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The Strain Hardening Behaviour of Supersaturated Al-Cu Alloys

Julien da Costa Teixeira[1,2], Yves Bréchet[3] , Yuri Estrin[1,4] and Christopher Hutchinson[1]

[1]ARC Centre of Excellence for Design in Light Metals, Department of Materials Engineering, Monash University, Clayton, VIC, 3800, Australia

[2]Institut Jean Lamour, Dépt SI2M, Ecole des Mines, Parc de Saurupt, 54042 Nancy, France

[3]SIMAP, Institut Nationale Polytechnique de Grenoble, St. Matin D'Hères, 38000, France

[4]CSIRO Process Science and Engineering, Clayton South, 3168, VIC, Australia

A commonly accepted picture of the effect of solid solution additions on the strain hardening of Al alloys is through their influence on the overall dislocation storage rate via a retarding effect on dynamic recovery. This can be clearly illustrated as a decrease in the slope of a classical Kocks-Mecking (KM) plot representing the dependence of the strain hardening coefficient on the difference between the flow stress σ and yield stress σ_y. The solute elements are usually assumed to have a negligible effect on the initial (stage II) strain-hardening rate, Θ_{II}.
Recent experimental observations suggest that this simplified picture does not apply to Al-Cu solid solutions. The present contribution considers the strain-hardening behaviour of a series of Al-Cu solid solution alloys as a function of applied strain-rate at room temperature. The solute content is shown to have a strong effect on the initial hardening rate but a negligible effect on the slope of the KM plot. The initial hardening rate shows an approximately logarithmic dependence (i.e. weak) on strain-rate. Certain potentially plausible mechanisms for the solute effects on strain hardening are considered and shown unlikely to be able to explain the experimental observations. We propose a mechanism associated with the strengthening of dislocation junctions.

Keywords: *strain hardening, deformation, Al-Cu alloys.*

1. Introduction

The solute elements in Al alloys can have an effect on strength in two ways: through inhibiting dislocation motion thus affecting the yield stress (σ_y), or modifying the strain-hardening behaviour. In systems such as the Al-Cu based 2xxx series, the solutes are predominantly used to form a distribution of precipitates that increases the yield strength. The Cu atoms that remain in solid solution tend to have a comparatively small effect on the yield strength. Both contributions to the yield strength have been thoroughly investigated. The role of copper in solid solution on the strain hardening has received very little attention. By contrast, another class of Al alloys, notably those of the 5xxx series, get their strength mainly from strain hardening. Mg is the primary alloying element in this respect, and its effect on both on the yield strength and the strain hardening is well known.

The commonly accepted picture of the effect of solute elements on strain hardening is through their influence on the dislocation storage rate via a retarding effect on dynamic recovery [1]. This can be clearly illustrated in a classical Kocks-Mecking (KM) plot [2] representing the dependence of the strain-hardening coefficient, $\left(\Theta = d\sigma/d\varepsilon\right)$, on the difference between the flow stress σ and yield stress σ_y. The effect of solute additions is to decrease the slope b of the diagram (Fig. 1a). This is often interpreted in terms of a decrease in the stacking fault energy and the attendant drop in the cross-slip probability of dislocations due to the solute additions. A direct consequence is an increase in the saturation stress σ_s. The stage II strain hardening rate Θ_{II} (Fig. 1a) is usually assumed to be comparatively unaffected by the solute concentration. Furthermore, the saturation stress σ_s is markedly strain-rate dependent, whilst Θ_{II} is not (Fig. 1b).

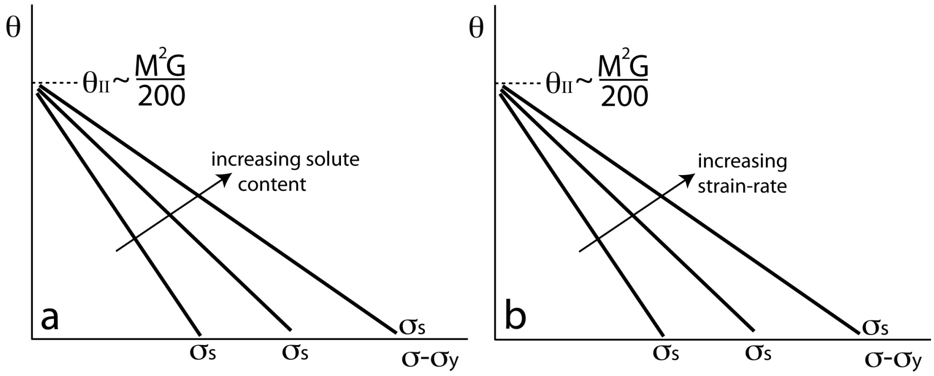

Fig. 1: Schematic illustration of simplified picture of KM plots showing effects of solute additions and applied strain-rate

However, this simplified picture does not always apply. It is known that solute additions can influence the initial hardening rate (Θ_{II} in Fig. 1) and this has been observed experimentally, for example, in the Al-Mg system at 78K, Cu-Al and Cu-Zn [3,4] and in Ni-Mo [5]. Recent experimental observations by Zolotorevsky *et al.* [6] suggest that this simplified picture (Fig. 1) also does not directly apply to Al-Cu solid solutions: the copper concentration does influence both Θ_{II}, and σ_s, with a dependence on Cu content which is rather pronounced.

The present article is devoted to experimentally studying the strain hardening behaviour in a series of Al-Cu solid solution alloys. The effect of solute content and applied strain-rate is examined and certain potentially plausible mechanisms for the effects on strain hardening are considered and shown to be unlikely to explain the experimental observations. A mechanism associated with the strengthening of dislocation junctions is suggested.

2. Experimental Procedure

Four Al-Cu alloy compositions (Al-1Cu, Al-1.5Cu, Al-2.3Cu and Al-3Cu (wt. %)) were prepared from high purity elements (99.99% purity) by casting into steel molds. After homogenization at 520°C for approximately 2 days, the ingots were hot rolled to 3mm thick sheet from which tensile samples with a gauge $5x3mm^2$ were spark machined. In all cases a solution treatment at 525°C for 1h was performed followed by quenching into water directly before mechanical testing. Tensile tests were carried out at room temperature using a screw driven Instron and strains were monitored using a 10mm extensometer at all times. Tensile tests were carried out for the selected alloys at strain-rates ranging from 10^{-5} to 10^{-1} s^{-1}. Selected strain-rate jump tests were also performed.

3. Results

In order to illustrate the influence of the bulk Cu content on the strain hardening behaviour, Kocks-Mecking (KM) plots [2] are shown in Fig. 2a for each of the solid solutions considered at a strain-rate of $\dot{\varepsilon} \sim 10^{-3} s^{-1}$. The most striking result is that the initial hardening rate depends strongly on the bulk Cu content while the rate of recovery (slope of KM plot) seems relatively unaffected. These observations are consistent with those recently reported by Zolotorevsky *et al.* [5].
An example of the effect of applied strain-rate on the strain hardening behaviour is illustrated in Fig. 2b for the Al-3Cu alloy. The material exhibits negative strain-rate sensitivity and it is clear that the initial hardening rate is strain-rate dependent. At lower bulk Cu contents, similar effects are observed but the effects are less pronounced.

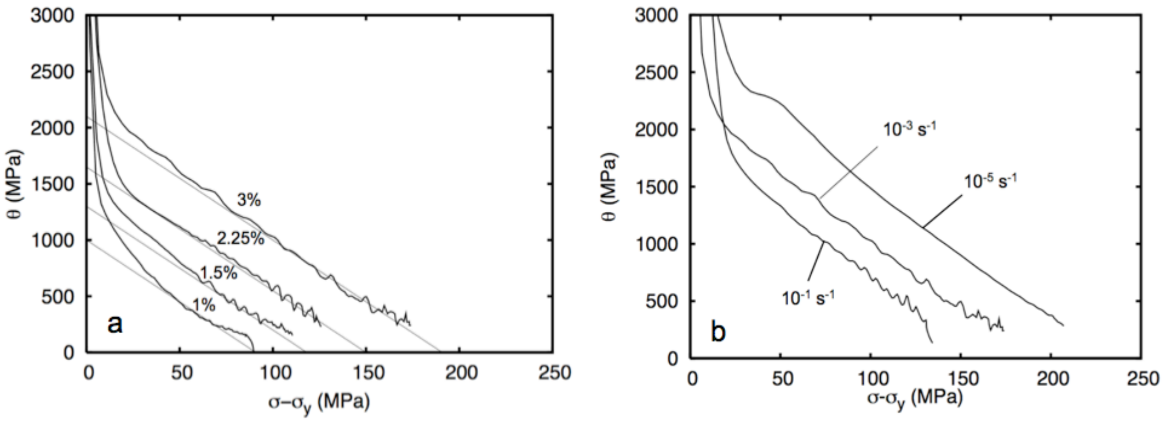

Fig. 2: KM plots showing (a) effect of solute content on the strain-hardening rate for an applied strain-rate of 10^{-3} s^{-1} and b) effect of applied strain-rate for the Al-3Cu (wt. %) alloy.

The effect of bulk Cu content and applied strain-rate on the initial hardening rate of the alloys is summarized in Fig. 3. It is clear that the initial hardening rate is approximately proportional to the bulk Cu content (Fig. 3a) and that the effect is rather large. The initial hardening rate more than doubles with an increase in bulk Cu content from 1 to 3%. The dependence of the initial hardening rate on applied strain-rate is approximately logarithmic in nature (i.e. weak) and increases with increasing bulk Cu content. These observations are clearly in contrast to the simplified picture shown in Fig. 1.

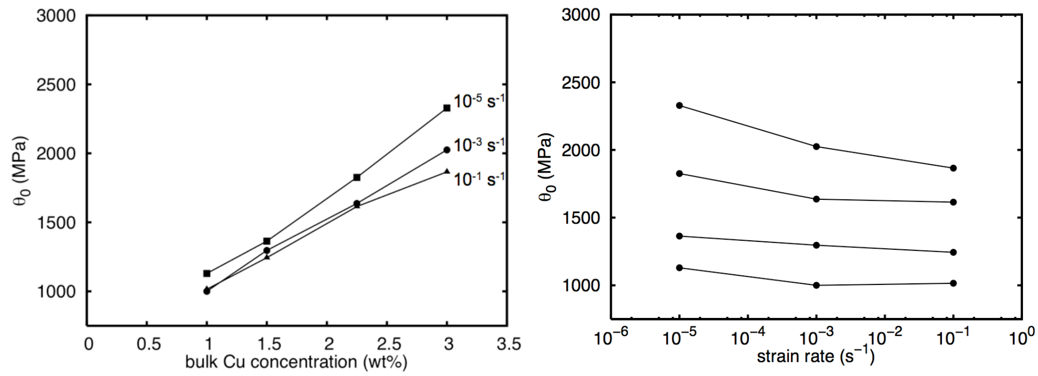

Fig. 3: Dependence of the initial hardening rate on a) bulk Cu content and (b) applied strain-rate.

4. Possible origins of the effect of Cu on the initial strain hardening rate

4.1. Dynamic Precipitation

The equilibrium solid solubility of Cu in Al at room temperature is less than 0.4 (wt. %). As a result, each of the alloys considered in this work is supersatured; a thermodynamic driving force for precipitation exists. The alloy containing 3 wt. % Cu (which has the highest driving force for precipitation) was examined using nuclear magnetic resonance after solution treatment, quenching into water and then room temperature rolling to a true strain of ~10% to investigate the possibility of strain-induced precipitation. No evidence for precipitation was found. NMR has been shown to be capable of detecting precipitation well before it is observable using transmission electron microscopy, e.g. [7]. It therefore appears unlikely that the effect of Cu on the initial hardening rate is due to dynamic precipitation effects.

4.2. Friction stress

Complex interactions may occur between dislocations and solute atoms during plastic straining leading, for example, to the Portevin Le Châtelier (PLC) effect. These interactions may lead to an increase in the friction stress and therefore the strain hardening rate. To test this possibility, consider the cases of pure Al and Al-3Cu for which θ_0 is equal to ~1000 and 2300 MPa (Fig. 2), respectively. The contribution to the overall strain hardening of the Al-3Cu alloy from the friction stress, θ_{SS}, is therefore 1300 MPa. As a result, at ε_p = 10% the contribution to the flow stress, σ_{SS}, would be ~130 MPa and at ε_p = 20%, the contribution is 260 MPa. Fig. 4a shows that experimentally, $\sigma - \sigma_y$ is equal to only 130MPa and 160MPa at ε_p = 10% and 20%, respectively, for this alloy. For the enhanced initial hardening to be due to a friction stress, all of the strain hardening at 10% strain would come from the friction stress and none from the dislocation forest. This is not expected for this system. Furthermore, at ε_p = 20%, the increase is σ_{SS} would be significantly higher than the experimentally observed $\sigma - \sigma_y$.

4.3. Solute effects on dynamic recovery: Deschamps *et al.* [8] model

Deschamps *et al.* [8] have presented a model to describe the effect of solute on dynamic recovery. In this model it is assumed that the solute atoms influence the rate of recovery via an increase in the critical spacing for dislocation annihilation. Instead of the change of the slope of the KM plots usually associated to the rate of recovery, the proposed model leads formally to a change of the initial strain hardening rate, which is confirmed by their experiments. On the surface this appears to give good qualitative agreement with the observations reported in this study. However, Deschamps *et al.*'s study was confined to solute contents less than 0.4 wt % whereas much larger solute concentrations are considered in the present study. Attempts to apply the Deschamps *et al.* model to the high solute alloys consider in this study leads formally to non linear KM plots (these are even concave), which are far from the present results.

4.4. Solute effects on dislocation junction strength (α)

Since dynamic precipitation, solute effects on the friction stress and solute effects on dynamic recovery appear unlikely to be able to explain the effect of the bulk Cu content on the initial hardening rate, we have considered the initial hardening rate in terms of the phenomenological model for strain hardening in pure FCC metals due to Kocks and Mecking [2]. In their approach, the initial hardening rate can be expressed as: $\theta_0 = \frac{M^2 \alpha \mu b k_1}{2}$, where M is the Taylor factor, μ is the shear modulus, b is the Burgers vector, k_1 is the efficiency with which a dislocation junction will form from a random encounter between moving dislocations and α is proportional to the stress necessary to break a dislocation junction that has already formed. It is conceivable that the concentration of solute in solution could affect either the dislocation-dislocation junction strength or the efficiency of junction formation.

In order to help determine the origin of the effects on the initial hardening rates, strain-rate jump experiments have been performed: first a strain-rate $\dot{\epsilon}_1$ is applied until $\varepsilon_p = \varepsilon_1$ and then a faster or lower strain-rate $\dot{\epsilon}_2$, is applied until necking. Two results may be expected:

i) Upon increasing the strain-rate, if α decreases and k_1 is constant, the flow stress will decrease at ε_1. The σ-σ_Y vs. ε_p curve beyond ε_1 should be superimposed on that of the single rate $\dot{\epsilon}_2$ stress strain curve. Such a situation is shown in Fig. 4a
ii) Upon increasing the strain-rate, if k_1 decreases and α is constant, the rate of dislocation storage will decrease at ε_1. To predict the strain hardening rate beyond $\varepsilon = \varepsilon_1$, it is necessary to know the dislocation density ρ at ε_1. Consider the situation shown schematically in Fig.

4b. $\rho(\epsilon_1)$ for the $\dot{\epsilon}_1$ curve should be equal to $\rho(\epsilon_2)$ for the $\dot{\epsilon}_2$ curve. Therefore it is expected that the stress vs. strain evolution beyond ε_1 will be the same as for the $\dot{\epsilon}_2$ curve beyond ε_2. Graphically the stress strain curve of the jump test beyond ε_1 should be superimposed to the $\dot{\epsilon}_2$ curve by a horizontal translation.

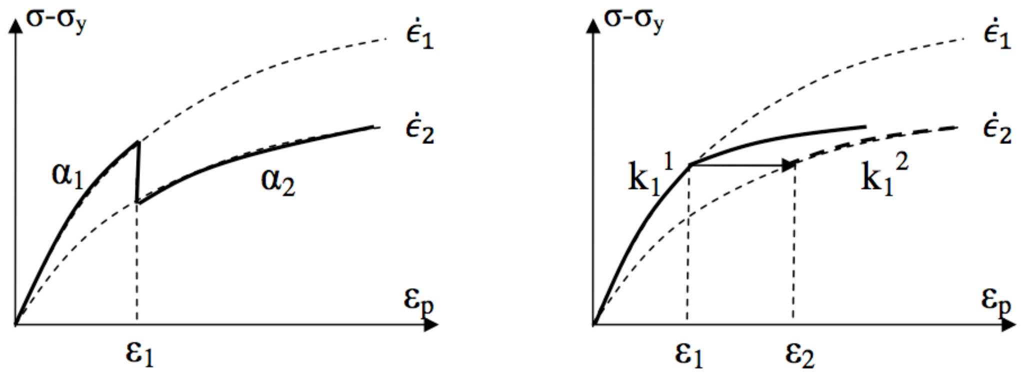

Fig. 4: Schematic illustration of the expected stress-strain behaviour resulting from a strain-rate jump test: a) the solute effect is through an influence on the dislocation-dislocation junction strength (α) and b) the solute effect is through an effect on the efficiency of junction formation (k_1)

Strain-rate jump tests have been performed for the Al-3Cu alloy and the results are shown in Fig. 5. Initially a strain-rate of 10^{-5} s^{-1} is applied until a strain of ~7% followed by an acceleration to a strain-rate of 10^{-1} s^{-1}. As shown in Fig. 5a, the result of the strain-rate jump test is not exactly that shown schematically in Fig. 4a. However, the horizontal translation of the curve (shown schematically in Fig. 4b) of the real data in Fig 5b shows that this situation is not exactly followed either. Figure 5c illustrates that although the instantaneous adjustment in the flow stress due to the strain-rate change is not as shown in Fig. 4a, the strain hardening rate does correspond to that expected from a solute effect on the dislocation-dislocation junction strength (i.e. Fig. 4a).

In summary, it appears that the effect of solute is manifest through an affect on the dislocation-dislocation junction strength (α) but during a strain-rate jump tests this is seen through an immediate adjustment in the strain-hardening rate but not of the flow stress.

Although the commonly accepted picture of the effect of solute elements on strain hardening is through their influence on dynamic recovery, this is not the first observation of an effect of solute on the initial hardening rate through a solute dependence of α. As also suggested in [3,4], it is thought that it is the parameter α which undergoes variations and that these are due to Dynamic Strain Ageing (DSA), i.e. to solute/dislocation interactions induced by plastic straining. The variation in α may be explained by the formation of solute aggregates near the dislocations cores that increase the apparent strength of the forests by pinning the mobile dislocation and by making more difficult the unzipping of the mobile dislocation from the forest [9,10]. It seems likely that the present results can be explained with an appropriate model of DSA. It is interesting that most models of DSA are developed to understand the Portevin-Le Chatelier effect, whilst the effect on the strain hardening behavior seems to be rarely mentioned. A key feature of the present observations is that the strain-rate dependence of the initial hardening rate (Fig. 3b) is very weak. Any diffusional process for the segregation of Cu to the dislocation junctions would be expected to show a power-law dependence on strain-rate. This is not observed experimentally. A quantitative model to describe the solute and strain-rate dependence of the initial hardening rate will be reported in an upcoming publication.

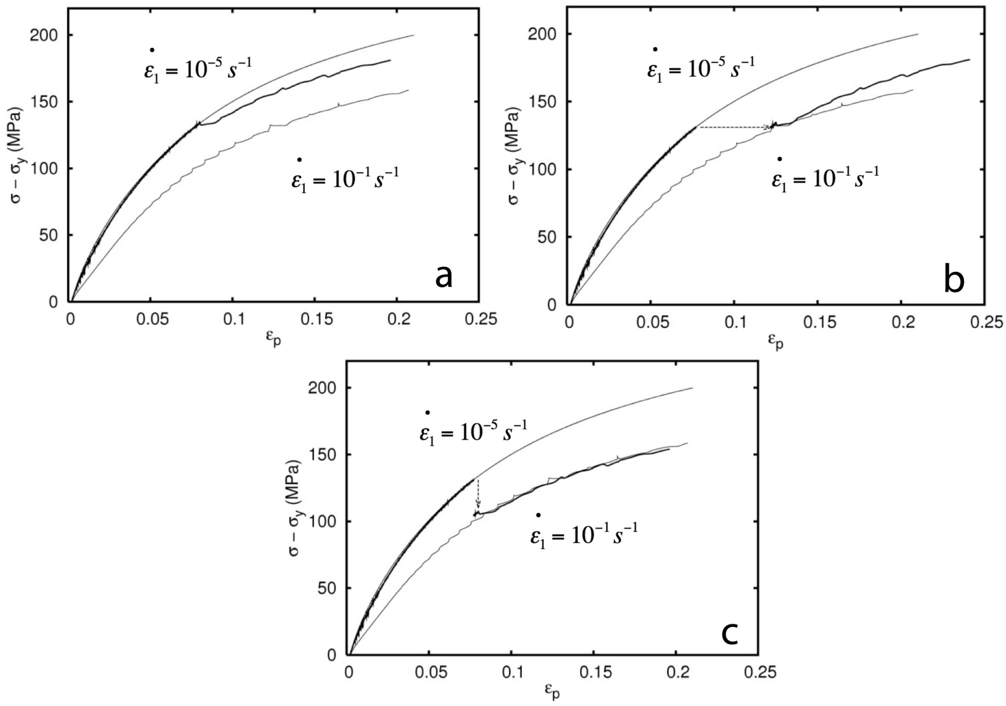

Fig. 5: Strain-rate jump tests for the Al-3Cu alloy: a) experimental result, b) horizontal translation of the flow stress curve after the strain-rate change (cf. Fig. 4b), c) vertical translation of the flow stress curve after the strain-rate change

5. Conclusions

Tensile tests in a range of Al-Cu solid solutions have been performed and the strong effect of solute Cu on the initial hardening rate is reported. Strain-rate jump tests suggest that the dominant effect of solute is through an affect on the dislocation-dislocation junction strength.

Acknowledgements

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