mechanical properties than the Al6061. Sajjadi and Beygi produced aluminum metal matrix composites reinforced with both micro and nano alumina particles using a bottom tapping squeeze casting facility [13]. Even though nanoparticle-reinforced metal matrix composites exhibited better mechanical properties, they had issues of agglomeration while the micron particles were uniformly dispersed in the matrix. Sajjadi and co-workers [14] investigated the microstructure and mechanical properties of aluminium - alumina micro and nanocomposites produced by squeeze casting. The researchers adopted a novel three-step mixing method that helped to improve the incorporation and uniform distribution of the nano reinforcement particles. Best mechanical properties were obtained at smaller alumina particle sizes. Yigezu and co-workers compared the performance of an aluminium alloy (AlCu4Mg2.5) reinforced with both alumina (50 μm) and SiC (50 μm) metal matrix composite produced by stir casting [15]. In terms of mechanical properties like UTS, the SiC-reinforced composite performed better than the alumina although in terms of ductility the alumina performed better. This trend can mainly be attributed to the ductile nature of the fracture in the alumina-reinforced composite, while in the SiC-reinforced composite the weak intermetallic phase Al_4C_3 formed resulted in brittle fractures. Abhishek and co-workers produced and characterized a A359/alumina metal matrix composite using an electromagnetic squeeze casting method [16]. The tensile strength of the cast composites increased with the increase in the weight fraction of alumina. Tahamtan and co-workers studied the effects of alumina reinforcing particle size (10 μm and 100 nm) in an Al-A206 matrix produced through semi-solid and liquid states [17]. The reinforcement was added in two different forms: as received alumina particles and in a pre-synthesized composite that was prepared by milling alumina with aluminium and magnesium powders. The researchers recommended adding the reinforcement in pre-synthesized forms rather than as received because the thinner interfacial reaction layer has been found to produce better tensile properties. Also, the researchers found that composites produced through a liquid state exhibited higher porosity when compared to the semi-solid state. In the liquid state during stirring, the vortex formed created turbulence which resulted in the entrapment of air resulting in higher porosity. The nanometer reinforced alumina exhibited better ultimate tensile strength (UTS) when compared to the micron-sized reinforced composite because of the fracture occurring through particle debonding. Heat treatment of 1 wt % of alumina in aluminum metal matrix composites resulted in significant improvement in mechanical properties such as hardness and compressive strength [18]. Similar to the work of Kumar and co-workers Lakshmipathy and co-workers produced metal matrix composites through stir casting but changed the matrix combinations to 7075Al/SiC and 6061Al/alumina [12,19]. The researchers mainly focused on the reciprocating wear behavior of metal matrix composites with three different reinforcement weight percentages (10, 15, and 20%) of SiC and Al_2O_3 having a size of 36 μm. An increase in the weight percentage of reinforcements resulted in higher hardness but the impact strength decreased. Maximum hardness of 50 Brinell hardness number (BHN) was recorded for the Al7075-20%SiC while the Al6061-20% alumina exhibited a lower value (37 BHN). Similarly, the wear resistance of Al7075-SiC composites was greater than that of Al6061- alumina which was mainly due to the lower volume loss because Al7075's matrix had a higher hardness. Microsized SiC and alumina have also been used together as reinforcement in aluminum metal matrix composites at different proportions to improve mechanical properties [20].

Based on the literature reviewed, all research on producing aluminum metal matrix composites by squeeze casting has used virgin matrices and reinforcement materials. This proposed research approach is novel, therefore, because for the first time aluminum metal matrix composite was produced using scrap aluminium alloy as a matrix and spent alumina catalyst from oil refinery waste as reinforcement material. The scrap aluminium alloy (chemical formula: AlSi4Mg3Mn2Fe1) closely resembled 6000-series aluminum alloy, with the most prevalent alloying elements being silicon, magnesium, manganese, and iron. The chemical composition is illustrated in Table 1. For comparision purposes, both virgin aluminium alloy grade AlSi7Mg and alumina were used as matrix and reinforcement materials, respectively. In this research work, four different aluminum metal matrix composites were produced using a squeeze-casting process and subjected to both material and mechanical property characterizations using different techniques.

Section snippets

Matrix and reinforcement materials

AlSi7Mg alloy billets and aluminium from scrap aluminium alloy were selected as matrix materials, and alumina and spent alumina catalyst were selected as reinforcing materials for developing the composites. The elemental composition of scrap aluminium alloy and spent alumina catalyst (Table 1) was determined through X-ray fluorescence (XRF) and energy dispersive X-ray spectroscopy (EDS) analysis, respectively [6]. The alumina powder (Alfa Aesar, Germany) was of high chemical purity with an …

Microstructural analysis

The optical microscopic images for the four different composites at 200× magnification are shown in Fig. 1. In the pictures, grey particles are a mixture of both the reinforcement and the eutectic phase of silicon, white regions are aluminium matrix, and black regions are porous defects. All microstructures exhibited an almost non-dendrite shape at the grain boundaries because of the squeeze pressure, which resulted in finer dendrites and decreased dendrite arm spacing [23]. Fig. 1(a) and (b) …

Conclusions

A novel approach was successfully utilized for the first time to produce aluminum metal matrix composites for potential industrial applications. The produced aluminum metal matrix composite is not only economical but also environmentally friendly because it uses scrap or waste materials. The key findings are summarized as follows:

- The micrograph analysis showed that the scrap aluminium alloy+alumina composite had a uniform distribution of reinforcements and the lowest porosity among the four …

…

Declaration of interest

None. …

Acknowledgement

The authors thank Sultan Qaboos University (SQU), Sultanate of Oman and the United Arab Emirates University (UAEU), Al-Ain, United Arab Emirates for providing research support through collaborative research project (SQU: CL/SQU-UAEU/17/04 and UAEU: 31N270). The Central Analytical and Applied Research Unit (CAARU) in SQU is acknowledged for providing support through analytical facilities such as SEM, XRF and XRD reported in this manuscript. The Surface Science Lab (SSL) in SQU is also …

Recommended articles

References (48)

N. Gangil *et al.*
Aluminium based in-situ composite fabrication through friction stir processing: a review
J. Alloys Compd. (2017)

J. Cui *et al.*
Recycling of automotive aluminum
Trans. Nonferrous Met. Soc. China (English Ed. (2010)

D.B. Miracle
Metal matrix composites - from science to technological significance
Compos. Sci. Technol. (2005)

H. Al-dhamri *et al.*
Use of alumina spent catalyst and RFCC wastes from petroleum refinery to substitute bauxite in the preparation of Portland clinker
J. Hazard. Mater. (2010)

Y. Zhang *et al.*

Environmental footprint of aluminum production in China
J. Clean. Prod. (2016)

A. Kumar *et al.*
Simultaneous improvement of mechanical strength, ductility and corrosion resistance of stir cast Al7075-2% SiC micro- and nanocomposites by friction stir processing
J. Manuf. Process. (2017)

S.A. Sajjadi *et al.*
Microstructure and mechanical properties of Al-Al2O3 micro and nano composites fabricated by stir casting
Mater. Sci. Eng. A (2011)

S.A. Sajjadi *et al.*
Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al2O3 composites fabricated by stir and compo-casting processes
Mater. Des. (2012)

M. Hossein-Zadeh *et al.*
Structural and mechanical characterization of Al-based composite reinforced with heat treated Al2O3 particles
Mater. Des. (2014)

J. Lakshmipathy *et al.*
Reciprocating wear behavior of 7075Al/SiC in comparison with 6061Al/Al 2O3 composites
Int. J. Refract. Met. Hard Mater. (2014)

View more references

Cited by (176)

2021, Journal of Hazardous Materials

Show abstract

Processing, Properties, and Microstructure of Recycled Aluminum Alloy Composites Produced Through an Optimized Stir and Squeeze Casting Processes

2020, Journal of Manufacturing Processes

Show abstract

A review on aa 6061 metal matrix composites produced by stir casting ↗

2021, Materials

Parameters of Porosity and Compressive Strength-Based Optimization on Reinforced Aluminium from the Recycled Waste Automobile Frames ↗

2021, Advances in Materials Science and Engineering

Optimization of stir–squeeze casting parameters for production of metal matrix composites using a hybrid analytical hierarchy process–Taguchi-Grey approach ↗

2020, Engineering Optimization

View all citing articles on Scopus ↗

View full text

ELSEVIER