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Influence of severe plastic deformation on dynamic strain aging of ultrafine grained Al–Mg alloys

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Abstract

This investigation addressed the influence of severe plastic deformation (SPD) on dynamic strain aging (DSA) of ultrafine grained (UFG) Al–Mg alloys with different Mg content. Confined channel die pressing (CCDP) carried out at room temperature was used for SPD. Microcharacterization by TEM revealed a remarkable grain refinement and retarded dynamic recovery with increasing Mg content and plastic strain during SPD. Mechanical tests with jumping and constant strain rates demonstrated a complicated deformation behaviors of the UFG Al–Mg alloys: (i) the critical strain ε_c for initiation of serrated flow increased considerably with increasing strain and Mg content contrary to the behavior of the coarse grained and non-deformed counterparts; (ii) the instantaneous stress response ($\Delta\sigma_i$) and the instantaneous strain rate sensitivity (m_i) during rate jumps were always positive and increased monotonically with CCDP pass and Mg content, however, they exhibited a distinctive asymmetry with respect to the strain rate jump direction, i.e. the values for strain rate towards down were about one order of magnitude larger than those for rate towards up and increased with progressing CCDP as well as with increasing Mg content; (iii) the steady state strain rate sensitivity m_s was negative and decreased firstly with progressing CCDP up to a certain strain and then increased again. This mechanical behavior of UFG Al–Mg alloys is discussed on the basis of recently developed DSA models by relating the microstructure evolution of Al–Mg alloys during SPD to the influence of SPD on DSA.

Keywords: Severe plastic deformation; Al–Mg alloys; Microstructure; Dynamic strain aging

1. Introduction

Severe plastic deformation (SPD) has been widely used to fabricate bulk NC and UFG metallic alloys with remarkably higher strength and improved ductility for structural applications at low and moderate temperatures. It is therefore of particular interest to explore how SPD will impact dynamic strain aging (DSA) and thus, the deformation behavior and mechanical performance of as-fabricated UFG parts. On the one hand, it is expected that the extremely high defect (dislocation and vacancy) density due to the large plastic strain, high grain boundary volume fraction due to the intensive grain refinement and deformation-induced precipitation or precipitate dissolution will affect DSA. On the other hand, DSA also strongly affects the strain hardening capability and hence, the plasticity/ductility and finally the mechanical properties of UFG alloys. Previous studies into these subjects have not provided useful theoretical guidance to a systematic utilization of UFG materials.

Serrated flow (or Portevin-Le Chatelier (PLC) effect), caused by dynamic strain aging (DSA) of solutes, leads to unstable yielding and flow that strongly affects material fabrication by plastic deformation. For this reason, many investigations on these phenomena have been carried out since the 1950s.

Cottrell was the first to propose an interaction of quasi-viscous moving dislocations with a solute atmosphere (or cloud) to interpret serrated yielding and jerky

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Nomenclature

A	material related constant
b	Burgers vector
$C(t_a, C_0)$	aging solute concentration
C_0	original alloy composition
C_∞	saturated aging concentration
C_v	vacancy concentration
d	grain size
D_0	diffusion pre-exponential factor
$\Delta E(t_a)$	binding energy between solutes and dislocation core
ΔE_∞^{core}	saturated binding energy
ΔG	Gibbs free energy of plastic deformation
k	Boltzmann constant
K	vacancy concentration prefactor
l_f	forest dislocation spacing
m	strain rate sensitivity
m_i	instantaneous strain rate sensitivity
m_s	steady state strain rate sensitivity
N	dislocation density prefactor
Q_m	effective activation energy for solute migration
r_{sol}	effective radius of solute atmosphere
r'_{sol}	solute atomic radius
T	absolute temperature
t_a	aging time of dislocations
t_d	intrinsic cross-core solute diffusion time
t_t	transition time
t_w	waiting time of dislocations in front of obstacles
V^*	activation volume
α	vacancy concentration exponent
β	dislocation density exponent
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_0$	strain rate pre-exponential factor
ε_c	critical strain for the onset of serrated flow
ρ	dislocation density
ρ_m	mobile dislocation density
ρ_f	forest dislocation density
σ	flow stress
$\sigma_{0.2}$	yield stress
σ_{th}	thermal stress component
σ_a	athermal stress component
σ_{DSA}	extra flow stress component contributed by dynamic strain aging
σ_{drop}	magnitude of stress drop during serrated flow
$\Delta\sigma_i$	instantaneous stress response upon strain rate jump
$\Delta\sigma_S$	steady state stress response
$\Delta\sigma_{th}$	change of thermal stress component upon strain rate jump
Ω	elementary strain
CCDP	confined channel die pressing
CG	coarse grained
DSA	dynamic strain aging
GB	grain boundary
PLC	Portevin-Le Chatelier
SPD	severe plastic deformation
SRS	strain rate sensitivity
nSRS	negative strain rate sensitivity
UFG	ultrafine-grained

flow as observed in steels and Al alloys during plastic deformation [1,2]. It is now generally accepted that serrated flow during plastic deformation of alloys is caused by DSA owing to the fact that solutes move to obstacles (e.g. junctions of forest and mobile dislocations) which block mobile dislocations via pipe and cross core diffusion and consequently, increase obstacle strength which further strengthens the material by increasing the activation stress of dislocation motion. The increased stress, thereby, enables mobile dislocations to break away from obstacle and to move freely until they meet the next obstacle [3,4]. DSA usually leads to a negative strain rate sensitivity (nSRS) of the alloy and makes itself felt by the PLC effect.

Van den Beukel et al. proposed vacancy-assisted models [4–7] for interpreting the onset of serrated yielding and the effect of DSA on SRS in Cu–Sn, Au–Cu and Al–Mg alloys. According to the vacancy-assisted model, DSA and the PLC effect were strain sensitive owing to the strain-dependent solute diffusivity and the strain dependent mobile dislocation density [6,7]. On the other hand, Kocks et al. proposed a strain hardening model incorporating pipe diffusion [8–10] based on the dislocation arrest theory originally proposed by Sleeswyk [11]. In this case, the solute mobility will mainly influence the strain hardening component but not the friction component of the flow stress and therefore, DSA and the PLC effect should be stress sensitive but not strain sensitive [4].

Kubin and Estrin proposed a model to assess the critical conditions associated with the PLC effect which is based on the strain dependence of both the densities of mobile (ρ_m) and forest (ρ_f) dislocations but not on the deformation-induced vacancy density [12–15]. The occurrence of serrated flow owing to DSA and its disappearance due to dynamic recovery as well as the phenomenon of an inverse strain and temperature dependence of the PLC effect were predicted for CuMn and Al–Mg solid solutions by the model and showed qualitative agreement with experimental observations [16,17]. Recently, a constitutive model of the PLC effect was proposed by Rizzi and Hähner who described the spatial–temporal dynamics of the PLC effect by analyzing the evolution of an additional activation enthalpy during DSA owing to solute clustering at a dislocation junction [18,19]. Moreover, based on a statistical theory of coupled dynamics between mobile dislocations