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HYBRID ALUMINUM MATRIX COMPOSITES REINFORCED WITH IN SITU MG_2SI AND AL_3NI PHASES

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Abstract: Aluminum matrix cast composites (AMCCs) are engaged materials for the fabrication of accountable and especially acute pieces utilized in the high-tech scope of industry such as automotive, aerospace, electronics, etc. In the present study, hybrid aluminum base composite reinforced with in-situ produced Mg_2Si and Al_3Ni particles were fabricated successfully in casting moods, and the structural features of inborn reinforcing compounds was evaluated in different thermal situations of solidification. For this issue, the composite microstructure was characterized by X-ray diffraction (XRD) and optical microscope (OM). In addition, the mechanical properties were evaluated by hardness test. According to the results, increasing in the cooling rate during solidification leads to the reduction of mediate size of the Mg_2Si initially crystals, enhancement of their dispensation uniformity and clear increasing of their final amount; meanwhile, the average size of Al_3Ni particles decreases significantly but their content is almost the same for different conditions.

Key words: Al-based in-situ composites, hybrid intermetallic reinforcement, microstructural analysis, hardness, solidification rate, particle size.

1. INTRODUCTION

The issue of fabricated materials with a predestined set of features for different applications is one of the most significant in the area of materials science and engineering. The feasibilities for more enhancing the mechanical and useful properties of standard alloys are inadequate for their prosperous contestation with advance structural and functional materials [1,2]. A way to achieve such goals is the application of aluminum (Al) matrix composites (AMCs) produced by pure Al or its alloys reinforced with distributed particles of intermetallics, oxides, carbides, silicides, borides and other refractory materials [3-7]. An important property of such compounds is the eventuality of planning their characteristics at the evolution step by adopting the particle size dispersion, morphological features and volume or weight percent of reinforcing phases [8]. It makes to produce not only structural, but also highly damping, heat-resistant, antifriction, electrotechnical and other useful materials with bold properties depending on the needs [9].

The most important agent limiting the vast industrial application of AMCs is the technological knots along with the little degree of positivism of the physico-mechanical features of the second phase in the matrix and, thus, in the final product. These problems are mainly created via poor wettability of the reinforcing particles by the matrix melt [3]. There is a noticeable number of technological routes helped to achieve AMCs [10,11]. Considering the quality and economic standards, as well as the feasibility of metallurgical processing during the fabrication, liquid-state routes of composites manufacturing such as: infiltration of porous powder preforms with matrix melts [12]; mechanical stirring of disintegrated particles into metallic melts [13]; methods based on the controlled chemical reactions at high-temperature which resulted in the endogenous reinforcing compounds in the matrix melt (in-situ process) [14] and others are preferable.

The mechanical mixing of the melt containing reinforcing particles, or stir casting method is the most widely utilized method for the fabrication of cast composites [15]. In spite of many advantages, this process has rigid bugs: oxidation and gas glut of the matrix alloy pending active stirring (as a result, raised porosity of castings [16]), poor bonding at the matrix-reinforcement interface, agglomeration of the reinforcing particles, the necessity for usage of special equipment. From the thermodynamic view, the composites produced by this process are none-equilibrium, and it can experience severe reactions between the matrix alloy and the reinforcing materials, resulting in the damage of the reinforcing components and formation of unwanted products of such interaction [17]. Furthermore, in stir casting methods it is hard to prepare continuous and full contact of the second phases with the matrix, eke the optimum level of interfacial interaction, which usually is the cause of unstable mechanical and functional properties of cast details.

Another engaged method instead of the stir casting process is liquid-state reactionary synthesis (in-situ process), which prepares the production of novel endogenous reinforcing components because of controlled exothermic reactions between the constituents of Al matrix composites directly pending their processing [14]. Composite materials achieved by in-situ methods have improved thermodynamic stability and better dispensation of the reinforcement, plus an increased degree of adhesion bonds along the interfaces of the matrix and reinforcing phases, which finally ensures better mechanical and operational characteristics [11]. The distribution of the new compounds can be adopted by selecting the technological types of mixing the phases imported in the in-situ reactions [18]. It is bold that the performance of most routes of endogenous reinforcing does not need the use of special rig. Therefore, it could be concluded that the creation of endogenous ceramic compounds directly in the matrix melt is a more economical solution than making exogenously-reinforced composites by ready-made expensive ceramic powders.

Among the many number of reinforcing phases, the particular attention of researchers is payed to the Mg_2Si intermetallic compound, as it can be easily created in-situ via ingot metallurgy at high volume fraction [14]. The possible for utilizing Mg_2Si as a reinforcing agent is related to the set of high physical and mechanical properties of this phase, such as low coefficient of thermal expansion (7.5×10^{-6} K^{-1}), high melting point (1358 K), high hardness (4.5×109 $N.m^{-2}$), low density (1.88 g/cm^3), high elastic modulus (120 GPa) [14]. Although, Al/Mg_2Si composites have not yet acquired a vast industrial application, due to the obtained degree of mechanical properties is relatively low owing to the structural characteristics of these compounds [19]. This is due to the coarse primary Mg_2Si phase, which leads to MMCs reinforced by Mg_2Si usualy having the weak mechanical properties. It is therefore critical to refine Mg_2Si by adding alloying elements like Cu [14], Sc [20], Ce [21] and Gd [22].

Another way to improvement the mechanical properties can be multi-reinforcing, i.e. the use of two or more reinforcing agents in one composite material [23]. A promising choice for use along with Mg_2Si for the reinforcing of an Al matrix is the intermetallic compound Al_3Ni, which have a low density (~4.03 g/cm^3), high melting point (~1127 K), considerable high-temperature mechanical stability up to 773 K, high Young’s modulus, attractive chemical stability, low coefficient of thermal expansion, high bulk modulus (~113 GPa), and is capable to be as heterogeneous nucleation sites for the α-Al grains leading to more increase of mechanical properties of the composites [24].

However, the working conditions above room temperature obligates higher requirements on their elevating temperature performance. The properties of Al-Mg_2Si alloys decline sharply, with temperatures rising [25-28].

To enhance the high-temperature strength of the as-cast Al-Mg_2Si alloys, adding Ni is considered as a useful way [29,30]. Numerous researchers indicated that Ni plays an important role in improving the room and high-temperature strength because created intermetallic compound Al_3Ni can remain stable below 350 °C [29-35].

In addition, the structure of endogenously-reinforced composites could be controlled by changing the cooling rate during crystallization and finally achieving a determined degree of properties [36].

The goal of the current study is to develop hybrid aluminum matrix composite (HAMC) reinforced with in-situ formed Mg_2Si and Al_3Ni particles via casting method and to evaluate the effect of thermal conditions of solidification on the morphology and size distribution of in-situ reinforcing phases.

2. EXPERIMENTAL

Composite materials were provided in a 6 Kg SiC crucible in an electric resistance furnace. Pure Al ingot (≥99.99 wt.% Al), magnesium ingot (≥99.9), silicon block (≥99.0) and nickel powder (≥99.5) were used during the melting. Because the importance of elemental loss during the melt preparation, amount of weight loss was considered as 5, 5, 10 and 15% for Al, Ni, Si and Mg, respectively. Note that the amount of weight loss for Mg (15%) was due to the high level of oxidation of this element in the used temperature range for preparation of the melt. Firstly, crucible was filled by Al ingot and heated up to melt formation. Then silicon and foil-wrapped magnesium preheated to 100 °C were added to Al melt at 700 ºC. After melting the charge components, it was manually disturbed by a graphite rod, followed by overheated to 750 °C and the canned nickel powder was added. The melt temperature was then increased to 850 °C and hold for 10 min until the in-situ reactions of the creation of endogenous reinforcing compounds. The temperature modes of the test were controlled by K-type thermocouple with a precision of ± 1.5 °C. The provided melt was cast at a temperature of 750 °C into cold copper and steel molds to achieve ingots with a diameter of 45 mm and a length of 70 mm. Table 1 shows the chemical composition of the in situ AMCCs.

Table 1. Chemical composition of AMCCs

Materials	Si	Mg	Ni	Fe	Zn	Mn	Cu	Ti	Cr
%Wt.	6.5	12.3	3.1	0.01	0.01	0.01	0.01	0.01	0.01

Specimens for microstructural characterization were sectioned from castings rods. Metallographic specimens were polished using standard methods and etched with 5% HF for near 10 s at room temperature. An optical microscope equipped with a picture evaluation system (Clemex Vision. Pro. Ver. 3.5.025) was utilized for determining the microstructural parameters.

Phase analysis was identified by X-ray diffractometry (XRD, Philips PW 1730, 40 kV and step of 0.02°) with Cu Kα radiation (λ = 0.15406 nm). Phase identification was performed in the High X'Pert software complex using the Crystallography Open Data database. The hardening was estimated by Brinell hardness using 5-mm indenter at 2500-N load. The hardness values were average of at least fifteen measurements. It should be noted that for simplicity, henceforth AMN word applies instead of Al/(Mg_2Si + Al_3Ni) (A, M and N letters refer to Al, Mg_2Si and Al_3Ni, respectively).

3. RESULTS AND DISCUSSION

Figure 1 highlights the microstructure of synthesized AMN composites under different solidification rate. In addition, the histograms of the size distribution of reinforcing particles is proven in Figure 2. Primary Mg_2Si particles formed in the steel mold have an irregular, coarse and dendritic morphology or turns into a hole crystals and its sizes can attain over of 50 μm. In common solidification conditions, the early Mg_2Si particles solidify withinside the shape of incomplete octahedrons that wax fast alonside the direction <100> to create the primary solid dendrite [37]. Due to the anisotropy growth of the Mg_2Si crystals, it is feasible the advent of complicated and dendritic-like systems with large sizes, which recognition stresses at their horned corners and planes, [38].

Therefore, the alteration of Mg_2Si particles may be a vital way in enhancing the mechanical properties of composite materials. An increment in the cooling rate pending solidification, owing to the use of a copper mold, results in decreasing the mean size of the primary Mg_2Si crystals to 8.5 μm, enhancement of the dispersion uniformity and notable increasing of their final amount (Fig. 3). Concurrently, there was no clear change in the morphology of the Mg_2Si particles during the crystallization with a raised cooling rate. Intermetallic compound Al_3Ni crystallize mostly in the form of dense and block crystals, and their content is almost the same for both of molds. When using the copper mold, the average size of Al_3Ni particles reduced to 5 μm. In addition, the size distribution of Mg_2Si and Al_3Ni particles is more uniform and nearby the Gaussian distribution, that is seen from the effects of distribution histograms (Fig. 2, c,d).

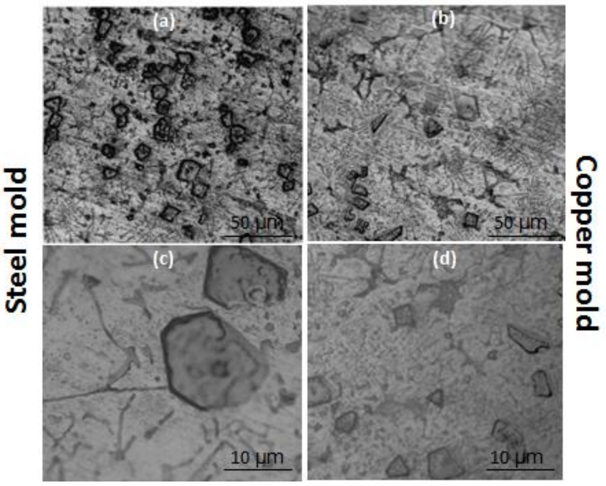

Fig. 1. Microstructures of as-cast AMN composite samples obtained using different types of molds.

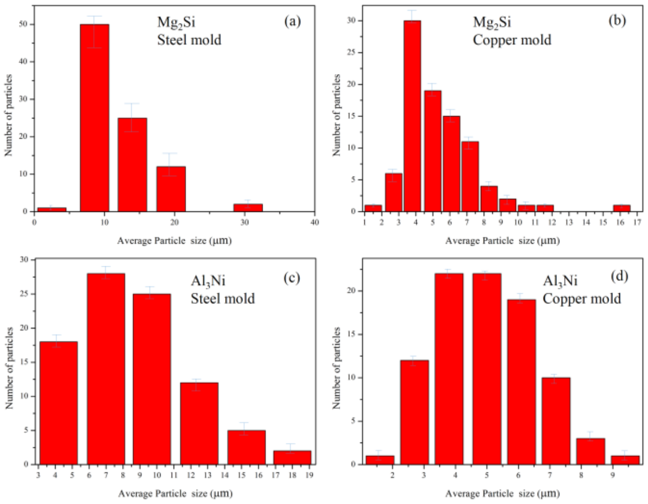

Fig. 2. Size distribution graphs of reinforcing phases in AMN composites specimens obtained at different cooling rates.

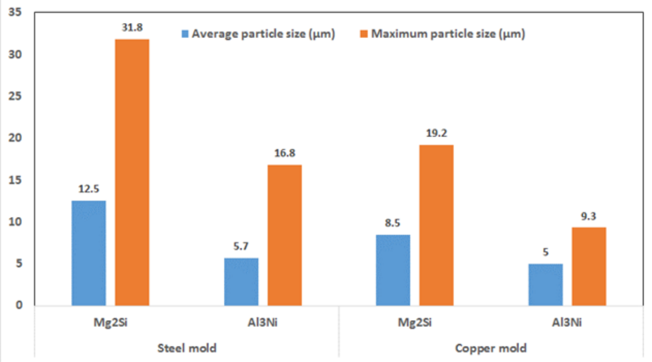

Fig. 3. Quantitative parameters of reinforcing particles in AMN composite.

The XRD graph proves that the structural phases of the received specimens are α-Al, Mg_2Si and Al_3Ni (Fig. 4). Therefore, it can be concluded that in-situ melt exothermic reaction occurred fully between the Ni powder and the Al ($3Al + Ni = Al_3Ni + 258$ kcal/mol), and also Mg and Si in a certain stoichiometric ratio produced Mg_2Si phase.

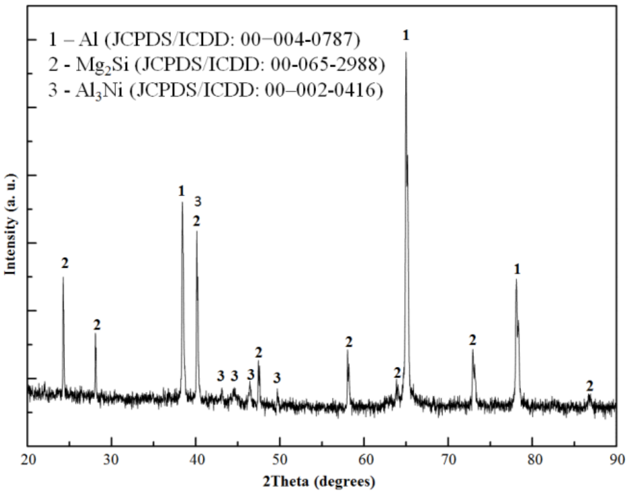

Fig. 4. XRD pattern of AMN composite

When applying a copper mold, the mean hardness value of AMN composites increments from 70.04 ± 1.23 to 122.91 ± 1.05 HBN. The increasing in the acquired hardness value is basically due to the crushing of the primary Mg_2Si particles, decreasing their size and an enhancement in the tedium of their distribution thorough the composite materials.

On the alternative hand, the space among the reinforcing particles reduces with the aid of using lowering their length. This issue become schematically proven in Fig. 5 and can be defined with the aid of using Equation (1), because the reinforcement particle size decreases, the space among the particles may even decreases ($\lambda_2 < \lambda_1$) [39].

$$\lambda = [4r\times(1-f)/3f] \qquad (1)$$

wherein λ is the space among the reinforcement particles, f is the particle extent fraction and r is the particle radius, assuming them spherical. In different words, in line with Equation (2) lowering the space among the Mg_2Si particles will boom the specified tension for dislocations motion among them, ensuring in a boom withinside the composite strength.

$$\tau_0 = Gb/\lambda \qquad (2)$$

wherein τ_0 is the specified tension for forcing dislocations to transport amongst reinforcement particles, G is the material's elastic modulus and b is the Berger's vector [39].

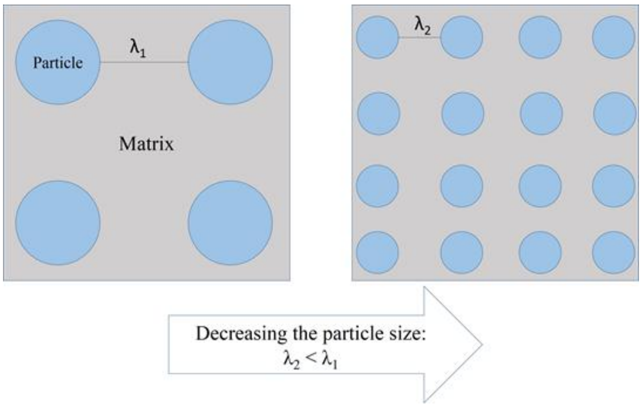

Fig. 5. Schematic of reducing the distance between the particles by decreasing the particle size.

This phenomenon is likewise defined via the Hall–Petch relationship.

$$\sigma_i = \sigma_0 + K/\sqrt{D} \qquad (3)$$

in which σ_o is the flow stress, σ_i is the pressure resisting the motion of dislocations, K is consistent and D is the grain length. According to Equation (3), as the grain size becomes smaller, flow stress additionally increases, main to excessive strength withinside the composite [39]. It needs to be cited that there may be a direct relationship between strength and hardness of a material.

Hence, it viable to manufacture HAMCs through a one-degree technique of casting via the advised technological solutions for simultaneous use of in-situ Mg_2Si and Al_3Ni intermetallic compounds. In addition, to prolong the potentials of meaning structure control to reach the required degree of mechanical and functional properties of cast counterparts, the mix of various types of reinforcing phases in one material could be used.

4. CONCLUSIONS

In current research, HAMC materials reinforced with in-situ particles Mg_2Si and Al_3Ni were produced successfully by melt state production process in different thermal conditions during solidification. The main results could be listed as follow:

The XRD pattern proves that the structural phases of the gained in-situ composites are α-Al, Mg_2Si and Al_3Ni.

An increase in the cooling rate of solidification by the use of a copper mold alternated steel mold results in decreasing the mean size of the primary Mg_2Si crystals from 12.5 to 8.5 µm and enhancement of the distribution homogeneity; synchronously, the mean size of Al_3Ni particles reduces from 5.7 to 5 µm but their amount is almost the same for both molds.

With increasing the solidification rate, the size histogram of Mg_2Si and Al_3Ni particles becomes more homogeny and near the Gaussian distribution.

The mean hardness value of AMN in-situ composites raises from 70.04 ± 1.23 to 122.91 ± 1.05 HBN when casting into the copper mold, which shows a 75.5% increase.

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