

# Solute Clustering and Rapid Hardening During Ageing of Al-Cu-Mg Alloys

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## INTRODUCTION

Al-Cu-Mg alloys which lie in the  $\alpha$ +S phase field and have a low Cu:Mg ratio exhibit a remarkably rapid hardness increase during ageing at elevated temperatures [1]. This rapid hardening phenomenon (RHP) occurs in Al-1.1Cu-xMg alloys that contain at least 0.5 Mg (at.%), and may provide > 50% of the total hardness increment within the first 100 seconds of ageing. Proposals to explain this phenomenon include the concept of solute cluster strengthening [2], where formation of solute-vacancy clusters act as strengthening agents by presenting a diffuse boundary of the pairing (or higher order combinations) of the clustered solute species and, more recently, the suggestion that the RHP arises from precipitation of very fine scale GPB zones [3].

The aim of the current work is to try and understand the underlying cause of the RHP during elevated temperature ageing of Al-1.1Cu-1.7Mg (at.%).

- [1] J.T. Vietz and I.J. Polmear, J. Inst. Metals **94** (1966), p. 410-419.
- [2] S.P. Ringer, T. Sakurai and I.J. Polmear: Acta Materialia **45** (1997), p. 3731-3744.
- [3] C.Y. Zahra and M. Dumont, Phil. Mag. **85** (2005), p. 3735-3742.

## AGE HARDENING

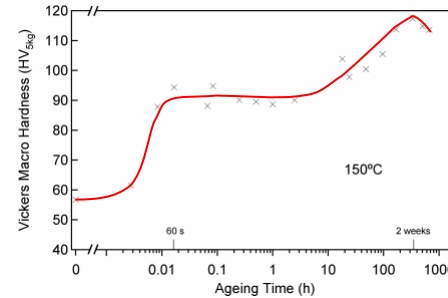
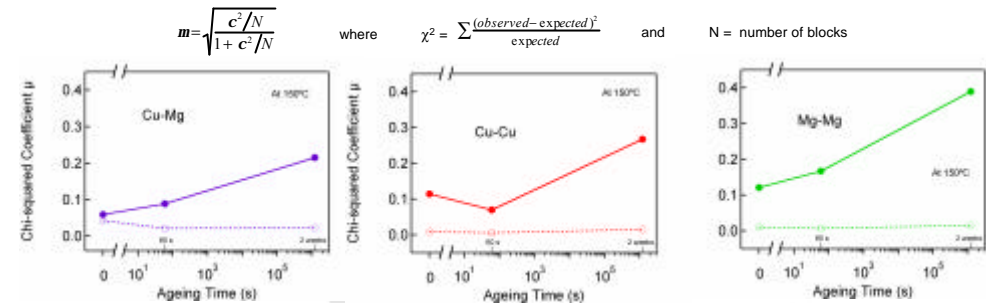


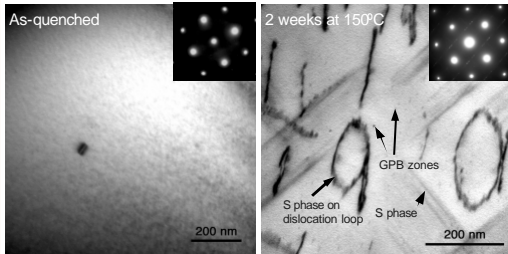
Figure 1: Age hardening curve for Al-1.1Cu-1.7Mg (at.%) at 150°C, exhibiting the RHP.

## ATOM PROBE TOMOGRAPHY - STATISTICAL ANALYSIS

The APT data was interrogated statistically by contingency table analysis for co-clustering of unlike solute species (i.e. clustering of Cu and Mg atoms), and like-like atom clustering was tested using a comparison of the experimental frequency distribution with a binomial frequency distribution that models random atom configuration. As the difference between observed (experimental) and expected (random) increases, chi-squared ( $\chi^2$ ) increases and so does  $\mu$ , which means increased tendency for clustering.

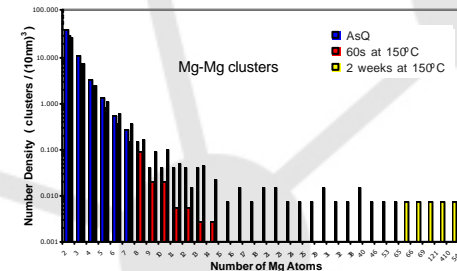
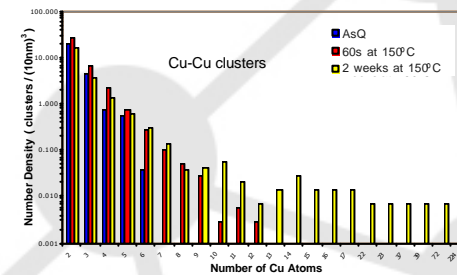
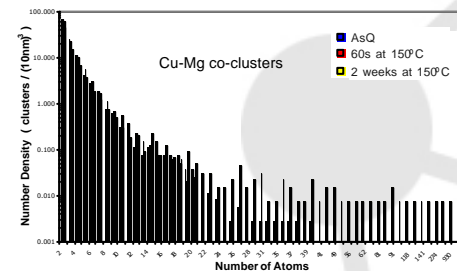


## TRANSMISSION ELECTRON MICROSCOPY



## ATOM PROBE TOMOGRAPHY - 3D MARKOV CHAIN

3D Markov Random Field data model is enforced through the atom probe data, where a solute atom is related to atoms in its vicinity using 12 nearest neighbours in the case of an Al FCC crystal lattice. The algorithm seeks out solute clusters by using these relationships, so that solute atoms related to each other form part of the same cluster. The frequencies of these clusters are counted and output according to cluster size.



## CONCLUSIONS

- The rapid hardening phenomenon exists during ageing of Al-1.1Cu-1.7Mg (at. %) at 150°C.
- In the peak aged condition, S phase has precipitated on the dislocation loops and GPB zones are also resolved.
- Using the chi-squared coefficient as a measure of clustering and comparing the experimental results to the random case, we see that like-atom clustering of the Cu and Mg solute atoms occurs in the as-quenched state. In all cases, clustering increases with ageing.
- The APT maps clearly show the clusters of Cu and Mg atoms. GPB zones were only detected after 2 weeks of ageing at 150°C, consistent with the TEM results.
- The RHP during elevated temperature ageing is therefore attributed to these clustering reactions of the solute atoms, but more work is needed to reveal particular details.
- Quantitative analysis of the APT results is provided by the 3D Markov Random Field model and is currently being used further to answer key questions regarding how both number density and cluster chemistry change during ageing.

## APT - 3D MAPS

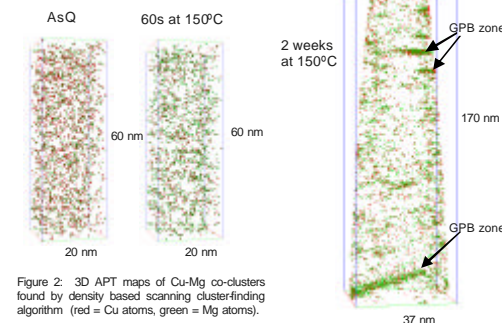


Figure 2: 3D APT maps of Cu-Mg co-clusters found by density based scanning cluster-finding algorithm (red = Cu atoms, green = Mg atoms).

## ACKNOWLEDGEMENTS

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