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The Strain Path Dependence of Plastic Deformation Response of AA5754: Experiment and Modeling

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Abstract. This work presents modeling of experiments on a balanced biaxial (BB) pre-strained AA5754 alloy, subsequently reloaded uniaxially along the rolling direction and transverse direction. The material exhibits a complex plastic deformation response during the change in strain path due to 1) crystallographic texture, 2) aging (interactions between dislocations and Mg atoms) and 3) recovery (annihilation and re-arrangement of dislocations). With a BB pre-strain of about 5 %, the aging process is dominant, and the yield strength for uniaxially deformed samples is observed to be higher than the flow stress during BB straining. The strain hardening rate after changing path is, however, lower than that for pre-straining. Higher degrees of pre-straining make the dynamic recovery more active. The dynamic recovery at higher strain levels compensates for the aging effect, and results in: 1) a reduction of the yield strength, and 2) an increase in the hardening rate of re-strained specimens along other directions. The yield strength of deformed samples is further reduced if these samples are left at room temperature to let static recovery occur. The synergistic influences of texture condition, aging and recovery processes on the material response make the modeling of strain path dependence of mechanical behavior of AA5754 challenging. In this study, the influence of crystallographic texture is taken into account by incorporating the latent hardening into a visco-plastic self-consistent model. Different strengths of dislocation glide interaction models in 24 slip systems are used to represent the latent hardening. Moreover, the aging and recovery effects are also included into the latent hardening model by considering strong interactions between dislocations and dissolved atom Mg and the microstructural evolution. These microstructural considerations provide a powerful capability to successfully describe the strain path dependence of plastic deformation behavior of AA5754.

Keywords: Latent hardening, Strain path dependence, Aging, Recovery, AA5754
PACS: 00. GENERAL

INTRODUCTION

It is necessary to accurately simulate material response during metal forming processes in order to increase the productivity of automotive part manufacture. However, during metal forming processes, the materials often exhibit complex anisotropic plastic behavior. In particular, multiaxial stress states promote strong multiple slip activities, leading to frequent dislocation interactions, and in turn resulting in different hardening rates for different slip systems. Consequently, it is challenging to simulate material deformation responses as a continuum model. To overcome these challenges, accurate models require an in-depth understanding of plastic deformation mechanisms. Over past decades, there have been great efforts to understand the mechanism of plastic deformation, in particular the relationships between dislocations, texture and plastic anisotropy of polycrystalline materials. These efforts have developed effective models for simulating anisotropic plastic response of materials [1-3]. Here, the visco-plastic self-consistent (VPSC) model is used with the incorporation of *(i)* latent hardening, *(ii)* interactions between dislocations and dissolved atoms, and *(iii)* static recovery to enhance the linkage between constitutive models and underlying physical mechanisms, and ultimately to model the plastic deformation response of AA5754 during multi-path straining.

PLASTIC STRESS-STRAIN BEHAVIOR OF AA5754: EXPERIMENT

The material used in this investigation is a commercially available AA5754-O sheet. The as-received (AR) material exhibits a higher strain hardening rate for balanced bi-axial (BB) than for uniaxial tension loading conditions, in particular after a high degree of plastic deformation (Fig. 1a). The material also undergoes dynamic strain aging (DSA) due to strong interactions between dislocations and solute atoms (e.g., Mg). The dynamic strain

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aging results in an increase in yield strength accompanied by serrated flow stress (Fig. 1b) and negative strain rate sensitivity (i.e., the material tends to be stronger during plastic deformation with a lower strain rate) [4, 5].

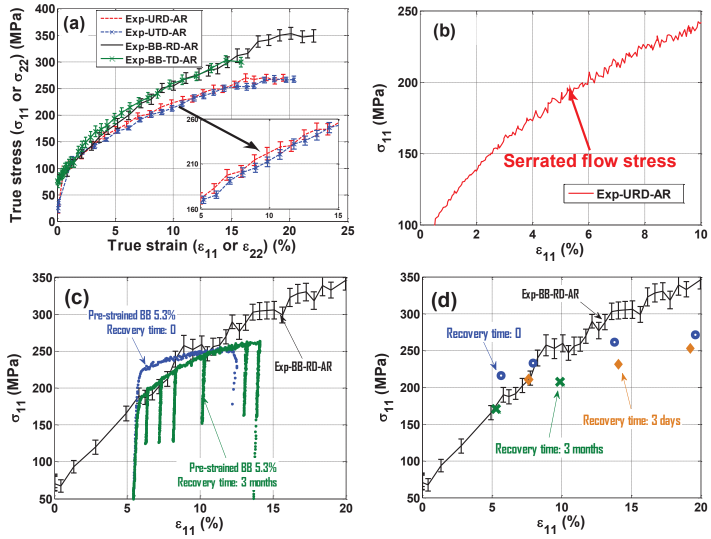
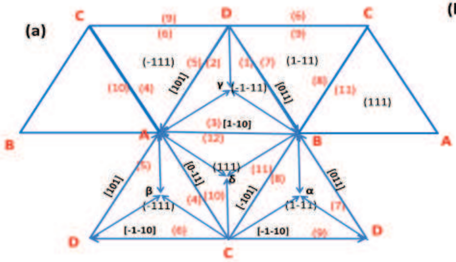


FIGURE 1: (a) Stress-strain response of AA5754 as-received (AR) material during BB, URD and UTD (The 11 (or 22) direction corresponds to the rolling (or transverse) direction). (b) Serrated flow stress. (c) Flow stresses in the RD during BB straining and URD reloading intermediately after BB straining and after 3 months of recovery. (d) Yield strength of AA5754 during URD reloading (shown as single points) with respect to degrees of pre-straining and to time of static recovery. Note: The yield strength is measured as the proof stress at 0.1 % offset strain.

Changing the strain path from BB to uniaxial tension significantly affects the plastic stress-strain response of the material. Here we focus on the material deformation response when changing path from BB to uniaxial tension in the rolling direction (URD) since the same response reported below is also observed when changing path from BB to uniaxial tension in the transverse direction (UTD), but to a smaller extent. This may be due to the fact that the material hardens slightly less for UTD than for URD (inset in Fig. 1a). The error bars associated with each experimental data point are measurement uncertainties described in Iadicola *et al.* [6]. Depending on the degree of pre-straining, the yield strength of the material during reloading along the second path can be either higher or lower than the flow stress during previous plastic deformation. The yield strength during URD is observed to be higher than the flow stress during BB pre-straining of about 5.3 % true strain (Fig. 1c). The strain hardening rate of the material after changing path at small strains is, however, lower than that for BB pre-straining. Larger BB pre-strains reduce the yield strength (and increase the hardening rate – not shown here) of BB deformed specimens. For example, the yield stress of a sample reloaded uniaxially along RD after BB straining of 7.8 % true strain is almost the same as it was during BB straining (Fig. 1d). The yield strength of the material during URD reloading is usually lower than that during BB straining higher than 10 % true strain (Fig. 1d). This is because of dynamic recovery which, through mechanisms such as cross slip, reduces the dislocation density and rearranges dislocations to form more stable energetic configurations such as dislocation cells and walls [7]. Static recovery (in air) at room temperature helps pre-strained samples regain strain hardening and therefore ductility (Fig. 1c, d).

MODELING

There are 24 $\{111\}<110>$ slip systems for face-centered-cubic (FCC) materials. Twelve of these are depicted in the Thompson tetrahedron in Fig. 2a. Beside the self-interaction of dislocations in the same slip plane, there are four typical types of latent interactions between dislocations moving in primary slip plane and those in secondary slip planes (Fig. 2b): The Lomer-Cottrell (LC), Hirth (H), co-planar (Cop) and co-linear (Col) interactions [4, 8, 9]. The stress-strain deformation behavior of AA5754 during BB loading along RD direction is modeled by VPSC program with basic self-hardening values (shown in Table1) and with different latent hardening strengths relative to self-hardening. The values of latent hardening strengths used and shown in Fig. 3a (which were calibrated based on the BB data) can pretty well model both stress-strain behavior (Fig. 3a) and texture development after 20 % BB straining (Fig. 3b) (Note: VPSC with the same self-hardening values and no latent hardening gives a much underestimate of stress response during BB loading, Fig. 3a). These same values of self- and latent hardening also predict the material response well during URD straining of the as-received material (Fig. 3a) and the corresponding texture evolution after 15 % strain (Fig. 3c).



(b) Latent hardening interactions of dislocations in FCC materials

Dislocations moving in slip system	Interacting secondary slip systems			
	Lomer-Cottrell	Hirth	Collinear	Coplanar
1	6, 9; 8, 11	4, 10	7	2, 3, 5, 12
2	4, 10; 6, 9	8, 11	5	1, 3, 7, 12
3	4, 10; 8, 11	6, 9	12	1, 2, 5, 7
4	3, 12; 8, 11	1, 7	10	5, 6, 2, 9
5	1, 7; 3, 12	8, 11	2	4, 6, 9, 10
6	1, 7; 8, 11	3, 12	9	4, 5, 2, 10
7	2, 5; 3, 12	4, 10	1	8, 9, 6, 11
8	3, 12; 4, 10	2, 5	11	7, 9, 1, 6
9	2, 5; 4, 10	3, 12	6	7, 8, 1, 11
10	2, 5; 6, 9	1, 7	4	11, 12, 3, 8
11	1, 7; 6, 9	2, 5	8	10, 12, 3, 4
12	1, 7; 2, 5	6, 9	3	10, 11, 4, 8

FIGURE 2: (a) Expansion of the Thompson tetrahedron and (b) sources of latent hardening interactions in FCC materials.

TABLE 1: Main input parameters for VPSC with the Voce constitutive model (Equation 6-1 in [10])

Inclusion-Matrix interaction	τ_0	τ_1	θ_0	θ_1
n^{eff}=10	81	30	100	0

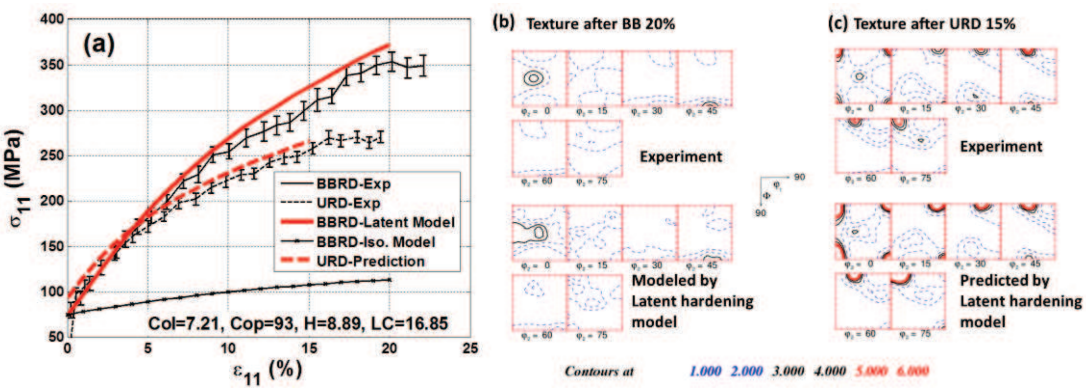


FIGURE 3: (a) Modeling of flow stress during BB and URD of AR samples. Texture conditions after (b) BB straining of 20 % and (c) URD of 15 % of AR samples.

Since the material is strengthened by solid solution which delays cross slip activity, it is likely that dynamic strain aging (DSA) is dominant in uniaxial deformation response of the BB deformed material (which was pre-strained less than 10 %). In contrast, the influence of aging in the response of the material (which was pre-strained more than 10 %) is compensated by dynamic recovery. The strong interaction between dislocation lines and solute atoms requires higher stress to keep dislocations moving, resulting in higher yield stress. The DSA process also results in a low hardening rate and a higher damage because: *1)* the resistance to dislocation movement is mainly governed by short-range interactions between dislocations and dissolved atoms, and *2)* jerky movement of dislocations under the presence of dissolved atom atmospheres and negative strain rate sensitivity promotes deformation localization [4]. This explains why: *(i)* there is overshoot in the yield strength during reloading of pre-strained material of 5.3 %, and *(ii)* the ductility and hardening rate of the pre-strained sample are low (Fig. 1c, Fig. 4a). In other words, the latent hardening can be negligible compared with hardening induced by self-interaction and interaction between dislocation and dissolved atoms. Consequently, for modeling the material response after pre-straining of less than 10 %, it is necessary to use (1) only self-hardening term, and (2) a higher yield stress than that during pre-straining. Indeed, VPSC with only self-hardening term and a higher stress value (which was obtained from experimental data) can successfully model the flow stress response during URD after BB pre-straining of about 5.3 % (Fig. 4a).

Static recovery (under zero-load) returns strained material towards the annealed state. During static recovery, (1) dislocations migrate, annihilate and form more stable energetic configurations, and (2) the interactions between dislocations and solute atoms are relaxed. The reduction in dislocation density and the relaxation of interactions between dislocations and solute atoms cause a decrease in yield stress. However, the formation of more stable configurations of dislocations provides effective means to restrict the movement of dislocations during reloading, resulting in an increase in hardening rates during reloading of recovered samples. Nes showed that the reduction in yield stress during static recovery of deformed Al-Mg alloys due to the annealing out of dislocations can be modeled by the following equation [11]:

$$R = 1 - \frac{kT}{A}\ln(1+\frac{t}{\tau}) \qquad \text{with } R \text{ is the fraction of residual yield strength, } R = \frac{\sigma_0^{deformed}\Big|_t - \sigma_0^{as-received}}{\sigma_0^{deformed}\Big|_{t=0} - \sigma_0^{as-received}} \tag{1}$$

k is Boltzmann's constant, *T*: Temperature (K), *A*: Coefficient relating to annealing process of dislocations during static recovery, *t*: recovery time, σ_0 :measured yield strength, τ : Coefficient relating to initial dislocation density and solute atom concentration during static recovery.

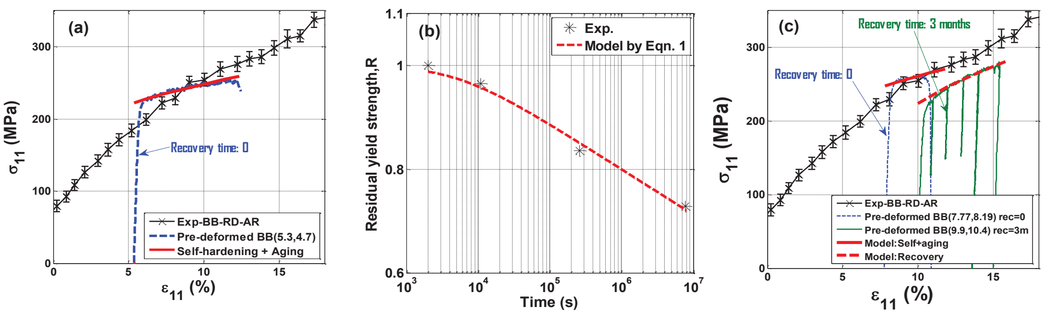


FIGURE 4: (a) Modeling of flow stress during URD of BB deformed sample. (b) Residual yield strength of deformed materials after static recovery. (c) The simulation of flow stress of recovered sample.

In this study, (1) the reduction of the yield stress during recovery is first modeled by using Equation 1 (Fig. 4b) and (2) the latent hardening is considered to be the same as it was during BB pre-straining. Indeed, the visco-plastic self-consistent model including these two factors successfully modeled the flow stress during URD reloading after static recovery of BB pre-strained material (Fig. 4c).

CONCLUSIONS

The response of pre-strained AA5754 materials during a strain path change is strongly governed by the degree of pre-straining amplitude, and is a consequence of the competition between dynamic strain aging and dynamic recovery. In addition, static recovery also significantly influences the stress-strain behavior of deformed AA5754 material, e.g., lowering the yield strength, increasing both ductility and strain hardening rate. As shown in this study, the incorporation of latent hardening into the VPSC model is an effective technique to model the plastic deformation response and texture development during BB and uniaxial straining. Including aging and recovery are necessary to successfully simulate the plastic stress-strain response of the material after changing path as well as after static recovery.

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