TEXTURE CHANGES DURING DEFORMATION OF A 7475 SUPERPLASTIC ALUMINUM SHEET ALLOY

M.T. PÉREZ-PRADO[†] and G. GONZÁLEZ-DONCEL*

*Department of Physical Metallurgy, Centro Nacional
de Investigaciones Metalúrgicas (CENIM), C.S.I.C.,
Av. de Gregorio del Amo 8, 28040 Madrid, Spain*

(Received 2 August 1999; In final form 18 October 1999)

The deformation mechanisms of a fine-grained Al 7475 superplastic alloy deformed under non-optimum conditions for superplasticity, but under which still several hundred per cent of elongation are achieved, have been studied by means of texture analysis. It has been found that crystallographic slip plays an important role in the deformation of this alloy under such conditions. After testing both along the rolling and the transverse directions, the orientations of the texture belonging to the α - and β -fibers are retained. This is not consistent with current models of deformation for randomly oriented polycrystals.

Keywords: Texture; Crystallographic slip; Superplasticity; Aluminum alloys

1. INTRODUCTION

Much effort has been devoted to studying the deformation of superplastic aluminum alloys under optimum conditions of temperature and strain rate, where often very high peak elongations, close to 1000%, are achieved (Langdon, 1982; Kaibyshev, 1992; Chokshi *et al.*, 1993; Nieh *et al.*, 1997). In some industrial applications like superplastic

* Corresponding author.

[†] Present address: Department of Mechanical and Aerospace Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0411, USA.

forming, however, these extreme conditions for superplasticity are not critical to obtain successfully components with complicated shapes. This is because the final strains required to achieve the final shape of the component are, generally, not too high; typically, equivalent to some hundred per cent tensile elongation. In other words, a “pure” superplastic deformation stage is not essential during superplastic forming. It is therefore, also necessary to understand the deformation processes involved during deformation of superplastic alloys when tested under non-optimum superplastic conditions. Furthermore, superplastic materials tested in non-optimum superplastic conditions, where slip plays an important role but still high tensile elongations can be achieved, are very adequate to study the specific slip processes which take place during deformation.

The aim of the present work is to investigate the deformation mechanisms operative during deformation of a 7475 fine-grained superplastic Al alloy tested under non-optimum conditions for superplasticity by means of texture analysis. Texture analysis has proved to be a powerful tool to investigate the microscopic deformation mechanisms of crystalline materials (Padmanabhan and Lücke, 1986; Pérez-Prado *et al.*, 1998a; Kocks *et al.*, 1998). In general, crystallographic slip has been associated with the retention or appearance of specific texture components, whereas grain boundary sliding usually causes texture randomization. Several investigations on superplastic materials based on texture analysis have reported somewhat unexpected observations that do not fit in the traditional description of superplasticity (Matsuki *et al.*, 1977; Kaibyshev *et al.*, 1978; 1981; Blackwell and Bate, 1993; Liu and Chakrabarti, 1996; Pérez-Prado *et al.*, 1998a). According to these studies, orientations belonging to the β -fiber, a common texture in FCC sheet alloys, are retained and strengthened during deformation of certain superplastic alloys under non-optimum and optimum superplastic conditions. This reveals that crystallographic slip can be also an important deformation mechanism during superplastic deformation.

The testing conditions utilized for the present research (400°C and 10^{-2} s^{-1}) were selected on the basis of a previous work (Adabbo *et al.*, 1989). This 7475 alloy is superplastic ($m=0.5$, where m is the strain rate sensitivity) at 400°C (and above this temperature) and at strain rates ranging from 10^{-5} to 10^{-3} s^{-1} . As strain rate increases at this testing temperature, the power-law breakdown regime for $m=0.5$ is

approached and crystallographic slip takes over grain boundary sliding progressively.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Aluminum 7475 alloy processed to achieve a fine grain size was used. The alloy was rolled to a final form of 1.5 mm thick sheet. The composition of the alloy is summarized in Table I.

Tensile tests were conducted in a computer controlled SERVOSIS testing machine. Dog-bone type samples of 10 mm gauge length and 5 mm width were machined with the tensile direction parallel to the rolling, RD, and transverse, TD, directions of the rolled sheet. Tests were conducted at 400°C and at a constant strain rate of 10^{-2} s^{-1} . These conditions are not optimum for superplastic behavior in this 7475 alloy but still allow tensile elongations of about 200%.

Texture measurements were carried out in the mid-layer of the as-received, heat treated and tested materials by means of the Schultz reflection method, using a SIEMENS diffractometer equipped with a D5000 goniometer and a closed Eulerian cradle. The X-radiation used was β -filtered Cu $K\alpha$. The direct pole figures (111), (200), (220), and (311) were obtained. The polar angle ranged from 0° to 90° in steps of 3°. From the pole figures the even part of the three-dimensional orientation distribution function (ODF) of the Euler angles φ_1 , Φ , and φ_2 was calculated by a harmonic series expansion method. The odd coefficients were approximated by an iterative procedure. The maximum rank of even and odd coefficients is 22 and 21, respectively. Sample surface preparation for both texture and microstructural examination involved abrasion on successively finer silicon carbide papers, polishing through 1 μm diamond paste, and final electro-polishing in a solution of nitric acid in methanol (20 : 80) at -22°C using a voltage of 7 V.

TABLE I Composition of the 7475 Al alloy used in this investigation

<i>Zn</i>	<i>Mg</i>	<i>Cu</i>	<i>Cr</i>	<i>Al</i>
5.7	2.1	1.5	0.2	Balance

3. RESULTS

The texture of the as-received rolled 7475 aluminum alloy is formed by a fiber which runs from the $\{011\}\langle 100 \rangle$, Goss, G, component to the $\{225\}\langle 554 \rangle$, copper-type, C, component in the Euler space. This is a common rolling texture of aluminum alloys and is shown in Fig. 1

FIGURE 1 Texture of the as-received 7475 sheet aluminum alloy represented as: (a) cuts of the unit domain of the Euler space ($\varphi_2 = \text{const.}$, $\Delta\varphi_2 = 5^\circ$) showing intensity levels of the ODF from 1 to 5 (at increments of 0.5) and, (b) skeleton line (thick line) of the fiber developed. As reference, the α - and β -fibers are also represented as dotted lines.

through cuts ($\varphi_2 = \text{const.}$) of the ODF (Fig. 1(a)) and through the position of its skeleton line (maximum intensity) in the unit domain of the three-dimensional Euler space (Fig. 1(b)). As reference, the skeleton lines of the α - and β -fibers are also illustrated in Fig. 1(b). As can be seen, the orientations of the fiber texture measured are very close to those of the β -fiber for φ_1 angles between 65° and approximately 90° (i.e. from the S component to the C component) and to those of the α -fiber for $\varphi_1 \approx 0^\circ$ (G component). The texture is rather well defined and some main texture components can be detected along the fiber. These main components are those orientations which are coincident with the α - and β -fibers. The peak intensities of these orientations are 5 (G) and 3.2 (C to S). The maximum intensity of the fiber for orientations away from the α - and β -fibers is about 2.2. The microstructure of the alloy showed a well defined grain size of about $10\ \mu\text{m}$.

Upon severe heat treatment ($500^\circ\text{C}/4\ \text{h}$) this alloy does not undergo significant microstructure and texture changes. No grain growth was detected. The same fiber texture shown in Fig. 1, with similar intensity values, has been observed. Even prolonged annealing (up to 24 h) at 500°C does not result in significant changes in the texture.

The mechanical response of this alloy under the conditions investigated is represented in Fig. 2 as a true stress vs. true strain curve corresponding to the longitudinal test. The flow stress is about 37 MPa and

FIGURE 2 True stress vs. true strain tensile curve of the 7475 Al sheet alloy tested at $400^\circ\text{C}/10^{-2}\text{s}^{-1}$ along RD.

FIGURE 3 Skeleton line of the fibers developed in the alloy 7475 Al during deformation at $400^\circ\text{C}/10^{-2}\text{s}^{-1}$ along the rolling direction (a) and the transverse direction (b).

the total elongation to failure is 200% (under optimum superplastic conditions elongations higher than 1000% are observed). A similar behavior is observed upon testing along the transverse direction.

The deformation textures of the 7475 alloy after uniaxial testing along RD and TD are illustrated in the unit domain of the three-dimensional Euler space shown in Fig. 3(a) and (b), respectively. As can be seen, a clearly different texture from that of the as-received material is developed upon testing. The resulting texture is also very dependent on the tensile direction. After longitudinal deformation, the orientations tend to group along the α - and β -fibers. The maximum intensity is approximately constant along both fibers ($\alpha + \beta$), ranging from 3.4 for the G and C components and 2.2 for the B component. After testing along the transverse direction, however, the orientations tend to cluster around the Brass, B, component and along the β -fiber, between the S and C components. The maximum intensity of the B component increases to about 3.3. The maximum intensity for orientations in the β -fiber decreases to about 2.1. The G component disappears after testing along the transverse direction.

4. DISCUSSION

The stability of the texture and microstructure of the as-received 7475 alloy reveals that it is fully recrystallized. This is characteristic of 7xxx series alloys which have undergone the thermomechanical processing developed for grain refinement (Wert *et al.*, 1981; Paton *et al.*, 1982; Hamilton *et al.*, 1982). The as-received texture, formed by orientations close to the α - and β -fibers, is a typical deformation texture predicted by

Taylor-type deformation models for low rolling degrees (plane strain) (Hirsch and Lücke, 1988).

The fact that the recrystallization texture of this 7475 alloy is a typical deformation texture is consistent with the occurrence of continuous recrystallization in this material. Although this process is not yet fully understood, it is known that it does not consist on the successive stages of nucleation and growth (formation and long-range migration of high angle boundaries), characteristic of discontinuous (or traditional) recrystallization. Instead, the microstructure evolves in a gradual and homogeneous fashion, similar to a recovery process (Humphreys, 1997). Thus, continuous recrystallization does not involve a texture change and deformation textures are retained during this process.

The isotropic mechanical behavior detected and the presence of a well defined texture after deformation is consistent with the fact that crystallographic slip predominates both when testing along RD and TD under the conditions investigated. However, the significant texture changes observed upon testing along RD and TD reveal that different slip systems may operate in each case.

It should be noted that, although the texture evolves differently after testing along RD and TD, in both cases all main orientations are concentrated on the α - and β -fibers. This is surprising since, according to geometric (Taylor-type) models of uniaxial deformation of polycrystals by crystallographic slip, the operation of 6 or 8 slip systems would give rise to the appearance of the $\langle 111 \rangle$ or the $\langle 001 \rangle$ fibers, respectively (Hosford, 1993; Reid, 1973). That is, the $\langle 111 \rangle$, or the $\langle 001 \rangle$ directions, respectively, should be oriented parallel to the tensile axis. None of these fibers were observed here.

A possible explanation for this result is the presence of a well defined texture in the as-received alloy. Geometrical models that predict texture evolution during uniaxial deformation of polycrystals usually assume a random starting texture. This is not the case here. Specific spatial orientation arrangements (such as deformation bands or clustering of particular orientations) may have a definitive influence on the uniaxial deformation of the 7475 alloy investigated. Further work on the study of individual orientations by electron back-scattered diffraction (EBSD) should be performed to confirm this hypothesis. The importance of the spatial arrangements of orientations has, however, already been pointed out by Hirsch (1990) for plane-strain deformation. According

to this author, the clustering of grains oriented as symmetric variants of the main components (which, in his study, were C, B, and S) allows compatible deformation with only two slip systems. It is worth noting that the textures obtained for this 7475 alloy after uniaxial deformation can be predicted by theoretical models for plane strain conditions.

The elongation achieved during the tensile tests presented here is close to 200% when testing both along the rolling and the transverse directions. Such high elongations cannot be achieved by “pure” crystallographic slip. Thus, to a certain extent, grain boundary sliding may occur simultaneously. This could also contribute to the fact that textures different from those predicted by theoretical models for uniaxial deformation are obtained.

The retention and strengthening of α - and β -fiber orientations during uniaxial deformation has been observed previously in other superplastic aluminum alloys deformed few hundred per cent under non-superplastic conditions (Matsuki *et al.*, 1977; Kaibyshev *et al.*, 1978; Bricknell and Edington, 1979; Kaibyshev *et al.*, 1981; Blackwell and Bate, 1993; Liu and Chakrabarti, 1996; McMahon, 1996; McNelley and McMahon, 1996; Pérez-Prado *et al.*, 1998b). Our present work adds more evidence pointing towards the possible existence of a common pattern of behavior for several superplastic aluminum alloys that cannot be framed in the traditional description of slip deformation.

5. CONCLUSIONS

The texture evolution of a fine-grained 7475 Al superplastic sheet alloy has been investigated after annealing and after deformation at 400°C and 10^{-2} s^{-1} , where “only” moderate elongations ($\approx 200\%$) (when compared to superplastic deformations), are achieved. The following are the most important findings of this research.

- (1) The texture of the as-received material is a typical rolling texture for aluminum alloys. It is formed by a fiber which runs from the Goss, G, component up to the $\{225\}\langle 554 \rangle$, C', component in the Euler space. The fiber is coincident with the β -fiber for φ_1 angles between 65° and approximately 90° (i.e. from the S component to the C component) and to those of the α -fiber for $\varphi_1 \approx 0^\circ$ (G component).

- (2) Upon prolonged annealing the texture remains unchanged and no grain coarsening is observed, revealing a very stable microstructure. The retention of a deformation texture after annealing is consistent with the occurrence of continuous recrystallization.
- (3) The same mechanical response is observed after testing at 400°C and 10^{-2} s^{-1} both along RD and TD. The elongations achieved are moderate ($\approx 200\%$). The presence of well defined textures after deformation suggests that the alloy deforms in the slip creep regime, where crystallographic slip predominates. The deformation textures observed after testing along RD and TD are, however, significantly different. After longitudinal tests, the orientations tend to spread along the α - and β -fibers in Euler space whereas after transverse tests, a texture mainly formed by the Brass, B, component (common to both the α - and β -fibers) is developed. This reveals that different slip systems may operate in each case.
- (4) The retention of orientations belonging to the α - and β -fibers upon deformation, already observed in other superplastic aluminum alloys, cannot be explained by geometrical models for deformation of polycrystalline materials (which predict the formation of the $\langle 111 \rangle$ or the $\langle 001 \rangle$ fibers, when 6 or 8 slip systems operate, respectively). This indicates that the spatial arrangement of orientations and perhaps the simultaneous occurrence of grain boundary sliding have a crucial influence in the deformation behavior of this 7475 alloy.

References

- Adabbo, H.E., González-Doncel, G., Ruano, O.A., Belzunce, J.M. and Sherby, O.D. (1989). Strain hardening during superplastic deformation of Al-7475 Alloy. *Journal of Materials Research*, **14**(3), 587–594.
- Blackwell, P.L. and Bate, P.S. (1993). The absence of relative grain translation during superplastic deformation of an Al–Li–Mg–Cu–Zr alloy. *Metallurgical Transactions*, **24**, 1085–1093.
- Bricknell, R.H. and Edington, J.W. (1979). Textures in a superplastic Al–6Cu–0.3Zr alloy. *Acta Metallurgica et Materialia*, **27**, 1303–1311.
- Chokshi, A.H., Mukherjee, A.K. and Langdon, T.G. (1993). Superplasticity in advanced materials. *Materials Science and Engineering R*, **10**, 237–274.
- Hamilton, C.H., Bampton, C.C. and Paton, N.E. (1982). *Superplastic Forming of Structural Alloys*, N.E. Paton and C.H. Hamilton (Eds.), p. 173, AIME, Warrendale, PA.
- Hirsch, J.R. (1990). Correlation of deformation texture and microstructure. *Materials Science and Technology*, **6**, 1048–1057.
- Hirsch, J. and Lüke, K. (1988). Mechanism of deformation and development of rolling textures in polycrystalline FCC metals. II. Simulation and interpretation of experiments on the basis of Taylor-type theories. *Acta Metallurgica*, **36**, 2883–2904.

- Hosford, W.F. (1993). *The Mechanics of Crystals and Textured Polycrystals*, 1st edn., Oxford Science Publications.
- Humphreys, F.J. (1997). A unified theory of recovery, recrystallization and grain growth, based on the stability and growth of cellular microstructures. I. The basic model. *Acta Materialia*, **45**(12), 5031–5039.
- Kaibyshev, O.A., Rodionov, B.V. and Valiev, R.Z. (1978). Peculiarities of dislocation slip during superplastic deformation of Zn–Al alloys. *Acta Metallurgica*, **26**, 1877–1886.
- Kaibyshev, O.A., Kazachkov, I.V. and Galeev, R.M. (1981). The influence of texture on superplasticity of the titanium alloy VT6. *Journal of Materials Science*, **16**, 2501–2506.
- Kaibyshev, O.A. (1992). *Superplasticity of Alloys, Intermetallics and Ceramics*, Springer-Verlag, Berlin, Germany.
- Kocks, U.F., Tome, C.N. and Wenk, H.-R. (1998). *Texture and Anisotropy*, 1st edn., Cambridge University Press.
- Langdon, T.G. (1982). The Mechanical properties of superplastic materials. *Metallurgical Transactions*, **13A**, 689–701.
- Liu, J. and Chakrabarti, D.J. (1996). Grain structure and microtexture evolution during superplastic forming of a high strength Al–Zn–Mg–Cu alloy. *Acta Materialia*, **44**, 4647–4661.
- Matsuki, K., Morita, H., Yamada, M. and Murakami, Y. (1977). Relative motion of grains during superplastic flow in an Al–9Zn–1Mg alloy. *Metal Science*, **6**, 156–163.
- McMahon, M.E. (1996). Grain boundary development in superplastic aluminum alloys. Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA.
- McNelly, T.R. and McMahon, M.E. (1996). An investigation by interactive electron backscatter pattern analysis of processing and superplasticity in an aluminum–magnesium alloy. *Metallurgical and Materials Transactions*, **27**, 2252–2262.
- Nieh, T.G., Wadsworth, J. and Sherby, O.D. (1997a). *Superplasticity in Metals and Ceramics*, 1st edn., p. 16. Cambridge University Press.
- Nieh, T.G., Wadsworth, J. and Sherby, O.D. (1997b). *Superplasticity in Metals and Ceramics*, 1st edn., p. 262. Cambridge University Press.
- Padmanabhan, K.A. and Lücke, K. (1986). An assessment on the role of texture in structural superplastic flow. *Zeitschrift für Metallkunde*, **77**(12), 765–770.
- Paton, N.E., Hamilton, C.H., Wert, J.A. and Mahoney, M.W. (1982). Characterization of fine-grained superplastic aluminum alloys. *Journal of Metals*, **34**(8), 21–27.
- Pérez-Prado, M.T., Cristina, M.C., Ruano, O.A. and González-Doncel, G. (1998a). GBS and crystallographic slip during superplasticity of Al–5%Ca–5%Zn. *Materials Science and Engineering*, **244A**, 216–223.
- Pérez-Prado, M.T., McNelly, T.R., Ruano, O.A. and González-Doncel, G. (1998b). Microtexture evolution during annealing and superplastic deformation of Al–5 Pct Ca–5 Pct Zn. *Metallurgical and Materials Transactions*, **29**, 485–492.
- Reid, C.N. (1973). *Deformation Geometry for Materials Scientists*, Pergamon Press, New York.
- Wert, J.A., Paton, N.E., Hamilton, C.H. and Mahoney, M.W. (1981). Grain refinement in 7075 aluminum by thermomechanical processing. *Metallurgical Transactions A*, **12**, 1267–1276.