Whiskers of Al_2O_3 as reinforcement of a powder metallurgical 6061 aluminium matrix composite

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Abstract

An Al-Mg-Si alloy matrix composite reinforced with 10% volume of alumina whiskers (Al_2O_3w) has been processed by powder metallurgy and investigated. The Al_2O_3w were produced as single crystal c-axis alpha alumina fibres at pre-pilot scale via Vapour Liquid Solid (VLS) deposition in a cold-wall air-tight furnace with alumina linings. As far as we know, this is the first report of the utilization of whiskers of Al_2O_3 as reinforcing elements for Al alloys. Tensile tests have been performed on the composite at room and high temperature. Results show that the AA6061 alloy reinforced with the as-produced Al_2O_3 whiskers has remarkably high mechanical properties at room temperature. This is attributed to the high quality of the Al_2O_3 single crystals and to the strong bonding attained between them and the 6061 alloy matrix.

Keywords: Composite materials; Microstructure; Mechanical properties; Aluminium, Alumina whiskers; Powder metallurgy.

1. Introduction

Particle-, whisker- and fibre-reinforced metal matrix composites can sustain higher loadings than the unreinforced equivalent matrixes. Whiskers are defect-free, very thin single crystal fibres, which are among the most resistant materials known. Among ceramic whiskers, α-Al_2O_3 grown with c-axis orientation are good candidates for use as strengtheners in composites because of their high elastic modulus, thermal and chemical stability, fracture strength, and creep resistance even at high temperatures [1-3]. However, the use of Al_2O_3 whiskers has been hindered up to now by its extremely high production cost. Accordingly, studies on metal matrix composites reinforced with Al_2O_3 has been limited to particles, see for example ref. [6, 7], and short fibres [8-11].

In this work, a novel method has been used for producing enough amount of c-axis α-Al_2O_3 whiskers, based on vapour-liquid-solid deposition (VLS) in Ar atmospheres containing metal vapours [12-14]. To explore the reinforcing potential of these whiskers, an AA6061 alloy powder has been blended with 10% volume of Al_2O_3 whiskers and consolidated by extrusion. Powder metallurgy is especially suitable for producing aluminium alloy matrix composites (AMCs) because it prevents some wettability problems of Al_2O_3 in molten aluminium and deleterious reactions with the Mg atoms of the matrix that may appear during casting routes [15]. The microstructure and tensile properties of the 6061/Al_2O_3w composite have been evaluated at room and high temperature.

2. Experiments

The c-axis α-Al_2O_3 whiskers were obtained employing a cold-wall air-tight chamber furnace with alumina linings using 450 g of quartz sand blended with 45 g of Ni powder. A complete explanation of the experimental procedure for the obtaining of the alumina whiskers can be found in (14). VLS Al_2O_3 whiskers morphology was examined by scanning electron microscopy (SEM) and their composition systematically controlled via energy-dispersive X-ray spectroscopy and X-ray diffractometry.

Gas atomised 6061 aluminium alloy powder (particle diameter < 50 μm) was blended with 10% volume of Al_2O_3w in a planetary ball mill at 100 rpm for 2.5 hours with a ratio of balls to material of 7:1. The blend was consolidated by extrusion at 723 K, ram speed of 0.3 mm/s and extrusion ratio of 27:1. A monolith 6061 alloy bar was also processed from the alloy powder for comparison purposes.

The consolidated materials were solution heat treated at 793 K for 0.5 hours and water quenched. Cylindrical tensile specimens of 3 mm diameter and 20 mm gauge length were employed to perform tensile tests on T6 specimens (maximum hardness). Yield stress ($\sigma_{0.2}$), ultimate tensile strength (UTS) and elongation to fracture (ε) were determined at room temperature (RT) and at 373 K, 473 K and 573 K at a strain rate of 5×10^{-4} s^{-1}. Elastic modulus was measured on cylindrical samples of 6 mm in diameter and 40 mm in length according to ASTM E1876 and C1259. Microstructural characterization was performed by SEM with a FEG JEOL 6500. Image analysis of the composite was performed on backscattered electron images and data treated with Image-Pro Plus software.

3. Results and discussion

Figure 1 shows a SEM micrograph of a bundle of the as-produced VLS c-axis α-Al_2O_3 whiskers that can exhibit lengths of hundreds of microns with aspect ratios that can be larger than 100 and a high level of size dispersion. In the bundles, apart from alpha-alumina, traces of Ni, Fe, Si and SiO_2 were detected as extrinsic contamination.

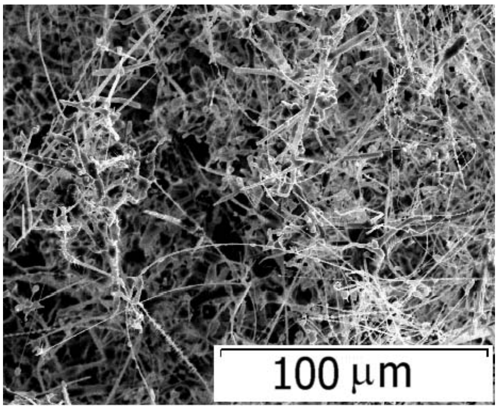

Fig. 1. VLS Al_2O_3 whiskers.

The 6061/Al_2O_3w extruded composite show no agglomerates and no band structure, typically found in extrusion of powders. The Al_2O_3 whiskers appear shorter in average indicating that they became broken during the processing. Image analysis revealed that the composite presents about 15% volume of Al_2O_3 whiskers, i.e. aspect ratio above 5, which are typically between 10 and 20 μm long and 2 to 4 μm in diameter. The remaining Al_2O_3 show an aparent aspect ratio below 5 and diameter of about 2 μm. Whiskers are aligned along the extrusion direction, so that 90% of them have their major axis inside an angle of less than 20º around this direction. This alignment occurred during the extrusion [16]. Apart from the Al_2O_3 whiskers, three types of particles appear as contamination from the alumina whiskers production process: Ni(Fe)-rich, Si-rich and Si- and O-rich particles. These will be described below in more detail.

In comparison with the unreinforced alloy, the 6061/Al_2O_3w composite presents significantly higher tensile (and specific properties) for the whole temperature range, Figure 2. Comparison with 6061 matrix composites reinforced with Al_2O_3 particles [5-7] shows the considerable advantage of Al_2O_3w, even when comparing with composites reinforced with 20% volume of particles [5, 7], while keeping an ε of 4%. In contrast, when test temperature is increased, tensile strength diminished more abruptly than in the other composites. On the other hand, elastic modulus of 6061/10%Al_2O_3w resulted in 90 GPa, higher than those of other 10%

volume Al_2O_3 reinforced composites [4, 7]. Moreover, specific elastic modulus of the composite is about 20% higher than that of the alloy matrix, i.e. 32x10^6 against 26x10^6 Nm/kg.

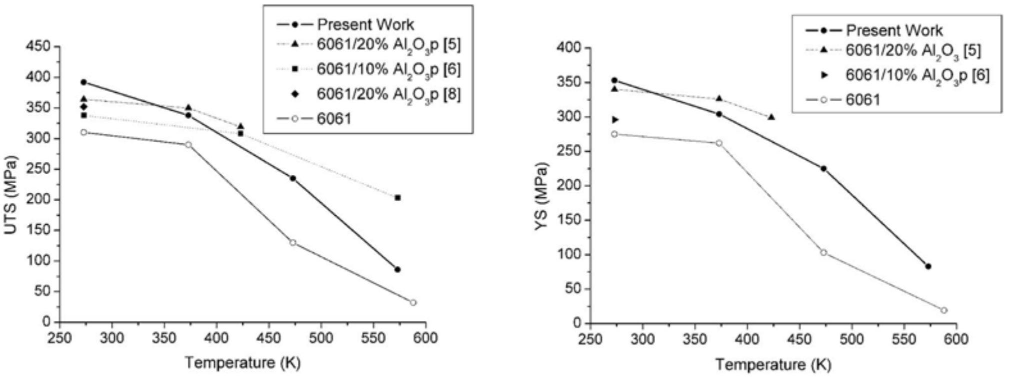

Fig. 2. UTS and $\sigma_{0.2}$ of 6061/10%Al_2O_3w, 6061 and comparable composites at different temperatures.

Figure 3a and b show backscattered images of longitudinal sections close to the fracture surface of specimens tested at RT. In addition to Al_2O_3, three types of particles are present. A first one appears brighter and is Ni-rich, with some Fe occasionally also being found. These particles are quite spherical in shape and of less than 5 μm in diameter. A second type, arrowed in Figure 3a, contains only Si, is bright-grey, irregular in shape and up to 30 μm in size. Finally, a third type, arrowed in Figure 3b, corresponds to SiO_2. These particles are very large polyhedrals (typically of about 100 μm in diameter) and are surrounded by a Mg and O-rich phase with Al_2O_3 whiskers sometimes embedded. Under RT tensile conditions the Al_2O_3 whiskers become mainly cracked, which indicates that the shear strength at the 6061 matrix/Al_2O_3 interface was higher than the Al_2O_3 whisker fracture strength, and thus, that a strong mechanical bond between matrix and reinforcement has been generated during the extrusion process [17]. With regards to the contaminating particles, those that are Ni-rich seem not to be affected during the tensile test so that most of them appear neither cracked nor debonded. In contrast, the Si particles appear mostly debonded from the matrix, whereas the SiO_2 particles appear catastrophically broken, with cracks running through them perpendicular to the loading direction. The fracture mechanism clearly changes at high temperature, as it is shown in the micrograph of Figure 3c. In this case, decohesion becomes the main cause of damage, so that void nucleation can clearly be observed at whisker and contaminant particle/matrix interfaces.

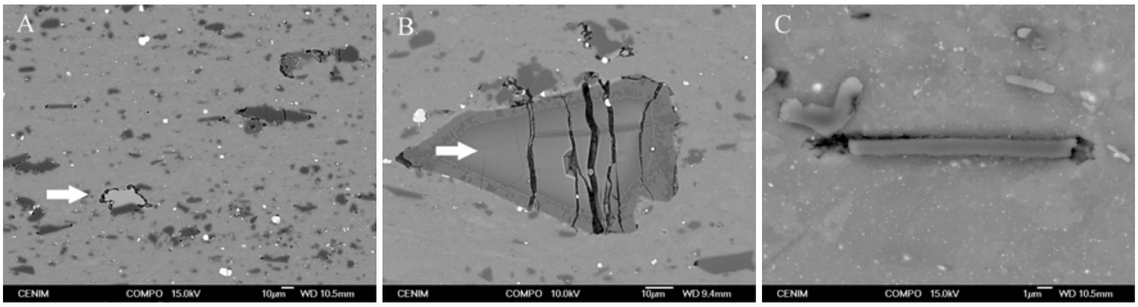

Fig. 3. Longitudinal sections close to the fracture surface of specimens tested at (a) and (b) RT, (c) 573 K.

The high RT tensile and specific tensile properties of the 6061/Al_2O_3w composite, even though it contains contaminating particles and even though the Al_2O_3w became broken during processing, validates the quality of the VLS alumina whiskers and the suitability of the fabrication route that promotes a strong bonding between matrix and reinforcement. Comparison with similar composites reinforced with Al_2O_3 short fibres or SiC whiskers is not straightforward because few results are available with the same matrix in T6. Composites with higher volume fraction of fibres or whiskers present, obviously, higher properties. For example, RT $\sigma_{0.2}$ and UTS of a 6061 alloy reinforced with 18% volume of short Al_2O_3 fibres [8] were 400 MPa and 470 MPa, respectively, and for 6061 reinforced with 20%SiCw [18, 19] were 440 MPa and 500 MPa, respectively, with similar UTS reported for a 6061/22%SiCw composite [20]. In all these materials, not only was reinforcement volume fraction about two times larger than in our composite material, but also median Al_2O_3w aspect ratios were as high as 100. This indicates that improved properties can be achieved for the 6061/Al_2O_3w composite by optimising the blending step, so that the large aspect ratio of the as-produced VLS Al_2O_3 whiskers can be preserved. Moreover, further improvement should be obtained if a cleaning protocol is applied to the Al_2O_3 bundles in order to eliminate the weakly adhered Si particles and the brittle SiO_2 ones.

4. Conclusions

VLS α-Al_2O_3 whiskers have been investigated as reinforcement in a powder metallurgy 6061/10% vol. Al_2O_3w composite. In comparison with the unreinforced alloy, the 6061/Al_2O_3w composite presents significantly higher mechanical properties and specific properties at room and high temperatures. At RT, comparison with 6061 matrix composites reinforced with Al_2O_3 particles shows the advantage of Al_2O_3w reinforcement, even when comparing with composites reinforced with 20% volume of particles. This is attributed to the high quality of the Al_2O_3 single crystals obtained by the VLS process and to the strong bonding between them and the 6061 alloy matrix attained during consolidation. Breaking of the whiskers occurred during processing. Three types of contaminating particles are present, coming from the VLS process: Ni(Fe)-rich, Si and SiO_2 particles. The first type did not affect tensile properties, whereas the other two clearly produced a deleterious effect. Improved properties are expected by enhancing the purity of the Al_2O_3w bundles and by preserving the high whiskers aspect ratio through optimisation of the blending parameters.

Acknowledgements

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Figure Captions

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