Deformation behavior and microstructural evolution in an ultra-fine grained Al-Mg-Si alloy at elevated temperatures

I. Sabirov[1,2], M.R. Barnett[1,2], B. Kashyap[3], Y. Estrin[1,4,5], I. Timokhina[2], P.D. Hodgson[1,2]

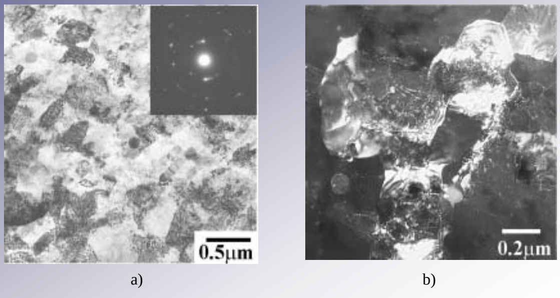
[1]ARC Centre of Excellence for Design in Light Metals, Clayton, Victoria, Australia
[2]Centre for Material and Fibre Innovation, Deakin University, Waurn Ponds, Victoria, Australia
[3]IIT Bombay, Powai, Mumbai, India
[4]Department of Materials Engineering, Monash University, Clayton, Victoria, Australia
[5]CSIRO Division of Materials Science and Engineering, Clayton, Victoria, Australia

1. Introduction

The 6xxx Al alloys are in wide use due to their superior corrosion resistance and low cost, along with good formability, weld ability and other properties. A better understanding of strengthening and flow properties of 6xxx Al alloys by manipulating the precipitation and grain refinement processes can provide more effective exploitation of these important alloys. The objective of the present work is to develop a submicron level microstructure in a commercial grade Al-Mg-Si alloy by equal channel angular pressing (ECAP) and to examine the microstructure, tensile properties and deformation mechanisms of the material over a wide range of strain rates and temperatures.

2. Material for investigation

Al6082 alloy is studied in solutionized condition. The billets 100x10x10 mm^3 are subjected to equal channel angular pressing (ECAP) at 100°C for 8 passes. The parameters of ECAP die: the angle of arc curvature (ψ=0°); the intersection angle (φ=90°).



a) b)

Fig. 1. Microstructure of the Al6082 alloy after ECAP at 100°C for 8 passes.

4. Thermo activation analysis

Activation energy

The ***apparent*** activation energy was calculated at the constant stress levels of 251 MPa, 200 MPa, 158 MPa, 126 MPa, 100 MPa, 79 MPa, 63 MPa, 50 MPa, 40 MPa by employing the Eq. 1. The ***true*** activation energy corresponding to the rate controlling mechanism was calculated using the Eq. 2

$$Q_a = -R\frac{\partial \ln(\dot{\varepsilon})}{\partial(1/T)}\bigg|_{\sigma} \quad \text{(Eq. 1)} \qquad Q_t = Q_a + RT\left[1+\frac{(n-1)T}{G}\left(\frac{dG}{dT}\right)\right] \quad \text{(Eq. 2)}$$

where dG/dT= -16 MPa.K^{-1}. The values of true activation energy Q_t were calculated both at the onset of plastic deformation (yielding) and at the steady state condition.

There is no effect of stress (temperature) on the true activation energy at the onset of plastic deformation. The Q_t values are in the range of 99.8 to 125.1 kJ/mol with the average value 107.2 kJ/mol. True activation energy at the steady state condition decreases from 152.1±1.5 kJ/mol at the lowest flow stress to 120.1±2.7 kJ/mol at the highest flow stress (Fig. 4a).

Activation volume

The activation volume *V* was estimated as

$$V = MkT(d\ln\varepsilon / d\sigma) = MkT/(m\sigma) \qquad \text{(Eq. 3)}$$

where *M* is the Taylor factor (equal to 3.06 for random textured Al) and *m* is the strain rate sensitivity. The activation volume decreases monotonically with increasing flow stress (Fig. 4b). This behaviour is consistent with the assumption that the thermally activated process controlling dislocation glide is associated with the forest junctions acting as pinning points.

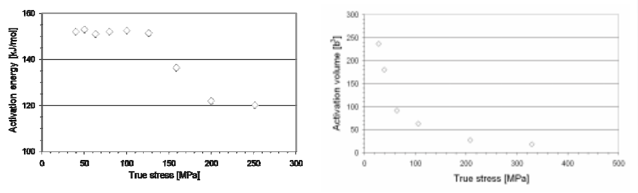


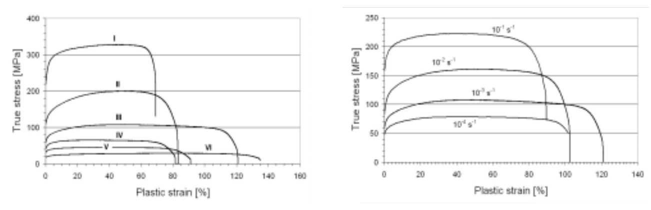
Fig. 4: a) True activation energy vs. true stress; b) activation volume vs. true stress.

6. Conclusions

1.An ultra-fine grained Al6082 alloy with a grain size of 0.2-0.4 mm can be successfully produced via ECAP at 100°C for 8 passes (Route B$_c$).
2.Very inhomogeneous plastic deformation in the form of profuse micro shear banding is observed in the material at temperatures of 100-150°C at all strain rates. At higher temperatures, 200-300°C, plastic deformation results in the formation of a bi-modal microstructure where coarse grains are embedded in a matrix of ultra-fine grains. Dislocation glide is observed within coarse grains.
3.True activation energy increases with decreasing flow stress. At low flow stresses (high temperatures), it is close to the activation energy for lattice self diffusion. It is suggested that the plastic deformation is controlled by dislocation climb.

3. Deformation behaviour

Tensile tests were carried out in an Instron 8801 machine in a temperature range of 100°C…350°C with the strain rates of 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4} s^{-1}.



a) b)

Fig. 2. True stress – strain curves for the Al6082 alloy, a) at the fixed strain rate of 10^{-3} s^{-1} (I – 100°C, II – 150°C, III – 200°C, IV – 250°C, V – 300°C, VI – 350°C); b) at 200°C for all strain rates.

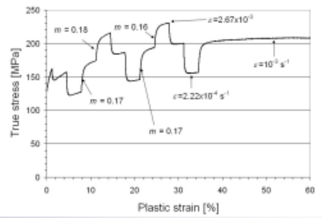
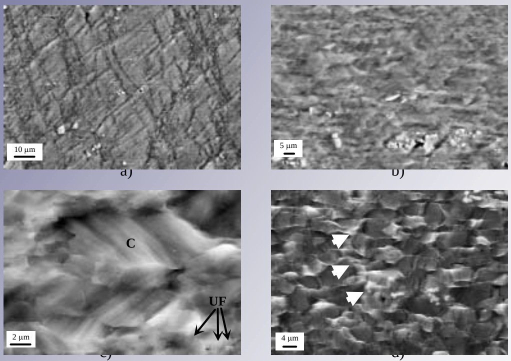


Fig. 3. Strain rate jump test for the Al6082 alloy at 150°C at the base strain rate of 10^{-3} s^{-1}.

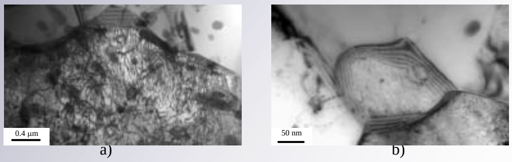
5. Microstructure evolved during tensile deformation

At low temperatures, in the range of 100-150°C, the deformation relief suggests a very inhomogeneous behaviour at all strain rates. Extensive micro shear banding is observed throughout the gauge length (Fig. 5a). An increase of tensile test temperature to 200-300°C resulted in the formation of a bi-modal microstructure at all strain rates. Coarse grains, elongated in the tensile direction with a length of 10-15 mm and a width of 3-6 mm, were embedded in a “matrix” of equiaxed ultra-fine grains 0.2-1 mm in size (Fig. 5b). Slip lines are visible within the coarse elongated grains (marked as “C” in Fig. 5c). High dislocation density (up to *p* = 1.9x10^{14} m^{-2}) was found within coarse grains (Fig. 6a), the ultra-fine grains are free of interior dislocations (Fig. 6b). There appeared to be no strong effect of strain rate on the surface relief and microstructure. Grain boundary sliding, resulting in local shearing along grain boundaries, was observed in sample tested at 350°C (marked by white arrows in Fig. 5d).



a) b) c) d)

Fig. 5. Deformation relief after tensile tests at strain rate of 10^{-3} s^{-1}: a) 100°C; b, c) 300°C; d) 350°C.



a) b)

Fig. 6. Microstructure after tensile test at strain rate of 10^{-3} s^{-1} at 300°C.

Acknowledgments

Authors acknowledge gratefully the Australian Research Council for financial support through the Centre of Excellence for Design in Light Metals and Federation Fellowship awarded to Prof. P.D. Hodgson