Al-based metal matrix composites reinforced with nanocrystalline Al-Ti-Ni particles

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Abstract. Al-based metal matrix composites containing different volume fractions of nanocrystalline Al$_{70}$Ti$_{20}$Ni$_{10}$ reinforcing particles have been produced by powder metallurgy and the effect of the volume fraction of reinforcement on the mechanical properties of the composites has been studied. Room temperature compression tests reveal a considerable improvement of the mechanical properties as compared to pure Aluminum. The compressive strength increases from 155 MPa for pure Al to about 200 and 240 MPa for the samples with 20 and 40 vol.% of reinforcement, respectively, while retaining appreciable plastic deformation with a fracture strain ranging between 43 and 28 %.

1. Introduction

Among the advanced engineering materials, Al-based metal matrix composites (MMCs) have been attracting considerable attention due to their remarkable mechanical properties, including low density, high strength and good fatigue and wear resistance [1,2]. In addition, MMCs offer the possibility to tailor their properties to meet specific requirements, which renders this type of materials quite unique in comparison to conventional unreinforced materials [1,2].

Different types of materials, ranging from the typical ceramic reinforcements, such as Al$_2$O$_3$ and SiC [1-3], to more unconventional reinforcements, such as quasicrystals [4,5] and complex metallic alloys (CMAs) [6], have been successfully used as reinforcements in MMCs. Other possible candidates as reinforcing agents in MMCs are amorphous, partially amorphous and nanocrystalline Al-based alloys, which have attracted widespread attention as potential candidates for structural as well as functional applications due to their high strength combined with low density [7-10].

To test the effect of the nanocrystalline particulate reinforcements on the mechanical properties of Al-based composites, in this work, Al-based MMCs reinforced with nanostructured Al$_{70}$Ti$_{20}$Ni$_{10}$ particles have been produced by powder metallurgy methods. The results reveal encouraging room temperature mechanical properties consisting of high strength combined with considerable plastic deformation.
2. Experimental
Milling experiments starting from pure elemental powder mixtures (purity >99.9 wt.%) with nominal compositions Al$_{70}$Ti$_{20}$Ni$_{10}$ were performed using a Retsch PM400 planetary ball mill and hardened steel balls and vials. No process control agent was used. The powders were milled for 100 h with a ball-to-powder mass ratio (BPR) of 10:1 and a milling intensity of 150 rpm. To avoid or minimize possible atmosphere contamination during milling, vial charging and any subsequent sample handling was carried out in a glove box under purified argon atmosphere (less than 1 ppm O$_2$ and H$_2$O). Al-based metal matrix composites consisting of elemental Al powder blended with different amounts ($V=20$ and 40 vol.%) of Al$_{70}$Ti$_{20}$Ni$_{10}$ powders were synthesized through powder metallurgy methods. Consolidation was done by uni-axial hot pressing followed by hot extrusion under argon atmosphere at 773 K and 530 MPa. The extrusion ratio was 4:1. The density of the consolidated samples was evaluated by the Archimedes principle revealing a relative density of about 98%. The phases and the microstructure were characterized by X-ray diffraction (XRD) using a Philips PW 1050 diffractometer (Co $K_{\alpha}$ radiation) and by scanning electron microscopy (SEM) using a Hitachi TM-1000 tabletop microscope. The Young’s Modulus was evaluated by ultrasonic measurements using an Olympus 5900 PR ultrasonic pulser-receiver. According to the ASTM standard for compression testing [11], cylinders with a length/diameter ratio of 2.0 (10 mm length and 5 mm diameter) were prepared from the extruded samples. The specimens were tested with an INSTRON 8562 testing facility under quasistatic loading (strain rate of 8x10$^{-4}$ s$^{-1}$) at room temperature. Both ends of the specimens were polished to make them parallel to each other prior to the compression test.

3. Results and discussion
The XRD patterns of the composites reinforced with different amounts of Al$_{70}$Ti$_{20}$Ni$_{10}$ particles are shown in Figure 1(a) along with the pattern of the as-milled Al$_{70}$Ti$_{20}$Ni$_{10}$ reinforcing powder. The pattern of the as-milled reinforcement is characterized by the presence of few broad diffraction peaks which can be identified as the Al$_3$Ti phase (space group Pm-3m). The diffraction peaks in are extremely broad, indicating that the phase formed is of nanometer dimensions.

Figure 1. (a) XRD patterns (Co $K_{\alpha}$ radiation) of the as-milled Al$_{70}$Ti$_{20}$Ni$_{10}$ powder and composites with 20 ($V=20$) and 40 vol.% ($V=40$) of Al$_{70}$Ti$_{20}$Ni$_{10}$ reinforcement. SEM micrographs for the consolidated composites with (b) 20 vol.% and (c) 40 vol.% of Al$_{70}$Ti$_{20}$Ni$_{10}$ reinforcement.
The pattern of the composite with \( V = 20 \) shows the presence of fcc Al along with the Al\(_3\)Ti phase. No sharpening of the diffraction peaks belonging to the Al\(_3\)Ti phase can be detected, indicating that none or negligible grain growth of the reinforcing phase has occurred in the current consolidation conditions (extrusion at 773 K and 530 MPa). Similar results can be observed for the sample with 40 vol.% reinforcement, where the intensity of the Al\(_70\)Ti\(_{20}\)Ni\(_{10}\) diffraction peaks are increased with respect to the composite with \( V = 20 \) due to the higher volume fraction of reinforcement. The detection of only two phases in the patterns of the composites with \( V = 20 \) and 40 indicates that no reaction between matrix and reinforcement to form additional phases took place during consolidation.

Figures 1(b) and 1(c) show the SEM micrographs taken from the cross-section of the consolidated composites. The images display a microstructure consisting of bright particles (the Al\(_70\)Ti\(_{20}\)Ni\(_{10}\) reinforcement) homogeneously dispersed in the Al matrix (the dark regions). The Al\(_70\)Ti\(_{20}\)Ni\(_{10}\) particles become more interconnected with increasing amount of reinforcement. Only few pores are visible, further corroborating the high density of the consolidated specimens.

Typical room temperature uni-axial compression true stress-true strain curves of the tests under quasistatic loading for the composite materials are shown in Figure 2(a) together with the curve for the extruded pure Al. The addition of the nanostructured reinforcement is very effective for improving the mechanical properties of the Al matrix. The compressive strength (the maximum compressive stress which the material is capable of sustaining \([12]\)) increases from 155 MPa for pure Al to about 200 for the samples with 20 vol.% of reinforcement, while retaining appreciable plastic deformation reaching an ultimate strain of 43 % before fracture occurs. With increasing the volume fraction of reinforcement to 40 vol.%, the compressive strength further raises to 240 MPa, and the strain at break is about 28 %. These results indicate that the addition of the nanostructured reinforcement leads to composite materials with compressive strengths exceeding that of pure Al by 30 – 50 %, while retaining appreciable plastic deformation. Besides the enhancement of the mechanical properties, the addition of the nanocrystalline reinforcement has a positive effect on the Young’s modulus of the composites, which increases from about 70 GPa for pure Al to 75 and 85 GPa for the composites with 20 and 40 vol.% of reinforcement, respectively [Figure 2(b)].

The strengthening effect of particles in metal matrix composites is generally attributed to two factors \([13]\): (i) the load bearing effect of the reinforcement, in which the reinforcement can share the applied stress directly by stress transfer from the matrix \([14-16]\) and (ii) the dislocation strengthening in the matrix, which is related to the nucleation of additional dislocations in the matrix due to the introduction of the reinforcement \([17,18]\). Recently, it has been found for composites with large

![Figure 2](image-url)

**Figure 2.** (a) Room temperature compression true stress-true strain curves for the hot pressed and hot extruded pure Al, composites with 20 vol.% \( (V = 20) \) and 40 vol.% \( (V = 40) \) of nanostructured Al\(_70\)Ti\(_{20}\)Ni\(_{10}\) particles; (b) Young’s modulus as a function of the reinforcement content.
amount of reinforcement (≥ 20 vol.%) that the mean free path of the matrix (i.e. the characteristic matrix ligament size \( \lambda \)) plays a dominant role in the strengthening of Al-based composites [6]. This size effect, similar to the strengthening by grain refinement, can significantly contribute to the strength of the material because the matrix/particle interface can effectively inhibit dislocation movement. The matrix ligament size can be remarkably reduced by using small reinforcing particles [6]. Due to their small size (< 20 \( \mu \)m), the present nanocrystalline particles are very effective in reducing the matrix ligament size \( \lambda \), which decreases from 15 \( \mu \)m for the sample with \( V = 20 \) to about 8 \( \mu \)m for the composite with 40 vol.% of reinforcement, therefore, explaining the observed increase of strength with increasing reinforcement content.

4. Summary
To test the validity of the nanocrystalline particulate reinforcements on the mechanical properties of composites, Al-based MMCs consisting of pure Al reinforced with different volume fractions of nanostructured Al\(_{70}\)Ti\(_{20}\)Ni\(_{10}\) particles have been produced by powder metallurgy methods. The results reveal encouraging room temperature mechanical properties. The compressive strength increases from 155 MPa for pure Al to about 200 and 240 MPa for the samples with 20 and 40 vol.% of reinforcement, respectively, while retaining appreciable plastic deformation with a fracture strain ranging between 43 and 28 %.

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