The effect of strain rate variations on the microstructure and hot deformation behaviour of AA2024 aluminium alloy

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Abstract

In the present paper the deformation behaviour of AA2024 aluminium alloy has been studied through double-hit compression testing in the temperature range of 350–400 °C. The initial strain rate was $0.1\,\mathrm{s}^{-1}$ and the second pass strain rates of 0.0001, 0.001 and $0.01\,\mathrm{s}^{-1}$ have also been tested. The results indicate that at high temperature and low strain rates, dynamic recrystallization has occurred during the second pass straining. Moreover, the flow stress is reduced by decrease of the strain rate during the hot work hardening (i.e., dynamic work softening) and in this case it is attributed to both the restoration process and particles coarsening during straining. In addition, this may be assisted by particles precipitation and their subsequent dynamic growth.

Key words: dynamic recovery, work softening, work hardening, dynamic precipitation

1. Introduction

During hot deformation of aluminium alloys, a substructure of dislocations and subgrains is formed by a combination of dislocation generation, annihilation and rearrangement. The dislocation structure is often heterogeneous with dislocation walls bounding cells whose interiors contain relatively few dislocations. These cells are usually grouped in blocks bounded by dislocation walls of higher misorentation than the ordinary cell walls. There are two kinds of dislocation walls during deformation including low angle cell walls (less than 2 or 3°) resulting from the random trapping of moving dislocations on the active slip planes (Incidental Dislocation Boundaries, or IDBs), and higher misorentation walls (3–15°) resulting from the different orientation change of the grains or groups of cells bounded by Geometrically Necessary Boundaries (GNBs). The role of the GNBs is the accommodation of the crystal rotations produced by different active slip system combinations in the adjacent cell blocks [1, 2].

Several detailed TEM studies have characterized the following typical stages of dislocation substructure evolution [3]:

(i) for $\varepsilon < 0.2$, the first decomposition of the grain into cell blocks occurs;

(ii) for $0.2 < \varepsilon < 1$, the average GNB misorentation increases while the cell size decreases and the cell walls collapse into sub-boundaries;

(iii) for $0.5 < \varepsilon < 2$, micro-band structures evolve into a lamellar structure.

If the strain rate is changed during deformation, then both the flow stress and the sub-grain size change. However, there is a disintegration of existing sub-grain boundaries, leading eventually to a larger sub-grain size. The excess dislocations released from the old sub-grain are eventually annihilated or incorporated into the sub-grain boundaries [4]. Baxter *et al.* [5] observed during and after transient strain rate, that the strain (time) intervals for the microstructural variable increase as: "random" dislocation density < sub-grain size/micro-band spacing < geometrically necessary dislocation density/micro-band misorentation. Therefore, with decreasing strain rate, GNBs can join the adjacent sub-grain (micro-band) boundaries to increase their misorentation and so retain the overall local lattice curvature [6, 7]. In other words, the main

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Table 1. Chemical composition of the AA2024 alloy

Element	Cu	Mg	Mn	Fe	Si	Ti	Zn	Al
wt.%	3.92	1.5	0.26	0.50	0.60	0.01	0.09	Base

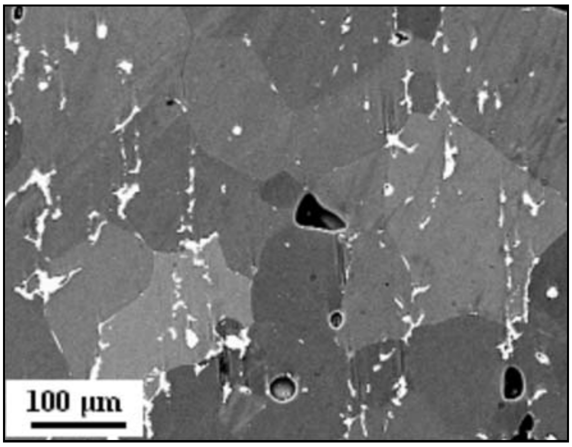

Fig. 1. Initial microstructure of 2024 Al versus direct extrusion.

mechanism of grain refinement can be directly associated with the grain splitting by a formation of internal GNBs followed by their transformation into large-angle boundaries [8]. As a result, highly inhomogeneous deformation can develop in the grain interiors and then provide formation of GNBs.

The present study is aimed to examine the grain refinement in as-extruded 2024 aluminium alloy under double-hit compression test. This article is organized as follows: details of the material and used experimental procedure are presented in Sec. 2 and experimental results are interpreted in Sec. 3.

2. Material and experimental procedure

The material was in the extruded condition and its composition satisfies the specifications for alloy AA2024 according to Table 1.

Cylindrical compression specimens with 10 mm in diameter and 15 mm length were machined parallel to the extrude axis. The samples were homogenized at 500 ℃ for 16 h (T_1). The initial microstructure is composed of dendrite lamellas lying parallel to the billet axis, as is shown in Fig. 1.

The samples were deformed in compression at constant crosshead speed using a modified servo-hydraulic system with an INSTRON-8500 controller equipped with a heating chamber. Specimens were strained to $\varepsilon = 0.4$ with the constant strain rate of $0.1\,\mathrm{s}^{-1}$ where steady state flow was achieved, and rapidly decreasing strain rate from $0.1\,\mathrm{s}^{-1}$ to 0.01, 0.001 and $0.0001\,\mathrm{s}^{-1}$, respectively. The time between the two tests was less than 1 second. The temperature was measured by an internal thermocouple placed very close to the specimens. Specimens were heated in a furnace to the deformation temperature and held for 300 s prior to the deformation (Fig. 2).

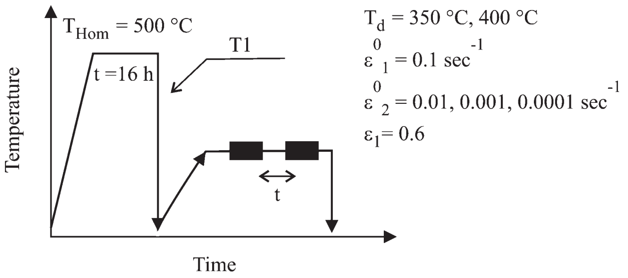

Fig. 2. Schematic thermo-mechanical process.

Teflon and graphite were used as a lubricant between the specimens and the plates.

After straining, samples were water quenched at room temperature within 3 s, in order to preserve the microstructure.

3. Experimental results and discussion

The true stress-true strain curves of specimens subjected to a strain rate drop are shown in Fig. 3. In the second test at 350 ℃, the flow stress increases with further straining and, after reaching its maximum value, it is reduced (Fig. 3a). The work softening is due to solute depletion, particle coalescence and enhancement of dynamic recovery. It may be seen that in most cases there is a transient period during which the flow stress drops and eventually reaches a constant stable value. At low second strain rate ($0.0001\,\mathrm{s}^{-1}$), the steady-state strain value is ~ 0.1, also with these conditions, dynamic softening has to occur but at higher second strain rate ($0.01\,\mathrm{s}^{-1}$) before reaching a new steady state, work hardening is produced.

Micrographs of specimens, with a reduction of strain rate at 350 ℃, are shown in Fig. 4. The boundaries of lamellar grains, roughly parallel to the billet axis (Fig. 1) and the compression direction, are gradually rotated by compression (Fig. 4) and become almost perpendicular to the compression axis. At a strain rate of $0.001\,\mathrm{s}^{-1}$ (Fig. 4b), many fine grains with moderate to large angle boundaries are developed in colonies accompanied by formation of relatively coarse grains with low to moderate angle boundaries.

In low secondary strain rate ($0.00001\,\mathrm{s}^{-1}$), deformation bands and GNBs are increased due to rotation and sliding of grain boundaries. This suggests that

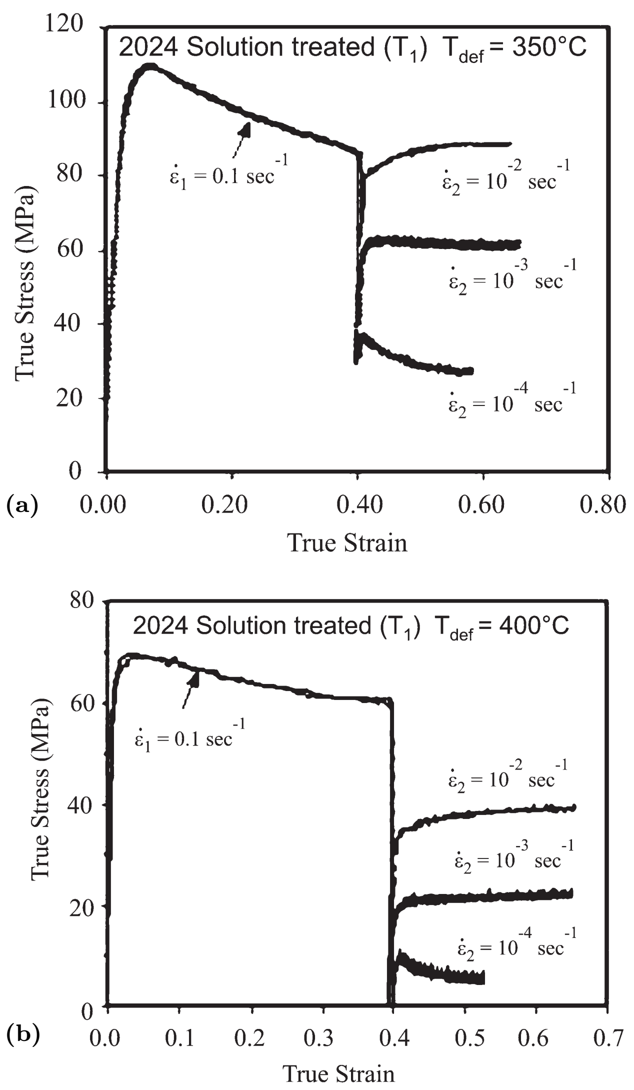

Fig. 3. True stress-true strain curves for specimens deformed at: (a) 350 ℃ and (b) 400 ℃ to a strain of 1, with strain rate of 0.1 s^{-1}, at which a strain rate reduction was imposed.

those deformation bands subdivide original coarse grains even at early stages of deformation. Further deformation leads to an increase in these misorentation angles and the numbers of GNBs. The present as-cast aluminium alloy has, however, an unusual coarse lamellar grain structure with non-symmetric shapes, i.e. having alternating straight and corrugated grain boundary segments (Fig. 1). When grain boundary sliding (GBS) takes place under such structure conditions, it may operate inhomogeneously and result consequently in development of inhomogeneous strain gradients followed by GNBs [9, 10]. However, the grain boundary sliding (GBS) takes place at present deformation conditions and plays an important role in fine-grained evolution and flow softening during deformation [11].

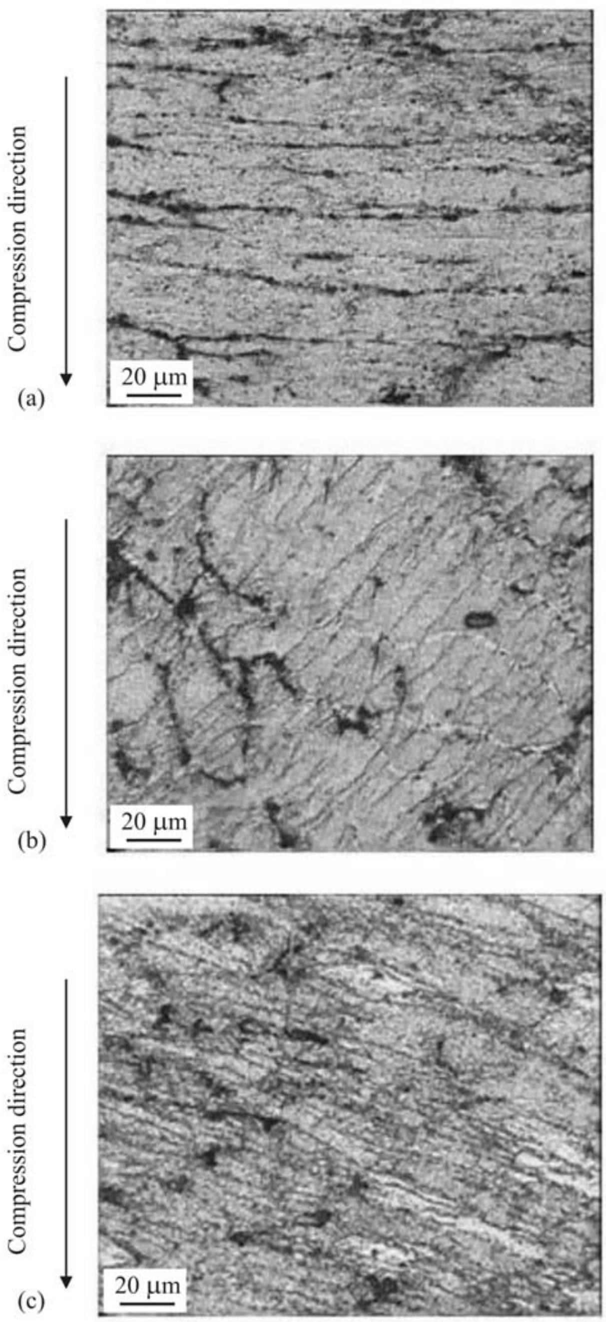

Fig. 4. Microstructure change of AA2024 Al alloy after compression at 350 ℃ with a strain rate of 0.1 s^{-1} and subsequently with reduced stain rate of (a) 0.01 s^{-1}, (b) 0.001 s^{-1} and (c) 0.0001 s^{-1}.

The flow stress is increased with further straining at 400 ℃ and after reaching maximum value, it is reduced (Fig. 3b). The work softening is due to solute depletion, particle coalescence and enhancement of dynamic recovery. Thus, the peak value at 400 ℃ is lower than the peak value at 350 ℃. It may be seen that in most cases there is a transient period during which the flow stress drops and eventually reaches a constant

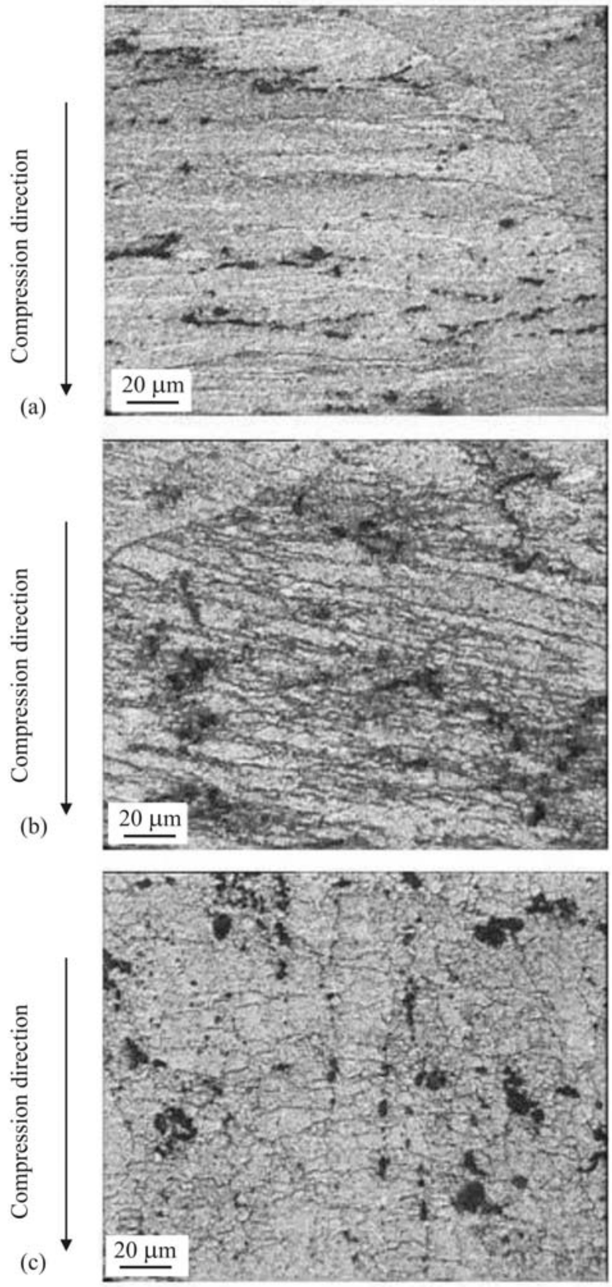

Fig. 5. Microstructure change of AA2024 Al alloy after compression at 400 ℃ with a strain rate of $0.1\,s^{-1}$ and subsequently with reduced strain rate of (a) $0.01\,s^{-1}$, (b) $0.001\,s^{-1}$ and (c) $0.0001\,s^{-1}$.

stable value. At low second strain rate ($0.0001\,s^{-1}$), the strain value that is required to reach a steady state is ~ 0.1, also with these conditions, dynamic softening has occurred, but at higher second strain rate ($0.01\,s^{-1}$) before reaching a new steady state, work hardening is produced.

Micrographs of specimens, which have undergone a reduction in strain rate at 400 ℃, are shown in Fig. 5. It is shown that at high secondary strain rate ($0.01\,s^{-1}$) the coarse and lamellar grains become almost perpendicular to the compression axis. At lower second strain rate ($0.001\,s^{-1}$), GBS can occur along inclined part of the original grain boundary, which becomes roughly parallel to the maximum shear stress in deformation. Under such conditions, GBS can easily take place and result in an early flow softening during deformation.

At a low strain rate ($0.0001\,s^{-1}$), flow softening should take place more clearly due to new grain axisymmetric evolution at original grain boundaries. During such processes, GBS taking place frequently in new fine-grained regions can accelerate increasing in the boundary misorentation and assist the rapid development of fine grains with large angle.

Another factor promoting grain refinement under hot deformation of the presented Al alloy can be an effect of second phase particles [7].

There is a strong interaction between lattice dislocations and θ'-Al_2Cu/S$'$-Al_2CuMg. In addition, many precipitates are located along deformation-induced boundaries. This suggests that these fine precipitates may restrict effectively an ability of lattice dislocation to long-range rearrangement and thus retard or prevent any relaxation of strain gradients developed in grain interiors. Strain gradients can be increased with further deformation, leading to development of GNBs there. This effect can additionally accelerate an increase in the misorentation of deformation-induced boundaries and their conversion into high-angle boundaries. Therefore, fine-precipitates should play an important role in operation of fine-grain during hot deformation of the presented Al alloy.

4. Conclusions

– GBS occurs inhomogeneously in the initial coarse and lamellar grains, resulting in local lattice rotation and forms deformation bands during double-hit compression testing.

– By decreasing the strain rate, GNBs can join the adjacent sub-grain (micro-band) boundaries to increase their misorentation and so retain the overall local lattice curvature. As a result, highly inhomogeneous deformation can develop in the grain interiors and then provide sites formation of GNBs.

– The number and the misorentation angle of deformation bands increase with decreasing strain rate and high temperature, finally causing new fine grains to form in the microstructure.

Acknowledgements

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