Available online at www.sciencedirect.com
ScienceDirect
Scripta Materialia 61 (2009) 1097–1100
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

The post-deformation recrystallization behaviour of magnesium alloy Mg–3Al–1Zn

A.G. Beer* and M.R. Barnett

CAST Co-Operative Research Centre, Centre for Material and Fibre Innovation, Deakin University, Geelong, Vic. 3217, Australia

Received 26 May 2009; revised 28 August 2009; accepted 2 September 2009
Available online 6 September 2009

Interrupted hot compression tests are employed to examine the kinetics of recrystallization in magnesium alloy Mg–3Al–1Zn. It is found that recrystallization results in an increase in the flow stress encountered in subsequent deformation. The increase in flow stress is used to infer the fraction of recrystallization and empirical equations are developed to describe the kinetics.

Keywords: Hot working; Annealing; Recrystallization kinetics; Magnesium alloy; Compression test

Grain refinement is a common approach to improving the strength and ductility of wrought magnesium alloys. Whilst the grain size can be reduced during hot deformation by the operation of dynamic recrystallization (DRX), post-dynamic recrystallization can occur during subsequent annealing or slow cooling, resulting in an increase in the final grain size [1–3]. In a previous study by the authors [3], the rate at which coarsening occurred during the annealing hot worked magnesium alloy AZ31 was examined and the kinetics of post-dynamic recrystallization was subsequently modelled based on the time required to reach the fully annealed grain size. This method, however, was found to be somewhat limited in that recrystallization was extremely fast under certain conditions and the material would recrystallize before it could be quenched. In the present work, interrupted hot compression tests are employed to more accurately examine the kinetics of the post-deformation recrystallization of magnesium alloy AZ31. It is shown that post-dynamic recrystallization leads to an unexpected increase in the flow stress.

Extruded magnesium alloy AZ31 (Mg–3% Al–1% Zn–0.2% Mn), with an initial grain size of 50 μm, was examined. Compression samples, 12 mm high and 8 mm in diameter, were deformed parallel to the extrusion direction at temperatures ranging between 350 and 500 °C and at strain rates between 0.01 and 1 s^{-1}. Samples were compressed to a strain of 1.0, annealed at the deformation temperature for times ranging from 0.1 s to 3000 s and then recompressed an additional strain of 0.5 (to yield a total strain of 1.5). A constant strain rate was maintained during the two deformation steps and a time delay between the steps, due to unloading and reloading, was determined to be 0.2 s (this is in addition to the applied annealing time).

The flow curves for the interrupted compression of AZ31 can be seen in Figure 1 for a temperature of 400 °C and a strain rate of 0.1 s^{-1}, with annealing times ranging from 1 to 100 s. For the first deformation step, the flow curves contain a region of work hardening followed by work softening, developing a peak in the stress–strain behaviour, after which a steady state stress is attained. This behaviour is typical of the occurrence of conventional DRX.

During the second deformation step, the stress–strain behaviour was found to vary with the degree of preceding annealing. When the annealing time was 1 s, the stress level upon reloading immediately attained that of the stress level at the end of the first deformation step and was maintained with further strain. However, when the annealing time was increased to 7 s, the material yielded at the stress corresponding to the end of the first step and then underwent work hardening to a peak stress. The peak flow stress increased with further annealing, reaching a maximum level for annealing times of 30 s and above.

Interestingly, very little difference was observed for the yield strength of the material during reloading, regardless of annealing time. This annealing response is different from what is commonly observed during the interrupted hot deformation of other metals, such as steel, copper and nickel [4–6], whereby the yield stress

* Corresponding author. E-mail: abeer@deakin.edu.au

1359-6462/$ - see front matter © 2009 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.scriptamat.2009.09.002

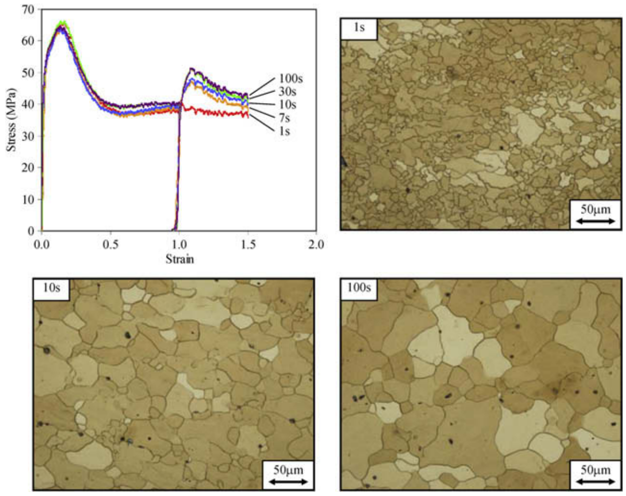

Figure 1. Flow curves for the double hit compression of AZ31, conducted at a temperature 400 °C and a strain rate 0.1 s^{-1}, with annealing for various times after the deformation was interrupted at a strain of 1. Also included are the corresponding microstructures developed by annealing for various times after deformation to a strain of 1.

drops with inter-pass holding. It is unclear why this is the case. Softening of the yield strength during recrystallization may be offset by an increase in yield strength due to changes in the way in which the deformation is accommodated during reloading. Grain boundary sliding has been identified as an important mechanism that is operative during the hot deformation of magnesium alloys [7]. It is possible that the contribution that grain boundary sliding makes to the overall deformation upon reloading would be reduced due to the larger grain sizes that are developed during post-deformation recrystallization (as was observed in Ref. [3]). It is also known that, during the hot working of magnesium alloys, deformation can be more readily accommodated within dynamically recrystallized regions of the material [8]. Post-deformation recrystallization would restore the microstructure and the lack of regions to immediately accommodate localized deformation may increase the yield strength upon reloading.

In Figure 1, it is clear that, for an annealing time of 1 s, the microstructure appears to have remained in its deformed state. It contains a large volume of fine dynamically recrystallized grains and the remnants of a few deformed original grains, which tend to be slightly pancaked and have serrated grain boundaries, are also observed. With an annealing time of 10 s, the microstructure has begun to develop larger grains, and a stable annealed grain size is observed after annealing for 100 s. During this annealing process, the average grain size of the material has increased from 11 to 29 μm.

The mechanism by which the deformed microstructure is restored during annealing is currently unclear. As there is a large percentage of the material which has undergone DRX during the first deformation step, it is believed that the dominant restorative mechanism operative during annealing is the continued growth of nuclei that formed during DRX, i.e. metadynamic recrystallization [9]. However, it must be acknowledged that there may have been some contribution of static recrystallization in regions of deformed original grains which did not dynamically recrystallize, and by normal grain growth once recrystallization was complete.

It is clear from Figure 1 that, as post-deformation recrystallization proceeds and larger grain sizes are developed, the degree of work hardening (the difference between the yield and peak stress) during reloading increases. This difference is given in Figure 2(a) as a function of annealing time for deformation conducted at a temperature of 400 °C and a strain rate 0.1 s^{-1}. The increase in the degree of work hardening follows a sigmoidal shape; no work hardening was observed for annealing up to 1 s, after which the degree of work hardening increased until a plateau level was reached after 30 s. The plateau in the degree of work hardening corresponds to a plateau in the annealed grain size.

The progress of post-dynamic recrystallization and the development of larger grains may be the cause of the higher peak flow stress seen during reloading. As recrystallization progresses, DRX nuclei grow and the dislocation density of the deformed structure is reduced. When the material is reloaded, nuclei are no longer present for DRX to proceed immediately after yielding; dislocations have to again be generated and the critical stress required to renucleate DRX in the recrystallized structure will be higher. Also, with larger grain sizes, less nucleation sites are available for DRX; the delay in the onset of DRX thus leads to higher peak flow stresses. It is unlikely that the higher peak flow stress seen during reloading is due to any texture strengthening during recrystallization as it has been shown that during the annealing of hot compressed AZ31 the texture does not change appreciably [2].

The post-deformation recrystallization behaviour is commonly examined using the fractional softening method [5]. Clearly, this method cannot be applied to the current material; no softening is observed. Instead, the progress of post-deformation recrystallization is thus inferred from the degree to which the peak flow stress increases during reloading. The fraction hardening, X, is defined as:

$$X = (\sigma_p - \sigma_y)/(\sigma_p^* - \sigma_y) \tag{1}$$

where σ_p and σ_y are the respective peak and yield stresses of the second deformation step and σ_p^* is the peak stress for long annealing times.

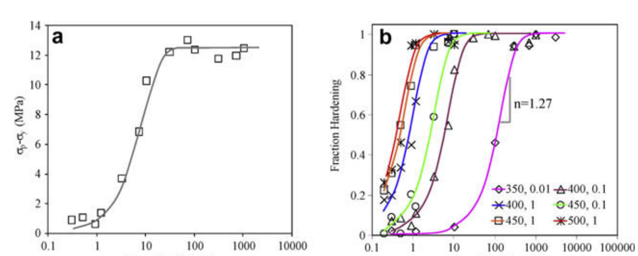

Figure 2. (a) The difference between the yield and peak stress, as a function of annealing time, during the interrupted compression of AZ31 (conducted at a temperature of 400 °C and a strain rate 0.1 s^{-1}) and (b) the fraction hardening as a function of annealing time for AZ31 deformed at temperatures and strain rates ranging from 350 to 500 °C and from 0.01 to 1 s^{-1}, respectively.