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ORIGINAL ARTICLE

Preparation and characterization of squeeze cast-Al–Si piston alloy reinforced by Ni and nano-Al_2O_3 particles

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Abstract Al–Si base composites reinforced with different mixtures of Ni and nano-Al_2O_3 particles have been fabricated by squeeze casting and their metallurgical and mechanical characterization has been investigated. A mixture of Ni and nano-Al_2O_3 particles of different ratios was added to the melted Al–Si piston alloy at 700 °C and stirred under pressure. After the Al-base-nano-composites were fabricated by squeeze casting, the microstructure and the particle distribution inside the matrix have been investigated using optical and scanning electron microscopes. Moreover, the hardness and the tensile properties of the resulted Al-base-nano-composites were evaluated at room temperature by using Vickers hardness and universal tensile testers, respectively. As a result, in most cases, it was found that the matrix showed a fine eutectic structure of short silicon constituent which appeared in the form of islands in the α-phase around some added particle agglomerations of the nano-composite structures. The tendency of this structure formation increases with the increase of Ni particle addition. As the ratio of the added particles increases, the tendency of these particles to be agglomerated also increases. Regarding the tensile properties of the fabricated Al-base-nano-composites, ultimate tensile strength is increased by adding the Ni and nano-Al_2O_3 particles up to 10 and 2 wt.%, respectively. Moreover, the ductility of the fabricated composites is significantly improved by increasing the added Ni particles. The composite material reinforced with 5 wt.% Ni and 2 wt.% nano-Al_2O_3 particles showed superior ultimate tensile strength and good ductility compared with any other added particles in this investigation.

1. Introduction

Aluminum–silicon alloys and their metal matrix composites have found applications in the manufacturing of various automotive engine components such as cylinder blocks, pistons and

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piston insert rings where adhesive wear (or dry sliding wear) is a predominant process (Deuis et al., 1997; Prasad and Krishna, 2011; Chen et al., 1997; Rajnovic and Sidjanin, 2007). However, most Al–Si alloys are not suitable for high temperature applications because tensile and fatigue strengths are not as high as desired in the temperature range of 500–700 °C (Yasmin et al., 2004). The pistons for high-speed engines are primarily made of aluminum alloys which contain about 11–13% silicon and approx. 1% each of copper, nickel and magnesium (Cheng et al., 2010). Moreover, the strength of aluminum–silicon materials can be increased by locally casting-in ceramic short fibers, thin single crystalline fibers (whiskers), or porous metallic parts (Cheng et al., 2010). These materials are called metal matrix composites (MMCs).

Al-based MMCs, reinforced with ceramics or metallic particles were developed as an alternative to materials with superior strength – weight and strength – cost ratios, high stiffness, and excellent thermal stability, which have great effects on improving wear, creep and fatigue resistance. Selecting reinforcement remains one of the most critical factors in realizing the best properties from the resultant MMCs. The widely used particles for reinforcing Al alloys are alumina (Al_2O_3) and silicon carbide (SiC). Besides their high hardness, they show low density and low cost compared with other reinforcements. In the past two decades, the wear resistance of the aluminum alloys reinforced with Al_2O_3 and SiC in many forms (particles, whiskers and fibers) and sizes has been described by a huge body of publications such as automotive, aerospace and military industries (Mahmoud et al., 2008, 2009, 2010; Mahadevan and Gopal, 2008; Sajjadi et al., 2012).

However, the poor toughness and the extra cost of metal matrix composites relative to aluminum alloys impose serious restrictions on their applications, especially at high volume fractions of the reinforcement (Zhang et al., 2002). Increasing the reinforcement volume fraction of the MMCs can significantly improve the strength and stiffness of the composites on one hand, but it drastically decreases the toughness and ductility on the other hand (Saha et al., 2002). This can be attributed to an increase in the severity of the triaxiality of stress in the matrix, which results in an earlier onset of void nucleation in the matrix and at the particle/matrix interface (Saha et al., 2002). It is widely recognized that the mechanical properties of metal matrix composites (MMCs) are controlled by the type, size, and volume fraction of the reinforcement phase(s), and the nature of the matrix-reinforcement interface. Superior mechanical properties can be achieved when fine, thermally stable and hard reinforcement(s) with good and clean interfacial bonding are dispersed uniformly in the metal matrix (Jiang et al., 2009). Such characteristics can be obtained when the size of the reinforcement phase(s) is reduced to lower than 1 μm. These materials are called "metal matrix nanocomposites" (MMNCs).

"Metal matrix nano-composites" (MMNCs) provide a new family of MMCs that contain particulate reinforcement of particle size ranging from 10 nm to 1 μm that are dispersed uniformly in the matrix, which possess not only high specific strength and excellent wear properties, but also good ductility and high fracture (Wu and Li, 2010; Silva, 2006; Yang and Li, 2007). Carbon nano-tubes, silica, aluminum oxide, titanium dioxide, zinc oxide, silicon carbide, polyhedral oligomeric silsesquioxanes (POSS) are examples for nano-particle fillers (Yang and Li, 2007). In the last two decades, metal matrix nanocomposites have witnessed tremendous growth, especially in the automotive industry for their capability to withstand high temperature and pressure conditions (Wu and Li, 2010).

A variety of methods for producing MMNCs on industrial scale have been developed, including powder metallurgy (PM) (Kang and Chan, 2004; Ma et al., 1996), high-energy milling (Sherif and Eskandarany, 1998; He et al., 1998) and severe plastic deformation (Valiev et al., 2000; Alexandrov et al., 1998), which is considered as solid state processing. The major critical problems facing these processes are contamination results from powder preparation and complexity of fabrication steps. Moreover, machining is required to obtain the desired final shape. The other group of the fabrication processes of MMNCs is the liquid-state processing, which includes infiltration techniques, stirring techniques, rapid solidification, as well as some in situ fabrication such as liquid–gas bubbling (Yu, 2010). These processes offer some advantages compared with the solid-state processing such as energy-efficient and cost-effective (Yu, 2010). However, reinforcement non-homogeneous distribution or particle agglomeration in the molten matrix and during solidification, and pore formation are considered the critical problems facing the fabrication of MMNCs by liquid-state processes (Yu, 2010). One of the liquid state processes that can be utilized in producing MMNCs is the Squeeze casting. In this process, the applied pressure and the instantaneous contact of molten metal with the die surface produce rapid heat transfer that yields a porous free casting with mechanical properties approaching the wrought product (Yu, 2010).

Piston is the key part of the engine as it works under high temperature, high pressure, corrosive and wearing conditions while running with high speed (Wu and Li, 2010). The pistons lie at the heart of the internal combustion engine and their reciprocating motion will generate severe stress on the piston crown, sidewall, and the piston's top rings. To reduce the HC emission, the piston top land must be very thin (Lee, 1998). In order to satisfy all these severe conditions, piston materials must have high strength, high toughness and light weight. Several strengthening technologies, such as pressurization have been developed in recent years to strengthen the piston alloys. However, it should be pointed out that the results of these techniques cannot satisfy the recent application requirements (Wu and Li, 2010). Obviously, new techniques are required to increase the strength of the Al piston alloys. In this case, adding hard particles to the Al alloy and decreasing the grain size are considered the optimum solution. By the way, it is important to record here that the most versatile and economical way to produce the AI piston is the conventional casting methods (Lee, 1998).

The present work aimed to obtain a new Al-alloy-based nanocomposite material by squeeze casting of excellent mechanical properties for piston application. The new nanocomposite material composed of Al-piston alloy (Hypoeutectic Al–Si alloy) as a matrix. Nickel and nano Al_2O_3 particles are added as reinforcement.

2. Experimental work

In this study, Al–Si alloy of chemical composition listed in Table 1 was used as a matrix material. The microstructure of the matrix shows fully dendrite grain structure as shown in Fig. 1(a). Ni powder with average particle size of 6 μm was