Engineering Properties via Microstructure Design of Commercial Scale Lightweight Nanoengineered Aluminum Composites

B. Yao[1], T. Patterson[1], C. Hofmeister[1], H. Heinrich[1], Y.H. Sohn[1], G. Wolfe[2], M. van den Bergh[2], K. Cho[3]
[1] Advanced Materials Processing and Analysis Center, University of Central Florida, Orlando, FL 32816-2455
[2] DWA Aluminum Composites, Chatsworth, CA 91311
[3] U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005

Introduction

Nanostructured aluminum (Al) alloy based metal matrix composites (MMCs) have attracted considerable interest due to their excellent properties (i.e., high strength, low density, and good corrosion resistance), technical and economical ease of manufacturing [1]. However, a low tensile ductility of these composites exhibited at room temperature can limit their practical use [2]. Recently, an Al tri-modal composite reinforced with boron carbide (B_4C) particulates has been fabricated successfully, which exhibited an extremely high yield strength and tailorable ductility [3]. The fabrication of this composite starts from the cryomilling of 5083 Al alloy powders with B_4C particles, which yields agglomerates containing sub-micron B_4C particles solidly bonded with nanocrystalline Al (NC-Al) grains. These B_4C/NC-Al agglomerates are then blended with coarse grain Al (CG-Al) powders, and consolidated to form the bulk Al tri-modal composites. Postulations built into processing of tri-modal Al composites suggest that the B_4C particles and NC-Al provide the high strength, and the presence of CG-Al phase controls the ductility of the composite. This paper highlights microstuctural features that influence the strength of tri-modal Al composites, based on our extensive structural and spectrometric characterization. Our research aims to provide a clear understanding of the strengthening and failure mechanisms of the multi-scale structured composites.

Processing Sequence

Figure 1 illustrates the manufacturing process of tri-modal Al MMCs. The cryomilling of B_4C particles and 5083-Al alloy powders is a critical initial step, which reduces the grain size of the Al phase down to less than 30nm, decreases the B_4C particle size, forms the solid B_4C/NC-Al bonding, and potentially mechanically alloys Nitrogen into the NC-Al. The cryomilling process also has other advantages including prevention of oxidation, suppression of recrystallization, formation of interfaces that can contribute to strengthening, and flexibility in constituent control. The B_4C/NC-Al agglomerates obtained through cryomilling process are then mechanically blended with 5083 CG-Al powders, and degassed under vacuum. The degassed powders can be consolidated with a variety of processes such as vacuum hot press (VHP), cold isostatic pressing (CIP) followed by hot press, or hot isostatic pressing (HIP). These composites are produced in general by secondary processing under high or low strain rate (H- or L-SR) extrusion and rolling conditions.

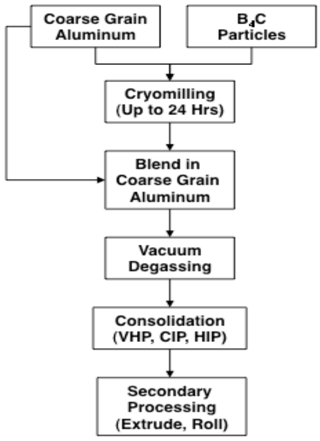

Fig. 1. Manufacturing processing of tri-modal Al MMCs.

In addition to starting composition, processing variables in each manufacturing step (e.g, cryomilling, blending, degassing, consolidation, and secondary processing) can significantly influence the final microstructure and thus properties. Extensive and quantitative microstructural analyses are being carried out at every manufacturing step to investigate microstructural development in tri-modal Al MMCs. This study will help optimize the commercial-scale manufacturing process, and contribute to the understanding of multi-scale microstructure-properties relationships, particularly for composites.

Trimodal Microstrcture and Strenghening Factors

The multi-scale microstructure of the tri-modal Al MMC is presented in Fig. 2. Using optical microscopy at low magnification, the CG-Al regions appear bright, while the B_4C/NC-Al agglomerates appear dark in Fig. 2(a). Fig. 2(b) presents a TEM bright-field image containing these three microstructural constituents. Exact dimensions and the distribution of each constituent of this composite is determined by the manufacturing process and will influence the properties. Although not complete, major strengthening factors for tri-modal Al MMCs may include:

1. Volume (or weight) fraction of each constituent, NC-Al, CG-Al and B_4C (e.g., starting composition held constant in this study at 14 wt.% B_4C, 56 wt.% NC-5083Al, and 30 wt. % CG-5083Al).
2. Grain size and distribution of NC- and CG-Al alloy.
3. Dispersoids (size and distribution) in NC- and CG-Al alloy (e.g., intrinsic precipitates).
4. Size and distribution of B_4C particle reinforcement.

5. Density and structure of dislocations in NC- and CG-Al alloy regions.
6. Size and distribution of hierarchal microstructural domains, e.g., CG-Al and (NC-Al+B_4C) agglomerates.
7. Composition, distribution and structure of Nitrogen incorporated during cryomilling.
8. Grain boundaries and interfaces (e.g., NC-Al and B_4C, NC-Al and CG-Al, CG-Al and B_4C)
9. Other impurity-associated strengthening by solution or dispersion reinforcement (e.g., Al_2O_3).

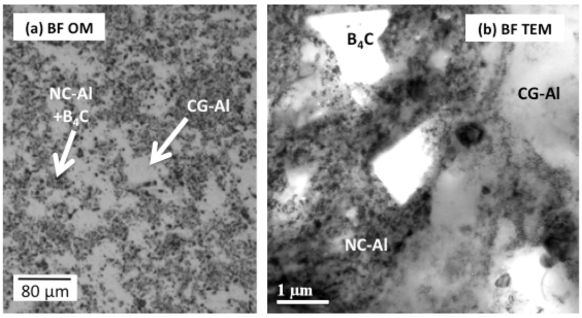

Fig. 2. The multi-scale microstructure of tri-modal Al MMCs examined by (a) optical and (b) TEM bright-field.

Figure 2(a) shows that the grain size of CG-Al can range from 30-100 μm, and is easily controlled during blending. Figure 3(a) shows a typical NC-Al microstructure after secondary extrusion (normal direction with aspect ratio 1:3). Typically, NC-Al grains less than 30μm in size are observed after cryomilling (up to 24 hours). Depending upon the manufacturing process (e.g., time and temperature) after cryomilling, an increase in grain size of the NC-Al is observed, and the reduction of NC-Al grain growth can strengthen the tri-modal Al MMCs. The dimension of B_4C particles gradually decreases during cryomilling. The B_4C/NC-Al agglomerates after a 24-hour cryomilling cycle contain B_4C particles ranging from less than 100 nm to several μm, as presented in Fig. 3(b) with an average size of several hundred nanometers. A high density of small dimension B_4C particles can increase the strength significantly.

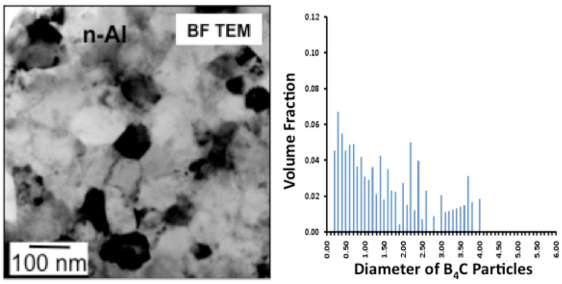

Fig. 3. Typical grain microstructure of NC-Al and particle size distribution of B_4C in trimodal MMCs.

The size and distribution of hierarchical microstructural domains, i.e., size and distribution of CG-Al and (NC-Al+B_4C) agglomerates can also significantly influence the overall performance of tri-modal MMCs. Figure 4 shows an optical micrograph of tri-modal Al MMCs with a great variation in the size and distribution of CG-Al and the cryomilled agglomerates (i.e., NC-Al + B_4C). The composite shown in Fig. 4(a) has a yield strength 25% higher than that shown in Fig. 4(b), despite a similar NC-Al grain size. Smaller CG-Al and cryomilled agglomerate domains would be beneficial.

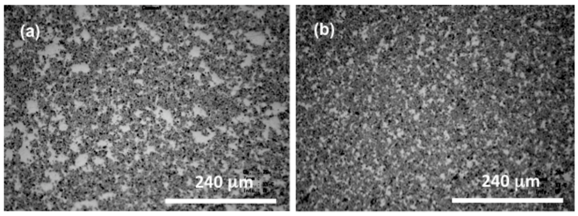

Fig. 4. Trimodal MMCs with variation in CG-Al and cryomilled agglomerate domain size.

Spectroscopic analysis by secondary ion mass spectroscopy (i.e., depth profiling) indicates that tri-modal MMCs with varying manufacturing processes vary in nitrogen content by a few orders of magnitude. A high concentration of N can strengthen the composite by supersaturated solid solutioning and/or dispersion strengthening (e.g., N-containing dispersoids). Extensive investigation by EELS/HRTEM demonstrates that the Nitrogen may not be distributed uniformly, instead, it is mainly located at amorphous domains inside the NC-Al phase and at the B_4C/NC-Al bonding interfaces. Mechanically trapped N during the cryomilling process can react with the crystalline phase, and form an amorphous phase locally without crystallization. A high density of dislocations inside the NC-Al, CG-Al and near the B_4C/NC-Al interfaces has been observed for the tri-modal Al MMCs, particularly after the secondary processing. Quantification of dislocation densities and structural characteristics of dislocations are currently being examined to elucidate the exceptional strength of tri-modal Al MMCs.

Conclusion

Critical factors contributing to the exceptional strength of tri-modal Al MMCs manufactured on a commercial scale were examined via comprehensive microstructural and spectroscopic analysis. Size and distribution of NC-Al grains, B_4C particles, CG-Al, and uniformity in distribution were examined. Other factors such as Nitrogen and dislocation density also play important roles for tri-modal Al MMCs. Commercial-scale manufacturing processes are being optimized based on a scientific understanding of multi-scale microstructure-properties relationships for tri-modal Al MMCs.

References

1. D.B. Miracle S.L. Donaldson: *ASM Metals Handbook* - Introduction to Composites., Vol. 21 (2001) 39-67.
2. Y. Wang, M. Chen, F. Zhou, E. Ma, *Nature*, 419 (2002), 912-915.
3. J. Ye, B.Q. Han, Z. Lee, B. Ahn, S.R. Nutt, J.M. Schoenung, *Scripta Mater.*, 53 (2005) 481-486.