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Influence of friction stir processing on the microstructure and mechanical properties of a compocast AA2024-Al_2O_3 nanocomposite

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ABSTRACT

The effect of friction stir processing (FSP) on the microstructure and mechanical properties of a semi-solid cast AA2024-1wt%Al_2O_3 nanocomposite was investigated. For comparison, plates of unreinforced AA2024 alloy were also cast and processed at the same FSP conditions (400 rpm, 20 mm/min). The microstructure of all the produced materials was investigated using optical microscopy (OM), scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD). Microhardness and tensile tests were carried out on the unreinforced AA2024 alloy and AA2024-Al_2O_3 nanocomposite before and after FSP. The addition of 1 wt% of Al_2O_3 nanoparticles significantly reduced the grain size of both the cast and FSPed microstructures, leading to a grain size reduction from 28 μm to 18 μm in the cast condition, and from 3.7 μm to 2.3 μm after FSP. The application of FSP to AA2024-Al_2O_3 nanocomposite enhanced the tensile strength and yield strength by 71% and 30%, respectively, in comparison to the as cast matrix, as a result of the uniform distribution of Al_2O_3 reinforcement and grain refinement of Al matrix. The combined application of compocasting and FSP resulted to be a promising method to treat casting defects and to produce nanocomposites characterised by good reinforcement dispersion and high strength and ductility.

1. Introduction

Aluminum matrix nanocomposites (Al-MNCs), characterised by reinforcing particles smaller than 100 nm, offer significant opportunities as structural materials, since they present enhanced mechanical properties in comparison to unreinforced matrix and microcomposites (MMCs) [1].

Liquid state processing of Al-based nanocomposites is strongly limited by the low wettability of ceramic nanoparticles into the molten metal; as a result, although they would enable the production of complex shape parts, traditional liquid routes such as casting are usually associated with particle clustering, high amounts of casting defects related to the addition of nanoparticles and particle segregation induced by the different specific gravity of the matrix and reinforcement [2,3].

Semisolid casting has been proposed as a possible production route to overcome such problems, by improving nanoparticle wettability due to the higher viscosity of the semi-solid matrix in comparison to the liquid state, which would also help facilitating the mechanical entrapment of the reinforcing phase [4,5]. The addition of reinforcing particles to the matrix at the semi-solid state in association with mechanical stirring is usually referred to as compocasting.

Al-based composites reinforced with Al_2O_3 nanoparticles were produced through the semi-solid casting route by El-Mahallawi et al. [6,7], who reported an enhancement of both tensile strength and elongation to failure associated with a refined structure in comparison to the unreinforced alloy. Although casting defects are reduced by semi-solid casting in comparison to liquid state routes, the presence of porosities and cavities associated with nanoparticles are however reported [6,7]. Zhou et al. [8] showed that wettability cannot be enhanced by simple mechanical stirring; in this regard, the authors reported that breaking the gas layer surrounding the particles would be necessary to improve particle wettability.

Al based nanocomposites have also been investigated as surface materials, aiming to exploit their mechanical properties and hardness to produce components with superior wear resistance. For this purpose, secondary processes are currently being investigated to obtain an even distribution of particles, usually difficult to be achieved by conventional surface treatments [9]. Friction-stir processing (FSP), an innovative thermo-mechanical processing technique adapted from the

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concept of friction stir welding, has recently been proposed to this aim [10–11]. The process is known to induce microstructural homogenisation, grain refinement and improved static properties in Al alloys [12–17]. Guo et al. used FSP to fabricate Al-based nanocomposites and studied the effects of the nano-Al_2O_3 particle addition on grain structure and mechanical properties [18]. They reported that the pinning effect of Al_2O_3 particles retarded grain growth following recrystallization during FSP and led to a more pronounced reduction in grain size [18]. Gandra et al. used FSP to develop aluminum based functionally graded MMCs and examined the effect of overlapping direction on the surface and thickness layer [19–21]. Overlapping by the retreating side was found to generate smoother surfaces, while overlapping by the advancing side led to more uniform thickness layers. In their study of wear behaviour of functionally graded MMCs the authors reported a reduction of wear rate by about 13% after an increase of about 30% in the hardness [21].

Developing new routes for the manufacturing of metal matrix composites (MMCs) is of considerable importance. These new routes are based on the combination of the conventional liquid state techniques and friction stir processing [22–25]. In situ mixed salt methods were used to fabricate aluminum-based composites that were subsequently processed by FSP to improve the distribution of reinforcing particles [22–24]. Recently, Ma et al. studied the microstructure and mechanical properties of in-situ nanosized TiB_2/Al–Mg–Si composites processed by friction stir processing [22]. They reported that the initial unprocessed composite had a grain size of 50–100 μm with the synthesized nanosized TiB_2 particles almost agglomerated to micrometric clusters at grain boundaries. Comparatively, after FSP, the nugget zone was characterised by fine and equiaxed recrystallized grains (1–5 μm in average grain size). The initial clusters were also broken up, while the nanosized TiB_2 particles were distributed much more uniformly in the matrix, acting as effective pins to interact with dislocations [22]. Also Chen et al. [23] studied the effects of nano particles on the microstructural evolution of FSPed in-situ TiB_2/6063Al composite. They observed homogenous redistribution of nanosized TiB_2 particles in a fine-grained in-situ AA6063/TiB_2 composite through FSP. More recently, Zhao et al. [24] investigated the effect of FSP on the microstructure and superplasticity of in situ nano-ZrB_2/2024Al composites. FSP resulted in grain refining of the cast structure and in the more even distribution of nanoparticles [24]. The effect of multipass FSP on the microstructure and mechanical properties of Al_3Ti/A356 composites was examined by Yang et al. [25], who found that after multi-pass FSP, both the strength and ductility of the composite samples were gradually enhanced [25].

The present study is intended to investigate the possibility to produce a AA2024-based composite containing Al_2O_3 nanoparticles, by combining compocasting technique and FSP. The aim is also extended to evaluate the effect of FSP, performed at fixed processing parameters, on the microstructural and mechanical properties of the produced composite.

Table 1
Chemical composition (wt%) of the AA2024 matrix.

Element	Cu	Mg	Mn	Fe	Si	Zn	Cr	Al
wt%	4.39	1.26	0.57	0.50	0.50	0.25	0.10	Bal.

Table 2
Characteristics of the reinforcing Al_2O_3 nanoparticles.

Reinforcement	Density [g/cm^3]	Structure	E [GPa]	Average Size [nm]	Melting point [°C]
γ-Al_2O_3	3.60	FCC	380	50	2054

2. Materials and methods

AA2024-Al_2O_3 nanocomposite was produced by adding 1 wt% of Al_2O_3 nanoparticles into AA2024 Al matrix at the semi-solid state through mechanical stirring. For comparison, the unreinforced AA2024 alloy was fabricated at the same conditions. The chemical composition of the matrix alloy and the properties of the reinforcing particles are reported in Tables 1 and 2, respectively.

The compocasting process for the unreinforced matrix alloy and its nanocomposite plates was carried out in a furnace designed for this work. The apparatus consists of a lift out graphite crucible with a maximum capacity of 500 g and a controlling heating system, provided with a stirring unit. Al_2O_3 nanoparticles were milled by high energy ball milling at 200 rpm for 2 min. in order to preliminarily eliminate particle clusters. Al_2O_3 nanoparticles were then wrapped in an aluminum foil and preheated at 200 °C for 2 h. A charge of 400 g of the matrix alloy was introduced into the crucible and heated up to 700 °C. The molten alloy was then degassed with hexachlorethane degasser tablets. After the degassing process, the pre-heated Al_2O_3 packages were simultaneously added to the matrix at 610 °C, while mechanical stirring was applied for 1 min at 800 rpm. The amount of Al_2O_3 nanoparticles was added to achieve 1 wt% of the produced casting. The unreinforced alloy and the composite were then cast in a stainless steel mould 250 mm long, 50 mm wide and 10 mm thick.

Friction Stir Processing (FSP) was then applied to the cast plates of the unreinforced alloy and nanocomposite. A H13 steel tool was used for sample processing (dimensions of the cylindrical tool: pin diameter 6 mm, pin length 6 mm and shoulder diameter 20 mm). A single FSP

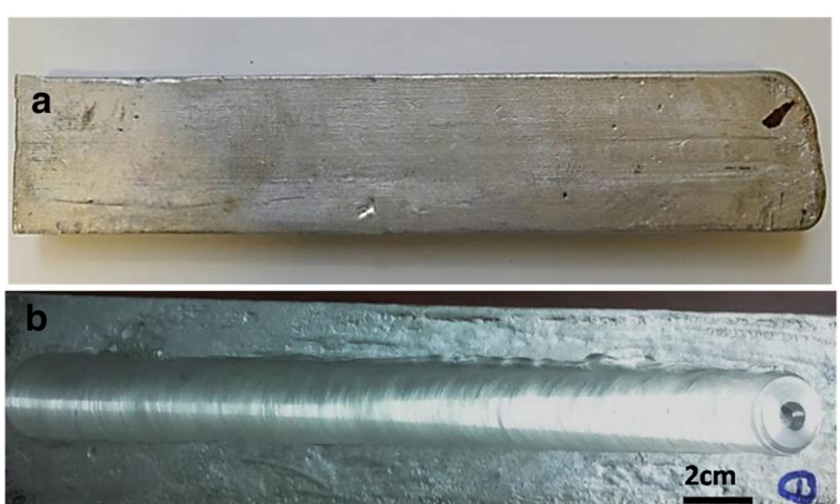

Fig. 1. Macrographs of AA2024-Al_2O_3 nanocomposite in the (a) as cast condition and (b) after FSP.