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# Structure and mechanical properties in a powder-processed icosahedral-phase-strengthened aluminum alloy

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ABSTRACT

Nanocomposite powder particles of aluminum with dispersed icosahedral quasicrystals were produced by gas atomization from an Al-Cr-Mn-Co-Zr alloy. Bulk dispersion-strengthened material was obtained from the powder by blind-die compaction and forging. The material exhibited an attractive combination of room temperature mechanical properties with a dynamic elastic modulus of 90.5 GPa, a tensile yield strength of 690 MPa with 6% elongation to failure, and a high cycle fatigue life of $10^9$ cycles at 207 MPa applied stress. The material also exhibited significant potential for elevated temperature applications with a modulus of 75 GPa and yield strength of 400 MPa at 300 °C.



Quasi-crystalline phases were first observed in rapidly solidified Al-Mn alloys [1–3], but have also been reported in a wide variety of ternary alloy systems. A good understanding has now been developed of quasi-crystalline structure [4–6] and the crystallography of the related approximant phases [7–9]. Although the complex aperiodic structures of quasi-crystals inhibit plasticity, dislocations do form in these materials, and some limited plastic deformation is observed [10–12]. There has been great interest in the possibility of incorporating quasi-crystals as strengthening dispersoids in metallic matrices. Results obtained from melt-spun ribbons indicate that exceptional combinations of properties might be achievable (e.g. [13,14]), but melt-spinning is not appropriate for the production of engineering materials in a useful form. As such, different processing strategies are required. There has been considerable progress in this regard for Mg alloys (e.g. [15–17]), but Al alloys are more challenging because of the higher critical cooling rates required for quasi-crystal formation (e.g. [18–20]). This has led to a variety of alternate approaches being adopted to obtain Al/quasi-crystal composites including: sintering mixtures of quasi-crystal and Al powders [21–23], mechanical alloying [24,25], mechanical mixing of quasi-crystalline particles into surface layers [26], and Al infiltration of porous quasi-crystalline preforms [27]. To our knowledge the only previous report of such materials being produced by consolidation of gas-atomized Al/quasi-crystal composite powder is an isolated study on an $Al_{94}Cr_1Mn_3Cu_2$ alloy by Haas et al. [28]. In this latter study, small (12 mm diameter) composite rods were produced by extrusion of powder, but this approach does not appear to have been pursued further.

In our studies we have explored the use of powder metallurgy routes to produce a range of advanced Al alloys with high strength and good thermal stability. In much of this work, the emphasis has been upon Al-rare earth-transition metal alloys with moderate glass-forming ability. A good understanding of the processing/structure/property relationships has been developed for Al-rare earth (RE)-Ni alloys [29–34]. These are marginal glass formers, but processing via a metastable vitreous intermediate allowed for the solubility limits of FCC Al to be bypassed. Upon consolidation, devitrification occurs giving a high volume fraction of strengthening $Al_{19}Ni_5RE_3$ plates. Initial attempts to extend this approach to Al/quasi-crystal composites were unsuccessful. Gas atomized powders of an Al - 5 Mn - 2 Ce (at. %) alloy were consolidated by warm extrusion [35]. While the alloy composition chosen was one at which quasi-crystals had been formed in previous studies [18, 36–38], the cooling rate was clearly insufficient, and a mixture of metastable crystalline phases was formed instead. These metastable phases included an $Al_{20}Mn_2Ce$ compound that had not been reported previously in this system. In a recent study by Coury et al. [39] on melt-spun ribbons of several Al-Mn-Ce alloys it has been shown that the $Al_{20}Mn_2Ce$ compound is a common feature in these alloys; and, it was also suggested that this phase is probably present in the earlier work by Inoue et al. [36] and Schurack et al. [18].

In subsequent work we have explored the use of rare-earth-free Al alloy compositions with the emphasis on identifying combinations of transition metals that lead to the formation of quasi-crystals at lower

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cooling rates. Here we present a study on bulk Al/quasi-crystal composites produced via the consolidation of gas-atomized powders of a quinternary Al-Cr-Co-Mn-Zr alloy. It is shown that the alloy powder contains a mixture of Al and an icosahedral quasi-crystal phase (I-phase). The large volume of material produced enables the mechanical characteristics of the material to be evaluated using standard mechanical tests, including dynamic modulus, tensile and high-cycle fatigue (HCF). These composites exhibit a very attractive combination of properties and it is proposed that materials of this type could form the basis of the first practical quasicrystal-strengthened aluminum alloy for structural applications.

The powder metallurgy route used here is similar to that adopted in our previous studies [33–35]. A master alloy with a composition of Al - 2.6 Cr - 1.6 Co - 1.5 Mn - 0.5 Zr (at.%) was produced by vacuum induction melting at Great Western Technologies (Troy, Michigan) and then cast into ingots. Powder was produced from this alloy at Valimet Company (Stockton, California) by gas atomization. The ingots were melted in a crucible under argon gas cover, and the molten stream was atomized using high-pressure helium gas. The powder was sieved to −450 mesh (≤34 μm) and then canned at DWA Aluminum Composites (Chatsworth, California). Approximately 50 kg of sieved powder was introduced into a 25 cm diameter CP Al extrusion canister, degassed dynamically by evacuating the can to $\approx 150 \times 10^{-6}$ Pa, and then sealed. The canned powder was consolidated by blind die compaction in a 4500-tonne extrusion press at H. C. Starck (Coldwater, Michigan). The cans were preheated to ≈ 310 °C, pressed, and then fan-cooled to room temperature.

The microstructures of the powder and the compacted material were evaluated by X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The XRD data were acquired in a Bragg-Brentano geometry using a PANalytical Empyrean diffraction system using CuKα radiation and equipped with programmable divergent slits and anti-scattering slits and a PIXcel detector. The PIXcel detector was used in line data collection mode. The XRD measurements were performed with a scan step of approximately 0.016° over a 2θ range of 10–95°. Phase identification was performed using the PANalytical software X'Pert High Score Plus with the ICDD PDF4 database. All of the XRD peaks obtained from the gas-atomized powder and from the blind-die compacted material corresponded to those expected for a two-phase mixture of FCC Al plus the I-phase. An example of one such data set with the main Al and I-phase peaks indexed is shown in Fig. 1(a). The morphology and distribution of the phases was investigated by SEM and TEM. Samples for SEM were prepared using standard metallographic techniques. Sections were ground to 1200 grit and then polished using 0.02 μm colloidal silica. Backscattered electron (BSE) SEM images were acquired from the as-polished surface using a FEI Teneo LVSEM at an accelerating voltage of 5 kV; an example of such an image from the blind-die-compacted material is shown in Fig. 1(b). The dispersoids appear bright in such images whereas the Al matrix is dark. The dispersoids adopt an equiaxed morphology, and the mean volume fraction measured from such images is approximately 35%, although this varies somewhat from area to area. Moreover, the sizes of the dispersoids are similar within each powder particle, but the size does vary significantly from one powder particle to another.

Further evidence of this can be seen in TEM data from the blind-die-compacted material. Thin-foil TEM samples were prepared by grinding sections cut through the material to 100 μm in thickness, punching 3 mm diameter disks, and then thinning to electron transparency by twin-jet electro-polishing to perforation using an electrolyte consisting of 90% methanol and 10% perchloric acid at approximately −20 °C and 20 V. TEM analysis was performed using a FEI T12 Tecnai S/TEM operated at 120 kV equipped with an ultra-thin window EDAX energy-dispersive X-ray spectrometer (EDXS). Quantification of EDXS data was performed using library standards on the basis of thin film approximation. A bright field (BF) TEM image obtained from a region where the prior powder particles are revealed particularly clearly is shown in Fig. 1(c). The dispersoids in the two prior powder particles in the center

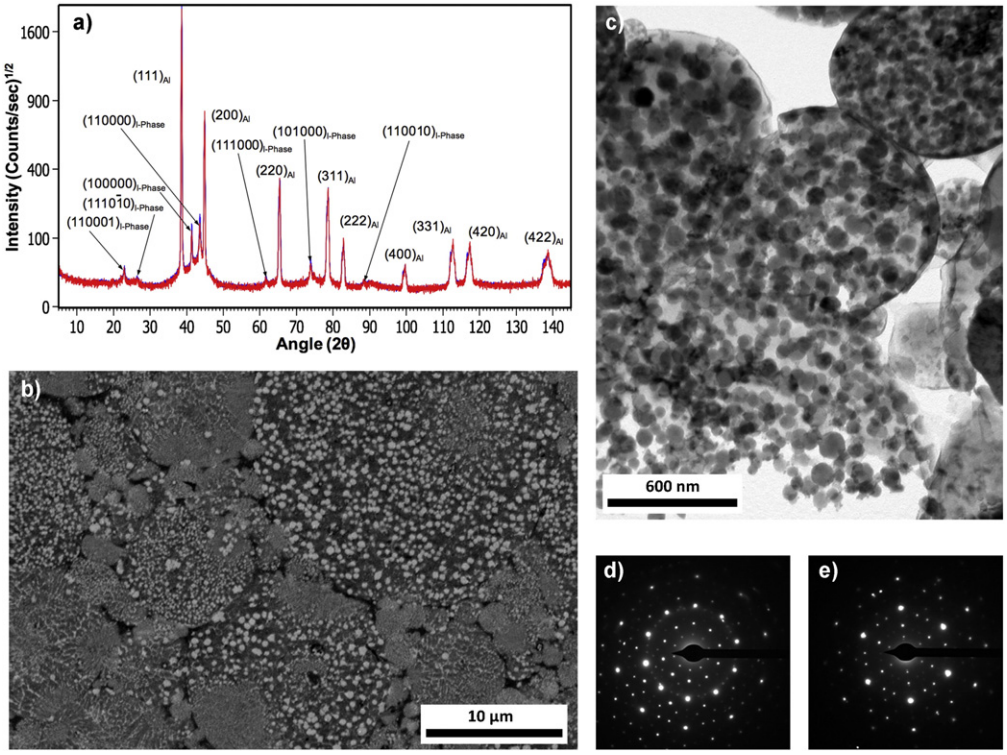


**Fig. 1.** Microstructural data from the gas-atomized and blind-die-compacted powder: (a) XRD data consistent with a two-phase mixture of FCC Al and I-phase; (b) BSE SEM image showing the distribution of the bright I-phase particles in the dark Al matrix; (c) BF TEM image showing the spherical morphology and the size uniformity of the I-phase within prior powder particles; (d) and (e) SADPs obtained from I-phase particles corresponding to the five-fold [000001] and three-fold [110000] zone axes, respectively.