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Microstructure evolution of 2195 Al–Li alloy subjected to high-strain-rate deformation

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ABSTRACT

2195 Al–Li alloy is firstly processed by means of split Hopkinson pressure bar (SHPB). Two means of loading methods are conducted at room temperature, namely uni-axial impact and multi-directional impact. The nominal strain rates reach up to $1.2\times10^{3}\ s^{-1}$ and $2.8\times10^{3}\ s^{-1}$ respectively, with the total strain 1.6 and 3.6. TEM microstructure observations reveal that initial coarse grains are refined significantly. The grains of uni-axial impacted sample are elongated, whose width/length average grain sizes are 178 nm and 311 nm. In contrast, the grains of multi-directional impacted sample are equiaxed with an average grain size of 362 nm. Dynamic recovery is suppressed during dynamic plastic deformation (DPD), dislocations could not reach equilibrium states. High densities of dislocations are generated, forming several kinds of configurations. Interactions of dislocation substructures and fragment of grains result in the refinement of grains.

1. Introduction

Grain refinement as an important approach to improve material properties has been investigated for long terms. Widespread interests have been aroused by ultrafine-grained (UFG) and nano-grained (NG) metallic materials for their high strength and superplasticity [1–4]. Since the development of equal channel angular pressing (ECAP) by V.M. Segal in 1977, various severe plastic deformation (SPD) processes such as high pressure torsion (HPT), multiple forging (MF), accumulative roll-bonding (ARB), etc. have been proposed [5–7]. Materials processed by these technologies exhibit high strength, considerable ductility and are free of voids. SPD has become one of the significant means to produce UFG/NG materials.

Grain sizes of UFG materials produced by SPD are in the sub-micron scale, further refinement of the grains is difficult [6–8]. Lu [9] and his group obtained bulk nano-structured pure Cu sample with high frequency of nano-sized twins by means of dynamic plastic deformation at liquid nitrogen temperature (LNT-DPD). Zeldovich [10] acquired Ti sample with periodical adiabatic shear bands (ASBs) by dynamic ECAP, the microstructures in ASBs are equiaxed nano-sized grains, while elongated grains with the size from 100 nm to 300 nm dominate in the matrix. All these researches provide us new avenues and ideas to process UFG/NG materials.

Unlike Cu and Ti, Al and its alloys possess high stacking fault energies. Plastic deformation is accommodated by dislocation slip. The refined grain/cell size is mainly determined by dislocation density. With the huge accumulative strain through SPD, a relatively high density of dislocations is attained in Al. For the effect of dynamic recovery, the generation and annihilation of dislocations could reach balance, limiting the increase of dislocation density and the further refinement of grains. Most of the reported grain sizes of Al processed by SPD are above 500 nm [11–13]. In this work, 2195 Al–Li alloy would be impacted for several passes by SHPB, the effects of high strain rate and loading methods on microstructures of Al alloy would also be investigated.

2. Experiment

2195 Al–Li alloy, composed of 4.0% Cu–1.0% Li–0.53% Mg–0.43% Ag–0.12% Zr and the balance Al (all in weight %), was used as starting material. Al billets were annealed at 723 K for 4 h in a salt-bath furnace to diminish the effect of residual stress and obtain homogeneous coarse grains. Average grain size of the as-annealed sample is 32 μm. Cylindrical sample (⌀22 mm × 28 mm) and rectangular sample (8 mm × 8 mm × 12 mm) were cut for uni-axial impact and multi-directional impact, respectively.

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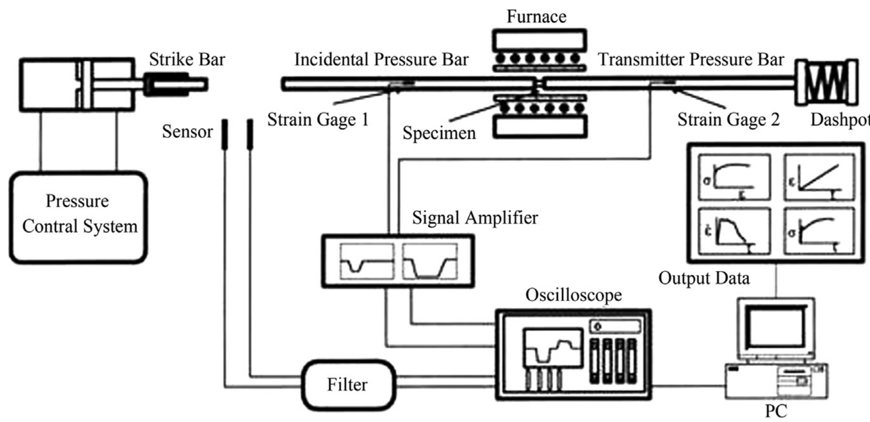

Fig. 1. Schematic diagram of SHPB.

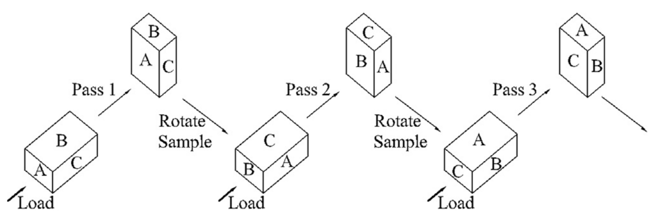

Fig. 2. Deformation scheme of multi-directional impact.

Two kinds of samples were processed by the split Hopkinson pressure bar (SHPB) at room temperature, Fig. 1 is the schematic diagram of SHPB. Cylindrical sample was deformed by uni-axial impact, a reduction about 15% was achieved per pass until to the height 5.4 mm. Rectangular sample was processed by multi-directional impact, a reduction about 30% was achieved per pass, and its deformation scheme was shown in Fig. 2. The deformation strain obtained during each pass is defined as $\varepsilon = \ln(h_0/h_f)$, where h_0 and h_f are the initial and final height of sample in each pass. The total strain is the sum of strains during each pass. Two kinds of samples were all performed 9 passes in all. The total strains of cylindrical sample and rectangular sample were 1.6 and 3.6 respectively. With the strain pulse signals of SHPB, engineering stress (σ), strain rates ($\dot{\varepsilon}$) and engineering strain (ε) could be calculated based on the following equations:

$$\varepsilon = -\frac{2C_0}{L_0}\int_0^t \varepsilon_r \, dt \tag{1}$$

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = -\frac{2C_0\varepsilon_r}{L_0} \tag{2}$$

$$\sigma = \frac{EA_0}{A}\varepsilon_t \tag{3}$$

where C_0 and E are elastic wave velocity and elasticity modulus of pressure bar respectively, L_0 is length of sample before impact, A_0 and A are cross-sectional areas of pressure bar and sample before impact.

Microstructures of the deformed samples were characterized by a Tecnai G^2 20 ST transmission electron microscopy (TEM) operated in bright field mode at 200 kV. Thin foils for TEM observations were prepared by mechanical grinding to a thickness of 60 μm, then electrochemical polishing at −30 °C with a Struers Tenupol-5 double jet electrochemical machine operated at 18 V. The electrolyte consists of 30% nitric acid and 70% methanol.

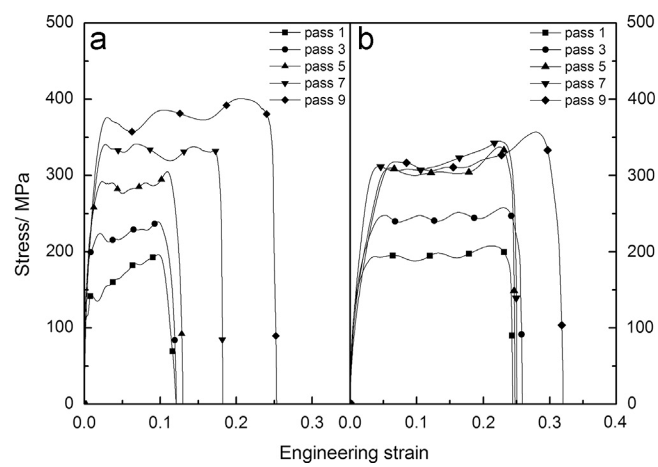

Fig. 3. Engineering stress–strain curves for 1, 3, 5, 7, 9 pass of the deformed samples. (a) and (b) are the stress–strain curves of uni-axial impacted sample and multi-directional sample respectively.

3. Results and analysis

3.1. Stress-strain response

Engineering stress (σ) and engineering strain (ε) are calculated according to Eqs. (1)–(3). Strain–stress (σ–ε) relationships of pass 1, 3, 5, 7, 9 are shown in Fig. 3, (a) and (b) are the σ–ε curves of uni-axial impacted sample and multi-directional sample separately. There is an increment of tens of MPa of the flow stress during each pass, indicating apparent strain and strain rate hardening effects. A relatively identical increment of flow stress during each pass is observed in Fig. 3(a). However, the flow stress of multi-directional impacted sample keeps in a stable range after the 5th pass which is shown in Fig. 3(b). Consequently, multi-directional impacted sample displays better plasticity.

3.2. Microstructural characterization

Fig. 4 shows TEM microstructures observed from the longitudinal section of uni-axial impacted sample. The microstructures are heterogeneous and most grains are elongated. The ring-like diffraction spots show a more random misorientation of the deformed sample. In other areas, where the subgrains are more equiaxed, the SAD patterns show larger misorientations. Width and length of crystallites were determined as the average length