Al-matrix composite materials reinforced by Al-Cu-Fe particles

J Bonneville, G Laplanche, A Joulain, V Gauthier-Brunet and S Dubois
Université de Poitiers, PHYMAT, CNRS-UMR 6630, SP2MI, F-86962 Chasseneuil
joel.bonneville@univ-poitiers.fr

Abstract. Al-matrix material composites were produced using hot isostatic pressing technique, starting with pure Al and icosahedral (i) Al-Cu-Fe powders. Depending on the processing temperature, the final reinforcement particles are either still of the initial i-phase or transformed into the tetragonal $\omega$-Al$_{0.70}$Cu$_{0.20}$Fe$_{0.10}$ crystalline phase. Compression tests performed in the temperature range 293K – 823K on the two types of composite, i.e. Al/i and Al/$\omega$, indicate that the flow stress of both composites is strongly temperature dependent and exhibit distinct regimes with increasing temperature. Differences exist between the two composites, in particular in yield stress values. In the low temperature regime ($T \leq 570K$), the yield stress of the Al/$\omega$ composite is nearly 75% higher than that of the Al/i composite, while for $T > 570K$ both composites exhibit similar yield stress values. The results are interpreted in terms of load transfer contribution between the matrix and the reinforcement particles and elementary dislocation mechanisms in the Al matrix.

1. Introduction
Icosahedral quasicrystalline (i-QC) materials exhibit very attractive mechanical properties such as high hardness, high elastic modulus and elevated yield stress. However, they all suffer from a serious drawback for industrial applications due to their extreme brittleness up to high temperatures. A possibility to take advantage of their high mechanical properties is to use them as reinforcement particles in composite materials.

The mechanical properties of Al-based composite materials reinforced by i-QC particles are little known, even unclear. Tsai et al. [1] were the first to produce Al-metal matrix composites (MMCs) reinforced by Al-Cu-Fe i-QC particles. Using a hot isostatic pressing (HIP) technique, they highlighted that for a processing temperature of 673 K the i-QC phase of the reinforcement particles was preserved, while at 873 K a phase transformation of the i-QC reinforcement particles occurred. In the latter case, the i-QC phase was transformed into the tetragonal crystalline $\omega$-phase with the Al$_{0.70}$Cu$_{0.20}$Fe$_{0.10}$ composition. Tsai et al [1] also investigated the macro-hardness of both MMCs, i.e. Al/i and Al/$\omega$ MMCs, using Vickers indentations. They found for the two MMCs that the hardness $H_v$ increases with increasing volume fraction, $V_f$, of the reinforcement particle. In addition, they obtained that for $V_f$ ranging between 5% and 15% Al/i and Al/$\omega$ MMCs exhibit similar hardness, while for $V_f = 20\%$ and 25% $H_v$ is higher for the Al/i MMC than for the Al/$\omega$ MMC. The latter result was later confirmed by Kaloshkin et al. [2], but surprisingly these authors also found that the flow stress measured by compression tests was higher for the Al/$\omega$ MMC than for the Al/i MMC.
The aim of the present study is therefore to examine in detail the consequence of the phase transformation of the reinforcement particles on the mechanical properties of Al/Al-Cu-Fe MMCs. For this, Al/Al-Cu-Fe MMCs with reinforcement particles of the i-QC phase and of the ω-phase were produced using a hot isostatic pressing technique with an initial mixture of pure Al and i-QC Al-Cu-Fe powders. Crystallographic and chemical composition investigations were performed on the as-synthesised MMCs to identify the resulting phases. Compression tests were performed on the two types of MMC at constant strain-rate in the temperature range 293K-823K. The mechanical properties of both MMCs are reported and the results are interpreted in terms of possible strengthening sources.

2. Experimental procedures

Experimental details concerning i-QC powder processing and Al/Al-Cu-Fe MMC synthesis have already been reported elsewhere [3, 4]. They are here briefly summarised. A HIP method is used for producing both MMCs, which consists in hot pressing a green compact composed of a mixture of pure Al and i-QC Al-Cu-Fe powders. For the two composites, the initial volume fraction of the i-QC Al-Cu-Fe powder was adjusted in order to obtain a final volume fraction of 40% of Al-Cu-Fe reinforcement particles [3]. The main difference concerns the sintering temperatures, which is set to 673K for preserving the i-QC phase of the reinforcement particles and to 823K for producing the i-QC to ω-phase transformation. Pure Al samples were also produced by the same HIP process at 823K for a direct estimate of the reinforcement particle strengthening efficiency.

The crystallographic structure of the MMCs was determined by XRD experiments using a Bruker D501 diffractometer. Chemical composition was investigated by Energy Dispersive X-Ray Spectroscopy (EDXS) in a JEOL 5600LV scanning electron microscope. Deformation tests were performed in compression at a nominal strain rate of 1.4 x 10⁻⁴ s⁻¹ over the temperature range 293K-823K.

3. Experimental Results

3.1. Crystallographic features

Figure 1 shows two XRD profiles obtained on the two Al/Al-Cu-Fe MMCs after the HIP process at T = 673 K (fig. 1a) and T = 823 K (fig. 1b). All peaks are indexed in fig. 1a according to the Al face-centred cubic (fcc) structure and the i-QC Al-Cu-Fe structure and in fig. 1b according to the Al-fcc structure and the ω-Al-Cu-Fe structure. No other peak corresponding to an eventual third phase is detected in each profile that is, at the level of XRD detection, each MMC can be considered as two-phase materials. EDXS analyses confirm XRD patterns of figure 1a and 1b. The chemical composition of the reinforcement particles are Al₀.₆₄₉Cu₀.₂₂₆Fe₀.₁₂₅ for profile 1a and Al₀.₇Cu₀.₂Fe₀.₁ for profile 1b, which correspond to the i- and ω-phase respectively. It must be noticed that a third composition close to...
to $\text{Al}_{0.732}\text{Cu}_{0.058}\text{Fe}_{0.210}$ is detected by EDXS in some places inside the reinforcement particles of both MMCs. The latter phase is not detected by XRD due to its low volume fraction, but certainly corresponds to the $\lambda$-$\text{Al}_{13}\text{Fe}_{4}$ phase already reported in [5]. A low Cu content is also detected by EDXS at some places in the Al matrix of the two MMCs.

3.2. Mechanical properties

Figure 2 shows typical stress-strain curves of the two MMCs and pure Al at room temperature (RT). The shape of the stress strain curves is similar over all the investigated temperature range. After yielding, plastic deformation consists in a short transient with strong hardening that is followed by a plastic stage of almost steady state conditions. The stress drops on the Al and Al/i curves are due to load relaxation experiments. The conventional $\sigma_{0.2\%}$ proof stress, defined at 0.2% plastic strain, extracted from these curves is reported in fig. 3 as a function of temperature. A clear strengthening is observed for the two MMCs as compared with pure Al. The temperature dependence of $\sigma_{0.2\%}$ allows us to distinguish at least two temperature regimes. In the low temperature regime, below 550K, the Al/i MMC exhibits higher $\sigma_{0.2\%}$ values, which however decrease more rapidly with increasing temperature than those of the Al/i MMC. Above 550K, $\sigma_{0.2\%}$ behaves similarly for the two MMCs. It is remarkable that a break in the $\sigma_{0.2\%}$ temperature dependence is observed at approximately 550 K for pure Al as well.

4. Discussion

Using a HIP process we produced two Al-MMCs reinforced by Al-Cu-Fe particles. Depending on the synthesis temperature, the reinforcement particles are either of the initial i-QC phase or of the o-tetragonal phase in agreement with Tsai et al. [1]. This is also coherent with the high temperature (T>773K) phase diagram of Al-Cu-Fe [6, 7], which indicates that the i-QC phase does not coexist with the Al phase. In principle, the phase transformation occurring at $T = 823$ K from the i-QC to the o-phase only requires Al diffusion from the Al particles toward the i-QC particles and is accompanied by a volume expansion of the initial i-QC reinforcement particles. The phase transformation occurs with a migration of the Al/Al-Cu-Fe interfaces. Little Cu diffusion from the i-QC particles into the Al matrix is also revealed for the two MMCs, which may lead to matrix solid solution hardening.

The $\sigma_{0.2\%}$ stresses are larger for the two MMCs than for pure Al and exhibit with temperature for all materials two distinct temperature regimes. Several contributions can be responsible for the large flow stress strengthening of the two MMCs as compared to pure Al [8]. In particular, load transfer between matrix and reinforcement particles is considered as the major cause of strengthening for this type of
MMCs [9]. Load transfer is also very dependent from the type of interface between the matrix and the reinforcement particles. At low temperature, the interfaces are either of Al-fcc/i-QC type or Al-fcc/ω-tetragonal type depending on the considered MMC. It seems reasonable to assume that interfaces between quasiperiodic and periodic structures have different properties than interfaces between two periodic structures, which may partially explain the low temperature difference in $\sigma_{0.2\%}$ between the two MMCs. The stiff decrease of $\sigma_{0.2\%}$ with temperature for the Al/ω MMC can be hardly attributed to load transfer only, because it would require a drastic change in the interface nature, which is not expected at low temperature. Other contributions, such as geometrically necessary dislocations, grain sizes and thermal expansion coefficients, are not sufficient for explaining the recorded difference in $\sigma_{0.2\%}$ between Al/i-QC and Al/ω MMCs [10]. Transmission electron microscopy observations, not presented here, clearly demonstrate that plasticity takes place in the soft Al matrix [3, 11]. They also highlight that dislocation obstacles are of different nature in the two composites. Only pinning points are observed on dislocations in the Al/i-QC composite while small ω-particles impede dislocation movement in the Al/ω composite, with sizes ranging between 100 nm and 300 nm. This may account for the large stress increase of Al/ω MMC in comparison to Al/i-QC MMC [11]. At high temperature, similar recovery processes take place in the both matrices. Then, the difference between MMCs and pure Al mainly results from load transfer. Al/i-QC interfaces evolve with increasing temperature to Al/ω interfaces in agreement with the similar measured $\sigma_{0.2\%}$ values for both composites.

5. Conclusion

Two Al-MMCs were synthesized using a HIP technique. Depending on processing temperature, the initial i-QC phase of the reinforcement particles is preserved (T = 673K) or transformed into the ω tetragonal phase (T = 823K). A strong strength improvement is recorded for the two MMCs in comparison with pure Al. In addition at low temperature, $\sigma_{0.2\%}$ is larger for Al/ω MMC than for Al/i-QC MMC, which may be partly ascribed to better load transfer from the matrix to the reinforcement particles, resulting from better interfaces in the Al/ω MMC. The temperature dependence of $\sigma_{0.2\%}$ necessitates however to take into account dislocation mechanisms into the Al matrix. At high temperature, load transfer seems to be the major strengthening contribution for the two MMCS.

Acknowledgments

Région ‘Poitou-Charentes’ is acknowledged for financial support through a PhD fellowship.

References

[1] A. P. Tsai, K. Aoki, I. Akihisa, T. Masumoto : J. Mater. Res. 8, 5-7 (1993).
[2] S. D. Khaloshkin, V. V. Tcherdyntsev, A. I. Laptev, A. A. Stepashkin, E. A. Afonina, A. L. Pomachik, V. I. Bugakov: J. Mater. Sci. 39, 5399-5402 (2004).
[3] T. El Kabir, A. Joulain, V. Gauthier, S. Dubois, J. Bonneville: J. Mater. Res. 23, 904 (2008).
[4] G. Laplanche, A. Joulain, J. Bonneville, R. Schaller, T. El Kabir: submitted to J. Alloys Comp. (2009).
[5] E. Giacometti, J. Fikar, N. Baluc, J. Bonneville, Phil. Mag. Lett. 82, 183 (2002).
[6] F. Faudot, A. Quivy, Y. Calvayrac, D. Gratias, H. Havemel, Mater. Sci. Eng. A 133, 383 (1991).
[7] D. Gratias, Y. Calvayrac, J. Devaude-Rzepski, F. Faudot, H. M., A. Quivy, J. Non-Cryst. Solids 153-154, 482 (1993).
[8] T. W. Clyne and P. J. Withers: An Introduction to Metal Matrix Composites, Cambridge University Press (1993).
[9] F. Tang, I. E. Anderson, T. Gnaüpel-Herold, H. Prask, Mater. Sci. Eng. A 383, 362 (2004).
[10] T. El Kabir, PhD dissertation, University of Poitiers (2007).
[11] G. Laplanche, A. Joulain, J. Bonneville, V. Gauthier-Brunet, S. Dubois, T. El Kabir, accepted for publication in J. Mater. Res. (2009).