Materials Science and Engineering A 528 (2011) 6140–6145

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Developing superplasticity and a deformation mechanism map for the Zn–Al eutectoid alloy processed by high-pressure torsion

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ARTICLE INFO

Article history:
Received 21 January 2011
Received in revised form 30 March 2011
Accepted 17 April 2011
Available online 22 April 2011

Keywords:
Deformation mechanism maps
Flow mechanisms
High-pressure torsion
Superplasticity
Ultrafine grains

ABSTRACT

A Zn–22% Al eutectoid alloy was processed by high-pressure torsion (HPT) for 1, 3 and 5 turns at room temperature to produce an ultrafine grain size of ~350 nm. Tensile testing at a temperature of 473 K gave excellent superplastic properties with elongations to failure up to a maximum of 1800% at an imposed strain rate of 1.0×10^{-1} s^{-1}: this is within the range of high strain rate superplasticity and represents the highest elongation recorded to date for a specimen processed by HPT. It is shown that the experimental data are in excellent agreement with a deformation mechanism map constructed for a temperature of 473 K.

1. Introduction

Superplastic flow is associated with the ability of a polycrystalline solid to pull out uniformly, without necking, to a very high strain prior to failure. In a recent review, superplasticity was defined formally as elongations in tension of at least 400% and with measured strain rate sensitivities close to ~0.5 [1]. This elongation and strain rate sensitivity were selected specifically to avoid confusion with the solute drag flow mechanism where the strain rate sensitivity is generally close to ~0.33 and it is possible to achieve high tensile elongations [2]: for example, there is a recent report of elongations up to 325% under conditions of solute drag creep in Al–Mg alloys [3].

There are two fundamental requirements for superplasticity [4]. First, the grain size must be very small and typically less than ~10 μm. Second, the testing temperature must be within the diffusion-controlled regime which means in practice a temperature at or above ~0.5 T_m, where T_m is the absolute melting temperature.

Over the last two decades, processing through the application of severe plastic deformation (SPD) has provided an excellent opportunity for achieving significant grain refinement in bulk solids. Although several techniques for SPD processing are now available, attention has centered primarily on the two procedures of equal-channel angular pressing (ECAP) [5] and high-pressure torsion (HPT) [6]. As tabulated in a recent review, there are now more than fifty reports describing the occurrence of superplastic flow in metals processed by ECAP [7]. By contrast, and primarily because the processing operation is generally conducted using very thin disks, there are only a small number of reports of superplasticity in materials processed by HPT. These results are summarized in Table 1 where it is apparent that the highest elongation achieved to date is ~1600% when processing an Al–3% Mg–0.2% Sc alloy by HPT using a sample in the form of a small bulk cylinder [9].

It is well-known that two-phase eutectic and eutectoid alloys are especially attractive materials for achieving superplastic flow because grain growth is then limited by the presence of the two separate phases. There are several reports describing the superplastic properties achieved in the Zn–22% Al eutectoid alloy after processing by ECAP [20–25] or by using the similar process of cross-channel extrusion [26] and there are also some limited reports of superplasticity in the Pb–62% Sn eutectic alloy processed by ECAP [27,28]. Nevertheless, no reports are at present available describing superplastic properties achieved in any eutectic or eutectoid alloy after processing by HPT.

Recent experiments on the Zn–22% Al eutectoid alloy have revealed unusual physical characteristics when processing by HPT. First, in the early stages of deformation agglomerates of Zn-rich and Al-rich grains are produced near the edges of the disks lying in

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doi:10.1016/j.msea.2011.04.053

Table 1
Reports of superplasticity after processing by HPT.

Material	Maximum elongation to failure	Type of HPT sample	Reference
Al–3% Mg–0.2% Sc	~500%	Disk	Sakai et al. [8]
	~1600%	Cylinder	Horita and Langdon [9]
Al–4% Cu–0.5% Zr	~800%	Disk	Valiev et al. [10]
Al-1420	~750%	Disk	Mishra et al. [11]
Al-1421	~670%	Disk	Islamgaliev et al. [12]
Al-1570	~1460%	Disk	Perevezentsev et al. [13]
Al-2024	~570%	Disk	Dobatkin et al. [14]
Mg–9% Al	~810%	Disk	Kai et al. [15]
Mg–10% Gd	~580%	Disk	Kulyasova et al. [16]
Mg AZ61	~620%	Disk	Harai et al. [17]
Ni_3Al	~560%	Disk	Mishra et al. [18]
Ti–6% Al–4% V	~575%	Disk	Sergueeva et al. [19]

bands delineating the direction of torsional straining [29]. Second, the high pressures imposed in HPT lead to a significant reduction in the distribution of rod-shaped precipitates of stable hexagonal close-packed Zn within the Al-rich grains [20,30] and hardness measurements show this leads to a weakening, rather than a strengthening, by comparison with the annealed and unprocessed alloy [29,31].

Accordingly, the present investigation was initiated with two specific objectives. First, to determine the feasibility of achieving good superplastic properties in the Zn–Al eutectoid alloy after processing by HPT and especially to compare results obtained on the Zn–Al alloy with the experimental data listed in Table 1. Second, to evaluate the potential for presenting the flow data in the form of a deformation mechanism map that provides an accurate representation of the mechanical properties of the alloy.

2. Experimental material and procedures

The alloy was supplied in the form of a plate having a thickness of 25 mm and it was machined into a rod with a diameter of 10 mm and then cut into billets having lengths of ~60 mm. These billets were annealed in air at 473 K for 1 h to remove any residual stresses. As described in earlier reports [29,31], the material contained a binary microstructure of Al-rich α and Zn-rich β phases with an average equiaxed linear intercept grain size of ~1.4 μm.

The processing by HPT was conducted at room temperature using a quasi-constrained HPT facility [6] and samples in the form of disks having diameters of 10 mm and thicknesses of ~0.80 mm. A compressive pressure was applied using a load of 49.0 t corresponding to an imposed pressure, P, of 6.0 GPa and the disks were torsionally strained at a speed of 1 rpm. The disks were processed by HPT for total numbers, N, of 1, 3 and 5 turns.

Following HPT, an electro-discharge machine (EDM) was used to cut the disks into miniature tensile specimens with gauge lengths and widths of 1 mm. Two separate tensile specimens were machined from off-center positions in each disk to minimize any effects of inhomogeneities in the central regions. Although all specimens had minor differences in their thicknesses, all cross-sectional areas were measured carefully before mechanical testing to give accurate information on the flow stresses. All specimens were pulled to failure in tension at a temperature of 473 K using an Instron testing machine operating at a constant rate of cross-head displacement and with initial strain rates in the range from 1.0×10^{-3} to $1.0\ s^{-1}$.

3. Experimental results

Fig. 1 shows the general appearance of the Zn–Al specimens after processing by HPT through 1, 3 and 5 turns and pulling to failure at 473 K using an initial strain rate of $1.0 \times 10^{-1}\ s^{-1}$: the upper specimen is untested. It is apparent that all specimens pulled out to exceptionally high superplastic elongations of >900% and the elongations increase with increasing numbers of HPT turns. A comparison with Table 1 shows that the maximum elongation of ~1800% after 5 turns represents the highest elongation reported to date in any specimen processed by HPT and it is even higher than the earlier report of an elongation of ~1600% when using a bulk cylindrical sample [9]. Since the testing strain rate for the samples in Fig. 1 is $1.0 \times 10^{-1}\ s^{-1}$, this result confirms the occurrence of high strain rate superplasticity which is defined formally as the occurrence of superplastic elongations at strain rates at and above $10^{-2}\ s^{-1}$ [32]. The increase in ductility with increasing numbers of turns is consistent with a reduction in grain size with HPT processing because earlier measurements gave measured grain sizes of ~440 and ~370 nm after 1 and 2 turns, respectively, and a relatively stable grain size of ~350 nm after a total of 4 turns [31]. It is also consistent with reports of increasing elongations with increasing straining in some alloys processed by ECAP [33]. Inspection shows that all samples in Fig. 1 exhibit very uniform deformation within the gauge section with no evidence for any significant necking. An absence of necking is an essential characteristic of true superplastic flow [34].

The effect of the testing strain rate is shown in Fig. 2 where all specimens were processed through $N = 5$ turns and then pulled to failure at 473 K at strain rates from 1.0×10^{-3} to $1.0\ s^{-1}$. Although all samples exhibit very high elongations within the superplastic regime, the two samples tested at the slowest strain rates show very clear evidence for necking within the gauge lengths.

Using the data shown in Fig. 2 after HPT through 5 turns, Fig. 3 plots the elongations to failure (upper) and the measured flow stresses, σ (lower), against the imposed initial strain rate, $\dot{\varepsilon}$, for

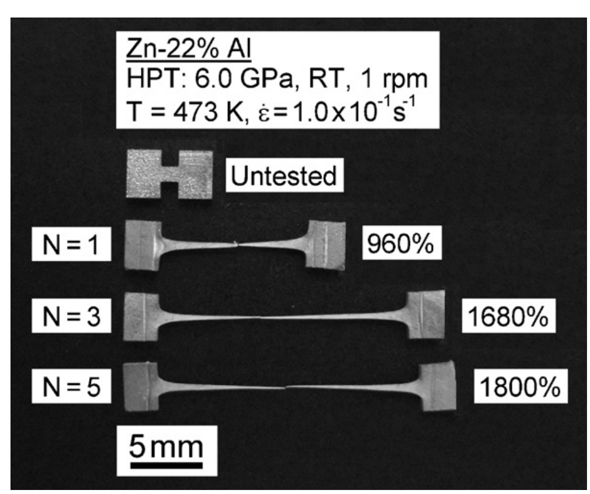

Fig. 1. Appearance of specimens processed by HPT for 1, 3 and 5 turns and pulled to failure at a strain rate of $1.0 \times 10^{-1}\ s^{-1}$ at 473 K: the upper specimen is untested.