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Strengthening mechanisms in an Al-Fe-Cr-Ti nano-quasicrystalline alloy and composites

S. Pedrazzini [a,*], M. Galano [a], F. Audebert [a,b,c], D.M. Collins [a], F. Hofmann [d], B. Abbey [e], A.M. Korsunsky [d], M. Lieblich [f], A. Garcia Escorial [f], G.D.W. Smith [a]

[a] Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK
[b] INTECIN, School of Engineering, University of Buenos Aires, Paseo Colon 850, Ciudad de Buenos Aires, Argentina
[c] Department of Mechanical Engineering and Mathematical Sciences, Oxford Brookes University, Wheatley Campus, OX33 1HX Oxford, UK
[d] Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK
[e] ARC Centre of Excellence in Advanced Molecular Imaging, La Trobe University, Victoria 3086, Australia
[f] Department of Physical Metallurgy, CENIM-CSIC, Avda. Gregorio del Amo 8, Madrid, Spain

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ABSTRACT

We report a study of the structure-processing-property relationships in a high strength $Al_{93}Fe_3Cr_2Ti_2$ nano-quasicrystalline alloy and composites containing 10 and 20 vol% ductilising pure Al fibres. The superimposed contributions of several different strengthening mechanisms have been modelled analytically using data obtained from systematic characterisation of the monolithic alloy bar. An observed yield strength of 544 MPa has been substantiated from a combination of solid solution strengthening, work hardening, precipitation hardening and Hall-Petch grain size dependent effects. These materials have been shown by other authors in previous published work to be highly sensitive to the size distribution of particles in the powder from which they are made, and the subsequent thermomechanical processing conditions. The processing condition employed in this study provided micron-sized grains with a strong [111] preferential orientation along the extrusion direction and a bimodal size distribution of the icosahedral nano-quasicrystalline precipitates. Both were deemed to be a significant contributor to the high yield strength observed. The addition of pure Al fibres was found to decrease the yield strength linearly with increasing Al content, and to augment the ductility of the composites.

1. Introduction

Novel, high performance aluminium-based alloys with nano-scale dispersoid phases offer exceptional mechanical properties, far superior to conventional aluminium alloys, making them attractive for widespread use in automotive and aerospace applications. In particular, nano-quasicrystalline Al-based alloys, produced through a rapid solidification process, have shown excellent tensile and specific strength properties [1–3]. However, their use has been limited by temperature sensitivity both during service and thermo-mechanical processing and the variation in performance depending on the bulk processing route used. Galano et al. [4] demonstrated that the addition of Ti, V, Nb or Ta alloying elements improves the thermal stability of the icosahedral phase within Al-Fe-Cr alloys in melt-spun ribbons.

Rapid solidification can be achieved by a number of methods, however gas atomisation is one of the few methods that can be used on an industrial scale. The influence of processing parameters during consolidation and their effect on the mechanical properties of the extruded material have been tested on nano-quasicrystalline $Al_{93}Fe_3Cr_2Ti_2$ at% alloy by Todd et al. [2]. They found that increasing the extrusion ratio of 25–50 μm powders from 10:1 to 14:1 at 400 °C provides a $<3\%$ increase in yield strength. Decreasing the powder particle size from 50 to 100 μm to 25–50 μm caused a much more substantial ~35% increase in yield strength during quasi-static, room temperature tensile tests. It is worth mentioning that Todd et al. [2] found a larger proportion of quasicrystals in the powder sizes between 25 and 50 μm than in the 50–100 μm range.

Systematic studies of nanostructured Al-based melt-spun ribbons to assess the resulting tensile strengths were conducted at room temperature by Audebert et al. [5] and at 350–500 °C by Galano et al. [3]. Each study suggested that the outstanding mechanical properties of the alloys were due to the combined effect of solid solution strengthening, particle dispersion and grain refinement strengthening. The influence of each strengthening mechanism on the resulting behaviour was not quantified in these studies. However, a study was performed on an $Al_{92.4}Fe_{1.2}Cr_{3.3}Ti_{2.4}Si_{0.7}$ at% alloy produced by powder metallurgy

* Corresponding author.

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and extruded at 450 °C from powder particles sizes <45 μm. The authors found that the Hall-Petch effect was the most dominant mechanism [6]. Vojtěch et al. [6] found that the Orowan strengthening effect was the next largest contributor, whilst solid solution strengthening was deemed to be negligible due to the hot processing method used. This assumes that a low solute content is retained in solid solution in the matrix following rapid solidification, heat treatment and thermal-mechanical processing.

Whilst the specific mechanical strength of nano-quasicrystalline $Al_{93}Fe_3Cr_2Ti_2$ at% alloys is far superior to any current commercial Al-based alloys, their ductility and strain to failure have thus far proven inferior. Nagy et al. [7], working with bars made by cryomilling a melt-spun $Al_{94}V_4Fe_2$ (at%) alloy with <1 μm pure Al powder then extruding at 420–450 °C, improved the overall ductility of the composites in comparison to the monolithic $Al_{94}V_4Fe_2$ alloy. In the present work, the correlation between the microstructure and mechanical properties of bulk processed nano-quasicrystalline $Al_{93}Fe_3Cr_2Ti_2$ at% alloy and composites with 10 and 20 vol% pure Al ductilising fibres has been investigated. A suite of multi-scale characterisation and mechanical testing tools have been used to quantify the contributions of different strengthening mechanisms to the overall strength of the alloy, then the rule of mixtures was used to predict the strength of the composites.

2. Experimental procedure

Gas atomised powder of nominal chemical composition $Al_{93}Fe_3Cr_2Ti_2$ and commercially pure Al powder were provided by Alpoco Ltd. and sieved to <25 μm. The powders were then weighed, mixed and packed into an Al can without prior compaction or degassing and extruded at CENIM, Madrid. Extrusions were performed at 380–400 °C, with a ram velocity of 0.3 mm/s and an extrusion ratio of 14:1. The conditions were selected based on the study performed by Todd et al. [2]. This process produced three bars ~1 m long and 12 mm in diameter prior to the removal of the extrusion can from each surface.

To visualise fibre distributions in 3D and to assess the content of residual porosity present in the samples, synchrotron X-ray micro-tomography was performed at the TOMCAT beamline at the Swiss Light Source (SLS). Two samples of size 1 mm diameter of each material containing nominally 0, 10 and 20 vol% pure Al fibres

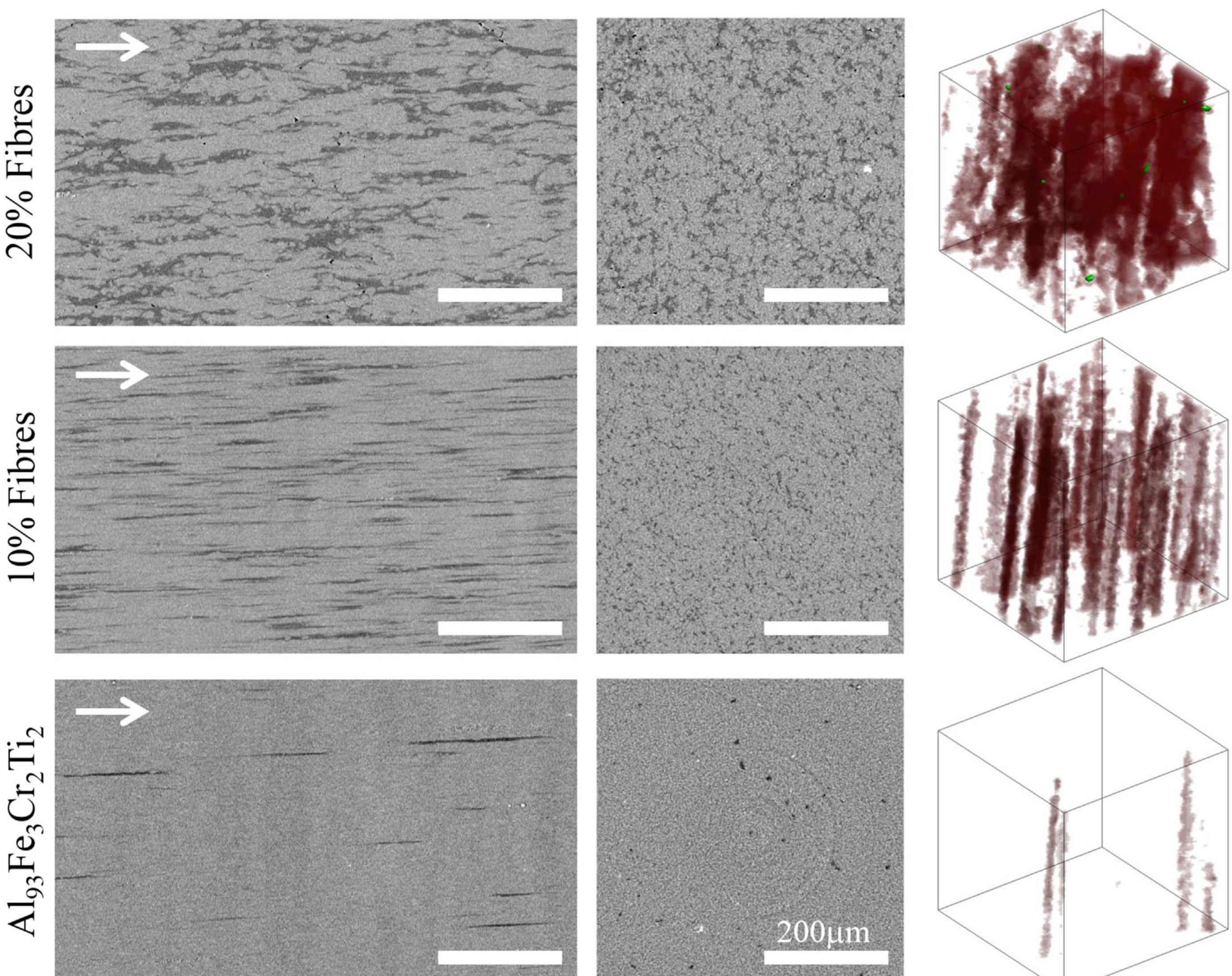

Fig. 1. X-ray tomography micrographs showing the distribution of pure Al fibres (dark grey) within the Al-Fe-Cr-Ti alloy matrix (lighter grey) for samples containing nominally 20%, 10% and 0% fibres. Longitudinal sections parallel (indicated by an arrow) and cross sections perpendicular to the extrusion direction are shown. Also shown are 3D cubes reconstructed and segmented from the tomography data. Fibres are rendered in translucent red, whilst voids (visible in the "20% Fibres" data) are rendered in green. The size of the rendered cubes is $74\times74\times74$ μm^3.