

Understanding the effect of GP zones on the work hardening in Al-Cu alloys

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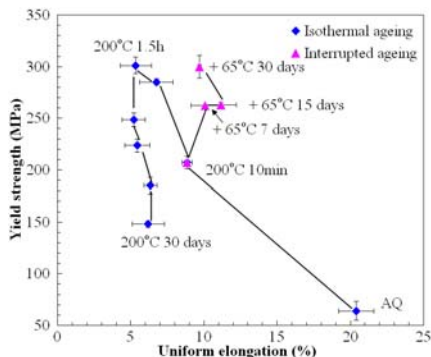
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Introduction

- Yield strength (σ_y) and uniform elongation (ϵ_u) typically exhibit an inverse correlation in engineering alloys.
- Recently experiments show that bi-modal precipitate distributions can simultaneously increase σ_y and ϵ_u of the alloys after interrupted ageing.
- To increase ϵ_u has to increase the work hardening at large strains. Based on Considere's criterion: necking occurs when the flow stress (σ_f) equal to the work hardening ($d\sigma/d\epsilon$).
- Shearable precipitates are generally not thought to enhance the work hardening as no contribution to the dislocation storage.

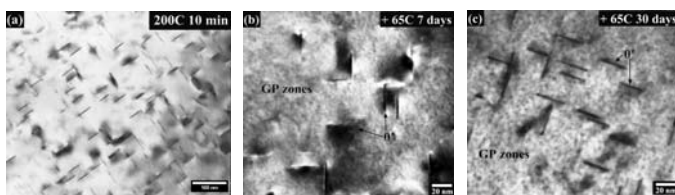
Experiment

- Material:** Al-4Cu-0.05Sn (wt.%)
- Heat treatments:** Isothermal ageing: 200°C up to 30 days
Interrupted ageing: 200°C 10 min + 65°C up to 30 days
- Tensile response:** Isothermal ageing: σ_y and ϵ_u inversely correlated
Interrupted ageing: σ_y and ϵ_u improved simultaneously

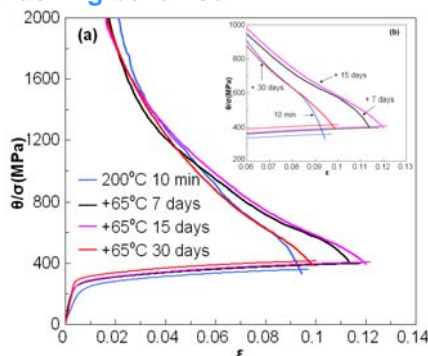


Microstructure:

- Isothermal ageing: only θ' precipitate
- Interrupted ageing: θ' precipitate + GP zones
- θ' precipitate has little change at 65°C
- The size of GP zones increases with time



Work hardening behaviour



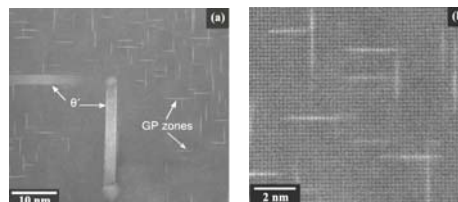
- $d\sigma/d\epsilon$ (θ) essentially the same at strains around 2-4%
- $d\sigma/d\epsilon$ (θ) clearly increases at large strains
- GP zones increase the work hardening at large strains

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Major question

How do shearable GP zones increase the work hardening at large strains?

- Multi-layer of GP zones or shear-resistant precipitates form instead?



HAADF images for 200°C 10 min + 65°C 30 days (undeformed)

- Definitely single layer of GP zones formed
- Intergranular back stress from GP zones?
 - No obvious contribution to the back stress after the formation of GP zones
- Strain-induced dissolution of GP zones? C.R. Hutchinson et al., ICAA 2008
 - Around 68% of GP zones dissolved after 10% deformation.
 - Cu concentration in solid solution increases with GP zones dissolved.
 - X_{Cu}^{ss} increases lead to the increase of dislocation-dislocation strength (α).

Modelling

Extending the model in containing both θ' and GP zones:

$$\sigma_f = \sigma_0 + \sigma_{ss} + \sigma_{GP} + (\sigma_\theta' + \sigma_\theta'')^{1/2} + \sigma < \sigma >$$

Strain-induced dissolution of GP zones

J.D. Teixeira et al., Acta Mater 2008
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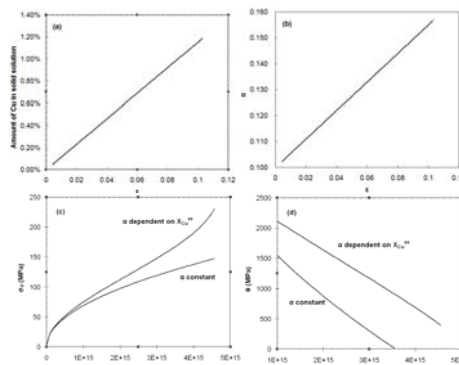
During deformation:

$$\sigma_{ss} \uparrow \quad \sigma_{ss} = K_{ss} X_{Cu}^{ss}$$

$$\sigma_{GP} \downarrow \quad \text{GP zones dissolved}$$

$$\sigma_d \uparrow \quad \sigma_d = M \alpha (X_{Cu}^{ss})^{1/2} \mu b \sqrt{\rho} \quad \frac{\partial \rho}{\partial \epsilon_p} = (k_1 \sqrt{\rho} - k_2 \rho + k_3) M$$

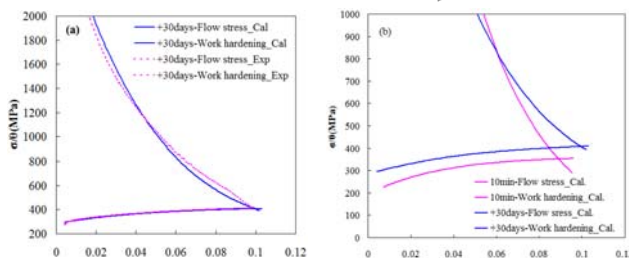
X_{Cu}^{ss} linearly with strain



α linearly with strain

$\alpha \uparrow \rightarrow \sigma_d \uparrow$

$\alpha \uparrow \rightarrow d\sigma/d\epsilon \uparrow$ at large strains



Calculated and experimental curves for interrupted ageing for 30 days

Calculated curves for 200°C for 10 min and interrupted ageing for 30 days

- Model works well in explaining the increasing work hardening at large strains.

Conclusion

- Simultaneous improvements of σ_y and ϵ_u are achieved through interrupted ageing.
- Strain-induced dissolution of GP zones is a feasible explanation for the improvement of work hardening from GP zones.