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# Investigation of aluminum-based nanocomposites with ultra-high strength

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ABSTRACT

Previously, we reported ultra-high compressive strength (up to 1065 MPa) for a bulk aluminum-based metal matrix nanocomposite [J. Ye, B.Q. Han, Z. Lee, B. Ahn, S.R. Nutt, J.M. Schoenung, Scr. Mater. 53 (2005) 481–486]. The mechanisms that are responsible for this significant strength increase over conventional materials (∼225 MPa, H. Zhang, M.W. Chen, K.T. Ramesh, J. Ye, J.M. Schoenung, E.S.C. Chin, Mater. Sci. Eng. A: Struct. Mater. Prop. Microstruct. Process. 433 (2006) 70–82) and even over other equivalent nanocrystalline materials (∼470 MPa, R.G. Vogt, Z. Zhang, T.D. Topping, E.J. Lavernia, J.M. Schoenung, J. Mater. Process. Technol., 209 (2009) 5046–5053) have not been studied in detail. The material consists of boron carbide reinforcement in a matrix with both coarse-grained and ultrafine-grained Al 5083; the processing introduces secondary phase dispersoids and dislocations. In this work, we systematically investigate the microstructural origins and the strengthening mechanisms, including Hall–Petch, Orowan and Taylor, as appropriate to each phase constituent. To provide insight into the relative contributions of these mechanisms, we calculate overall strength using rule-of-mixtures, modified shear-lag model, and Mori–Tanaka method.

## 1. Introduction

Particulate-reinforced metal matrix composites (MMCs) have the potential to provide tailored mechanical properties, for example, high specific stiffness and specific strength and creep resistance [1–3], which render them attractive for applications in the aerospace, defense and automotive industries to name a few [4–6]. Among the various MMCs, Al-based composites are of interest because of their low density and good formability [7,8]. These properties, in combination with recent interest in the high strength of nanostructured (NS) Al alloys [9–11] have prompted efforts aimed at using NS Al alloys as matrices in MMCs. These efforts have met with only limited success, partly as a result of the fact that the high strength in NS Al alloys is often accompanied with significantly diminished ductility [12–14]. A number of strategies have emerged in an effort to improve the poor ductility of NS materials [15–20]. In reference to these various strategies, numerous experiments have verified that the introduction of a bi/multi modal grain size distribution represents an effective approach to improve ductility while retaining a moderate strength level [17,21,22], because the NS microconstituent provides high strength while the coarse-grained (CG) microconstituent facilitates plasticity.

On the basis of these results, the novel concept of a tri-modal composite consisting of three phases: coarse-grained matrix, ultrafine- or nano-grained matrix and ceramic reinforcement was recently demonstrated [23]. $B_4C$ was selected as the ceramic reinforcement, because it ranks third in hardness, just after diamond and cubic boron nitride, and possesses a low density of 2.51 g/cm$^3$ (which is even less than that of Al) [24]. Al 5083 was selected as a matrix material, given its importance in many applications [25]. This tri-modal composite, when tested in compression, exhibited extremely high strength (up to 1065 MPa), with a compressive strain-to-failure value of 0.8% [23]. Although the level of plasticity in this material is still quite low, it should be noted that without the addition of the coarse-grained material, the consolidated cryomilled Al 5083 plus $B_4C$ failed in a brittle mode without any yielding [26]. Equivalent conventional and nanocrystalline materials exhibit significantly lower strengths (∼225 MPa [27] and ∼470 MPa [28], respectively), motivating the need to better understand the microstructural features that lead to this extremely high strength for an aluminum metal matrix composite.

There are two strengthening mechanisms that are typically associated with conventional MMCs: direct strengthening resulting from load transfer from the metal matrix to the reinforcing particle [29,30] and indirect strengthening resulting from the influence of reinforcement on matrix microstructure or deformation mode [31], such as dislocation strengthening induced by the deformation mismatch between the reinforcement and the matrix. In the case of the tri-modal composite, one needs to understand the individual roles of the UFG and CG microconstituents [29] and the accompanying grain refinement, Orowan (e.g., secondary phase dispersoids) and Taylor (dislocation based) strengthening mechanisms [32–35].

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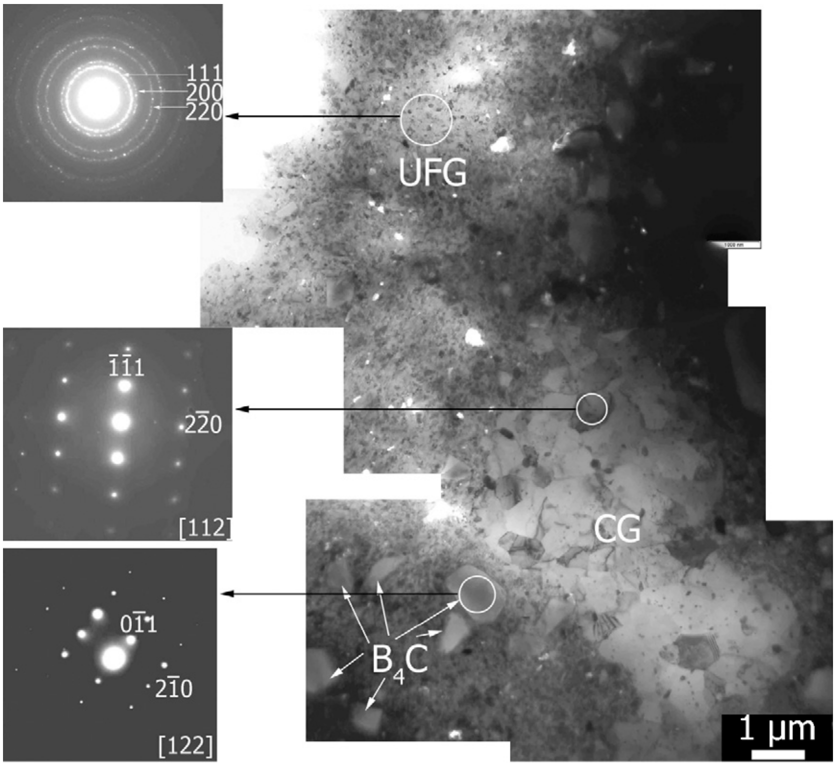

**Fig. 1.** The cursory distribution of coarse-grain (CG), ultrafine-grain (UFG) and $B_4C$ microconstituents in the tri-modal Al 5083 based composite and their corresponding selected-area electron diffraction (SAED) patterns. The SAED patterns were obtained from the circle areas; the plane indexes and zone axis are marked in them.

Published results show that the strength of a tri-modal Al 5083 based composite, as calculated from the Hall–Petch relationship, and invoking an Orowan strengthening mechanism and the rule-of-mixtures, was 792 MPa [23], which is about 273 MPa lower than the experimental value. This discrepancy, in addition to the lack of published studies on this material, suggests that the microstructural origins of the strengthening behavior require further study.

In this work, we have performed systematic microstructure studies on the UFG and CG Al 5083 matrix in the tri-modal Al 5083 based composite specifically aimed at characterizing the following: (1) grain size and distribution, (2) composition and distribution of secondary phase dispersoids by scanning transmission electron microscopy (STEM) and energy dispersive X-ray spectroscopy (EDX), (3) dislocation density and configuration by high resolution electron microscopy (HREM), and (4) interface structures between

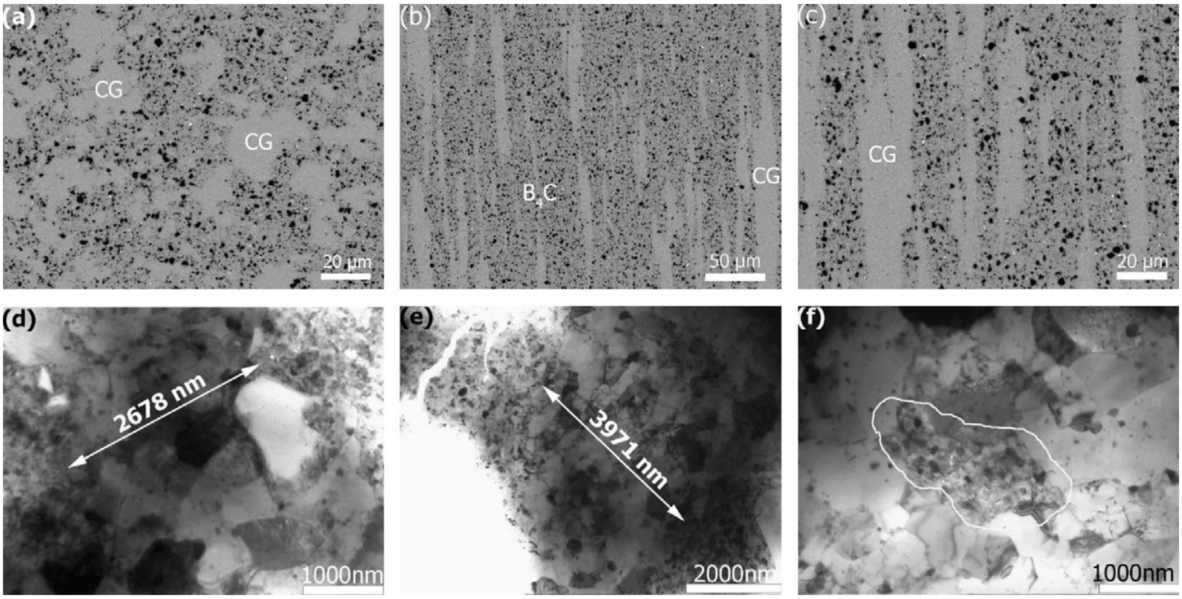

**Fig. 2.** Back-scattered electron images (BSE) showing the distribution of the UFG, CG, $B_4C$ microconstituents in the tri-modal Al 5083 based composite from (a) top view and (b and c) side view; (d and e) TEM images showing the distance between two UFG regions; (f) an UFG region (encircled by white line) enclosed by CG regions.