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Microstructure, mechanical analysis and optimal selection of 7075 aluminum alloy based composite reinforced with alumina nanoparticles

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HIGHLIGHTS

- Injection Al/Al_2O_3 powder is benefit way for improving nanoparticles distribution.
- Nanocomposites present superior mechanical properties.
- Extrusion process improved significantly mechanical properties of nanocomposites.
- Preference Selection Index is a simple and benefit method in material selection.

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ABSTRACT

Aluminum metal-matrix nanocomposites (AMMNCs) fabricated by conventional stir-casting process usually show high porosity and poor distribution of nanoparticles within the matrix. In the current study, for the improvement of nanoparticles distribution in the aluminum matrix and enhancement of the mechanical properties, a mixture of Al/nano-Al_2O_3 powders were injected by pure argon gas into the molten 7075 aluminum alloy and this mixture was extruded at high temperature. Mechanical behavior of the final product was investigated by tensile and compression tests, hardness measurements, Scanning Electron Microscopy (SEM), High Resolution Transmission Electron Microscopy (HRTEM) and Optical Microscopy. This nanocomposite exhibited some superior properties such as a fine grain microstructure and a reasonable uniform distribution of nanoparticles in the matrix. Mechanical experiments results confirmed that the addition of Al_2O_3 nanoparticles and the extrusion process effectively improved ultimate tensile strength, compression strength and hardness. In next step, we used a Preference Selection Index (PSI) materials selection method to select best combination of strength and workability of Al7075–Al_2O_3 nanocomposites. By this method, extruded Al7075/0.4 and 0.8 wt % Al_2O_3 has best combination of strength and workability.

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1. Introduction

Aluminum alloy 7075, a cold finished aluminum wrought product, has the highest strength of all aluminum screw machine alloys. Because of its extremely high strength, this alloy is used for highly stressed structural parts including aircraft fittings, gears and shafts and various other commercial aircraft, aerospace and transportation equipment [1]. Therefore, mechanical behaviors of this class of materials under constant and spectrum loadings are becoming considerably remarkable in the selection of appropriate alloys for industrial purposes [2]. Furthermore, there are still several attempts and researches in order to improve the mechanical strength of AA 7075 by different methods such as the addition of additives [3]. Typically most of the additives considered in this sphere are ceramics such as oxides, nitrides and carbides, due to their stability at high temperatures and the unique strength and

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stiffness [4]. However, most of the researches in this field were restricted to the investigation of matrix/micron particles [3,4]. Meanwhile, smaller submicron particles, particularly nano-sized particles, are more beneficial and influential for the production of high performance composites [2]. Mobasherpour et al. [2] reported that the hardness and the ultimate tensile strength of AA7075 reinforced with Al_2O_3 nanoparticles boomed dramatically by increasing the fraction of Al_2O_3.

Aluminum metal matrix nanocomposites reinforced with ceramic particulates provide intrinsic characteristics including high specific strength, high thermal conductivity, low coefficient of thermal expansion, creep and fatigue resistance that make them ideal candidates for aerospace and transportation industries [5,6]. Nano-sized ceramic particles, as reinforcement, strengthen the matrix with maintaining good ductility [7–10]. The key factor for the enhancement of properties lie in the nature of bonding of Aluminum/Ceramic interfaces [11,12].

Powder metallurgy, stir casting and squeeze casting are three conventional approaches for the production of aluminum/ceramic composites and each one is accompanied with its privileges and drawbacks [13]. Casting technique as one of the fabrication methods for metal matrix composites is the most economical approach for the manufacturing of these composites [14,15]. In casting technique, mechanical stirring process is famous and has some significant advantages, including applicability to wide range of materials, easier control of matrix structure, simple and inexpensive, flexibility, feasibility and excellent productivity for near-net shaped components [16].

However, there are some problems associated with stir-casting of MMCs such as, poor wettability, agglomeration and non-homogeneous distribution of the reinforcement in matrix [14–17]. There are some methods to improve the wettability of the reinforcement particles within the molten matrix alloy such as heat treatment of the ceramic particles before dispersion into the melt [17], injection of the particles with an inert carrier into the melt [17,18] and using ultrasonic vibration for dispersing nanoparticles in the melt [19]. Moreover, there are some other difficulties in the manufacturing of Al/Ceramic composites. For a tangible instance, some profound researches have been conducted by Bhushan et al. [3] in the characterization of AA7075 reinforced with SiC particulates, and the major issue in the aforesaid study was the formation of Al_4C_3 and Si at the interface that will result in exacerbation of mechanical properties. In order to prevent the formation of such detrimental compounds and elements in the interface, they have suggested the addition of alloying elements like Mg. Dasgupta et al. [20], Reda et al. [21] and Kim et al. [22] also did some studies on the various properties of AA 7075 composites distinctively. They reported that the hardness, wear resistance and tensile properties of the pre-aged composites ameliorated noticeably. Amongst the various classical metal-forming methods, extrusion process is commonly used as a secondary procedure that can result in the betterment of mechanical properties of MMCs [23].

Multiple criteria decision making (MCDM) methods are used to salve of problems in the presence of multiple conflicting criteria and divided by two main groups, multi objective decision making (MODM) and multiple attribute decision making (MADM) techniques [24,25]. In most of MADM techniques, the selection of the optimal material for given applications is made from the available alternatives based on their prioritized attributes while requires many complex calculations [26]. In the past, researchers usually reported the selection of materials based on classical MADM methods such as: Simple Additive Weighted (SAW) method [27], Weighted Product Method (WPM) [28], Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [29], Elimination and Et Choice Translating Reality (ELECTRE) [24], Analytic Hierarchy Process (AHP) [25], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [28], Complex Proportional Assessment (COPRAS) [30,31], COPRAS-G [32], Graph Theory and Matrix Representation Approach (GTMA) [27], VIse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method [25] and etc. Recently Preference selection Index method (PSI), a systematic scientific method or tool for design engineers, was developed by Maniya and Bhatt [33] as a new approach for solving the multi-attribute decision making problems. PSI has a distinct advantage over general ranking methods because, there is no need to assign a relative importance or priorities between material options or their attributes and design goals; hence the bias that is usually associated with other materials selection methods is eliminated. However, the overall preference values of such attributes are calculated using simple statistics. Using overall preference value, by calculating a preference selection index (I_i) for each alternative, each alternative with the higher PSI index value deemed the best option. Moreover, there is no requirement of computing the weights of attributes and results are obtained with minimum and simple calculations. Another advantage of PSI is its ability to rank the candidate materials for any given application and any number of attributes.

In this study, we employed a novel fabrication method for manufacturing of products, including injection of Al/Al_2O_3 nanocomposite powder within the molten AA 7075 by use of pure argon gas, mechanical stirring and then hot extrusion process. The role of the reinforcement additive and hot extrusion process on the tensile and compressive properties of the fabricated nanocomposites were investigated. Finally, we select best combination of strength and workability of $Al7075–Al_2O_3$ nanocomposites using Preference Selection Index (PSI) materials selection method.

2. Materials and methods

In $A7075/Al_2O_3$ nanocomposites, A7075 alloy as matrix (chemical composition is shown in Table 1), and nano-Al_2O_3 particles with the average size of 50 nm as reinforcement were used.

Aluminum matrix nanocomposites were produced by combinational stir-casting process (Fig. 1), while aluminum (μm) and alumina (nm) powders were mixed and injected into the molten aluminum by argon gas during mechanical stirring. Mechanical milling of Al/Al_2O_3 powders led to a uniform distribution of nanoparticles before injection (Fig. 2). Mechanical milling was performed by a planetary ball milling machine. The weight percent of consumed alumina powder was 0.4, 0.8 and 1.2. The powder injection temperature was fixed at 750 °C and the injection time was set between 7 and 20 min in accordance with the quantity of the injected particles. After injection, the stirring was maintained for 30 min to reach a homogenous mixture. The impeller speed and pouring temperature were set 450 rpm and 650 °C, respectively.

After production of the composite casting bars, for improvement of mechanical properties, the extrusion process was carried out by a hydraulic press with the maximum load capacity of 25 ton at constant speed of 50 mm/min, and the extrusion ratio ($\eta = (D_1/D_0)^2$) was 3.5. The die shapes and dimensions are shown in Fig. 3 and Table 2, respectively. Microscopic observations of the specimens were done by optical and scanning electron microscopy (Models: SEM JEOL 6360 and FE SEM F7600) and high resolution

Table 1
Chemical composition of 7075 Aluminum alloy (wt %).

Si	Fe	Cu	Mn	Mg	Cr	Zn	V	Bi	Al
0.4	0.5	1.2	0.3	2.1	0.18	0.2	5.5	0.2	Reminder

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