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Effect of particle dispersion on the mechanical behavior of Al-based metal matrix composites reinforced with nanocrystalline Al–Ca intermetallics

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ABSTRACT

Al-based metal matrix composites reinforced 20 and 40 vol.% of Al–Ca intermetallic particles have been produced by powder metallurgy. Two distinct approaches have been used for the dispersion of the reinforcing particles within the Al matrix: manual blending and ball milling. Manual blending leads to the agglomeration of the Al–Ca particles to form a cell network throughout the consolidated sample. On the other hand, the composites prepared by milling display a more homogeneous distribution of the reinforcing particles. This has a strong impact on the mechanical properties. The strength increases from 112 MPa for pure Al to 140 and 165 MPa for the blended composites with 20 and 40 vol.%, while the strength increases to 250 and 280 for the corresponding composites produced by milling. This behavior is linked to the reduced matrix ligament size characterizing the milled composites.

1. Introduction

Al based metal matrix composites (MMCs) are becoming very popular for aerospace and automobile applications due to their lightweight, high strength to weight ratio, large stiffness and wear resistance [1]. In order to improve the properties of the composites, the development of reinforcements with enhanced specific properties is a necessary prerequisite. Among the high-strength, lightweight reinforcement, the Al–Ca intermetallics Al_3Ca_8 (triclinic) and $Al_{14}Ca_{13}$ (monoclinic) [2] phases deserve a special attention for the use as reinforcing agent due to their extremely low density (1.859 and 2.013 g/cm^3, respectively). Al_3Ca_8 is one of the important intermetallic phase in the Al–Ca system that is associated with important mechanical properties. It is known to be hard, brittle and stable up to 852 K temperature [3].

In particulate composites, the reinforcement particles are added to strengthen the metal matrix. The mechanical properties of the MMCs strongly depend on the properties of the matrix and reinforcement, their distribution, volume fraction and size as well as on the interfacial strength between the matrix and reinforcement [1]. Due to their high surface area, small powder particles naturally tends to agglomerate to reduce their overall surface energy, making it difficult to obtain a uniform distribution of reinforcing particles by conventional processing methods. Good dispersion of the reinforcement in the matrix can be achieved by high-energy ball milling [4–8]. This technique, first developed by Benjamin [9] to produce nickel superalloys hardened by oxide dispersion, is now known as mechanical alloying or mechanical milling.

For most engineering applications, the composite powders have to be compacted to produce highly dense samples [10]. Among the different consolidation techniques, hot consolidation, which involves the simultaneous application of temperature and pressure, show a large potential for achieving fast and full densification of powders, thereby avoiding possible detrimental phase transformations or microstructural change (e.g. grain growth) during compaction. In addition, hot consolidation breaks the typical oxide layers that coat the powder particles, and hence gives improved bonding between the particles [11].

The present work aims at producing high-strength and lightweight materials suitable for structural applications. It focuses on novel Al-based composites, reinforced with nanocrystalline Al–Ca intermetallic particles with an emphasis on their microstructural features and corresponding mechanical behavior.

2. Experimental

Milling experiments on pre-alloyed $Ca_{65}Al_{35}$ ingots were carried out using a Retsch PM400 planetary ball mill with hardened steel balls and vials. The powders were milled for 200 h with a ball-to-powder mass ratio (BPR) of 10:1 and at

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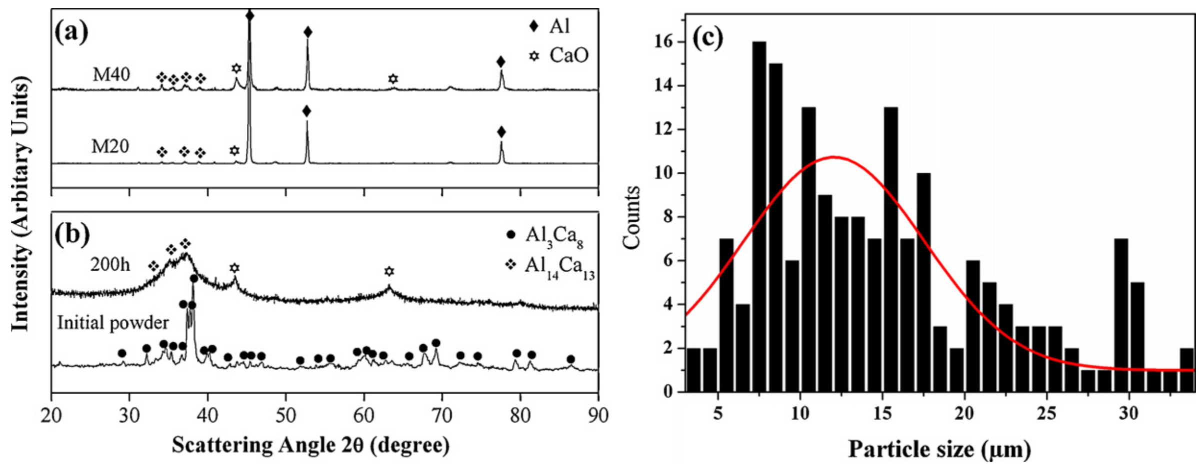

Fig. 1. XRD patterns (Co Kα radiation) of (a) the initial pre-alloy and Al–Ca powder milled for 200 h and (b) composites with 20 vol.% (M20) and 40 vol.% (M40) of Al–Ca intermetallic reinforcement. (c) SEM micrographs of the Al–Ca powder particles after 200 h of milling and corresponding size distribution (inset).

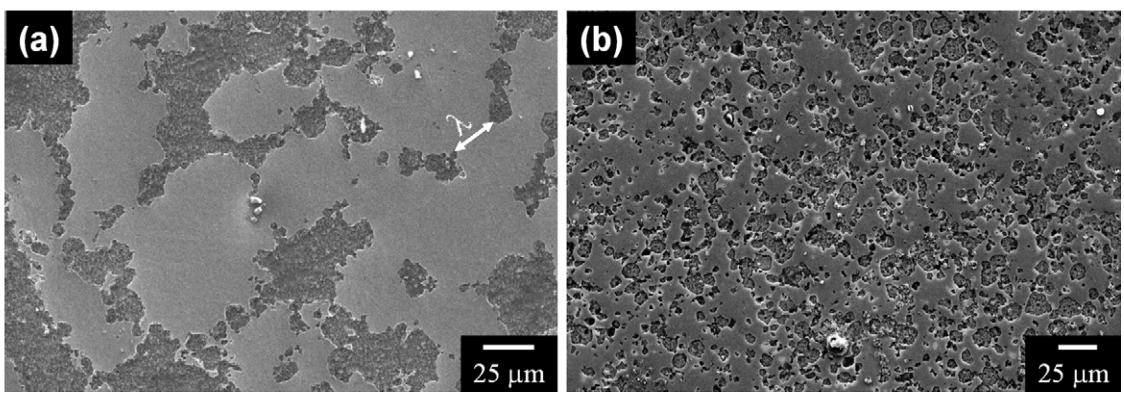

Fig. 2. SEM micrographs for the consolidated composites with 40 vol.% of Al–Ca intermetallics: (a) blended and (b) milled.

rotational velocity of 150 rpm in a sequence of 15 min milling intervals interrupted by 15 min break to avoid a strong temperature rise. All sample handling was carried out in a glove box under purified argon atmosphere (less than 0.1 ppm O_2 and H_2O). Structural characterization was performed by X-ray diffraction (XRD) using a Philips PW 1050 diffractometer (Co Kα radiation; λ = 0.17889 nm) and by scanning electron microscopy (SEM) using a Gemini 1530 microscope. The Rietveld method was applied for the profile-fitting structure refinement using the WinPlotR software package [12]. Powder mixtures consisting of pure Al with 20 and 40 vol.% of $Ca_{65}Al_{35}$ particles were prepared by manual blending as well as by 5 h of room temperature milling. The powders were then consolidated by uni-axial hot pressing at 673 K and 400 MPa. For comparison purposes, a bulk specimen was produced by hot pressing of pure Al powders using the same consolidation parameters as used for the composites. The density of the samples was evaluated by the Archimedes principle. The matrix ligament size (λ) was measured by superposing random lines on the SEM micrographs of the composites and its value was determined from dividing total length fell into the matrix (L) by the number of matrix region intercepts (N) as $\lambda = L/N$ [13]. Ten random lines were superposed on each micrographs and a minimum of three micrographs was used per composite. According to the ASTM standard for compression testing [14], cylinders with a length/diameter ratio of 2.0 (6 mm length and 3 mm diameter) were prepared from the hot consolidated samples. The specimens were tested at room temperature with an INSTRON 8562 testing facility under quasistatic loading (strain rate $\sim 1 \times 10^{-4}\ s^{-1}$). Both ends of the specimens were polished to make them parallel to each other prior to the compression tests. Microhardness of the as-milled powders was measured using a computer-controlled Shimadzu HMV-2000 hardness tester with applied load of 10 g and dwell time of 10 s. At least 20 readings were taken to calculate the mean hardness value. Cracked or non-symmetric indentations were not considered for the measurement.

3. Results and discussion

Fig. 1(a) and (b) illustrates the XRD patterns of the Al–Ca reinforcement and hot pressed composites. The initial powder (Fig. 1(a)) shows sharp Bragg peaks of the Al_3Ca_8 intermetallic phase. After 200 h of milling the Al_3Ca_8 intermetallic transforms into the $Al_{14}Ca_{13}$ phase. In addition, significant peak broadening can be observed. This can be attributed to the reduced crystallite size to the nanometer regime. Indeed, Rietveld structure refinement reveals a crystallite size of about 10 nm. The pattern also shows the presence of a small amount of CaO, which may be

Table 1
Density (d), yield (σ_y) and compressive (σ_c) strengths, fracture strain (ε_f) and hardness (Hv) for pure Al, composites with 20 and 40 vol.% AlCa particles dispersed by manual blending and milling.

	d (g/cm^3)	σ_y (MPa)	σ_c (MPa)	ε_f (%)	Hv
Pure Al	2.70	50	112	55	25
Al + 20 vol.% AlCa blended (B20)	2.51	59	140	29	33
Al + 40 vol.% AlCa blended (B40)	2.43	79	165	16	37
Al + 20 vol.% AlCa milled (M20)	2.55	103	250	31	76
Al + 40 vol.% AlCa milled (M40)	2.47	151	280	16	80