

## Full Length Research Paper

# The influence of transient strain rate deformation on the microstructure of AA2024 aluminum alloy in the low temperature range

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**Constant and varying strain rate deformation conditions have been applied to AA2024 aluminum alloy using hot compression testing in the temperature range of 200 - 300 °C. The initial strain rate of 0.1 s<sup>-1</sup> and the second pass strain rate of 0.0001, 0.001 and 0.01 s<sup>-1</sup> have been applied and tested. This research shows that in low temperature range with decreasing strain rate in the second pass, the straining hardening rate is increased. Increasing the strain rate and deformation leads to restoration processes and dynamic coarsening. Decreasing strain rate during the second pass straining increases the mobile dislocation density.**

**Key words:** Strain rate, hardening, deformation, dislocation density.

## INTRODUCTION

Approximately 15% of the world's primary aluminium production is used each year in the manufacture of cans for the beverage industry. With increasing demands from can manufacturers to lower production costs there is a growing need for an ever more detailed understanding and control of the micro-structural changes which occur during each stage of can production, particularly during thermo-mechanical processing (Davenport et al., 2006). It is widely recognized that having soundly based physical models of micro-structural evolution during thermo-mechanical processing is highly desirable if truly predictive capabilities in relation to the effect of process variables on subsequent processing and product properties are to be achieved. The benefits of having such predictive capabilities in the aluminum industry are clear (Castro-Fernandez et al., 2004).

During industrial hot working operations of forging, rolling or extrusion the strain rate varies during the deformation process and heat transfer leads to the development of temperature gradients and changes in the mean temperature of work piece. In the case of rolling

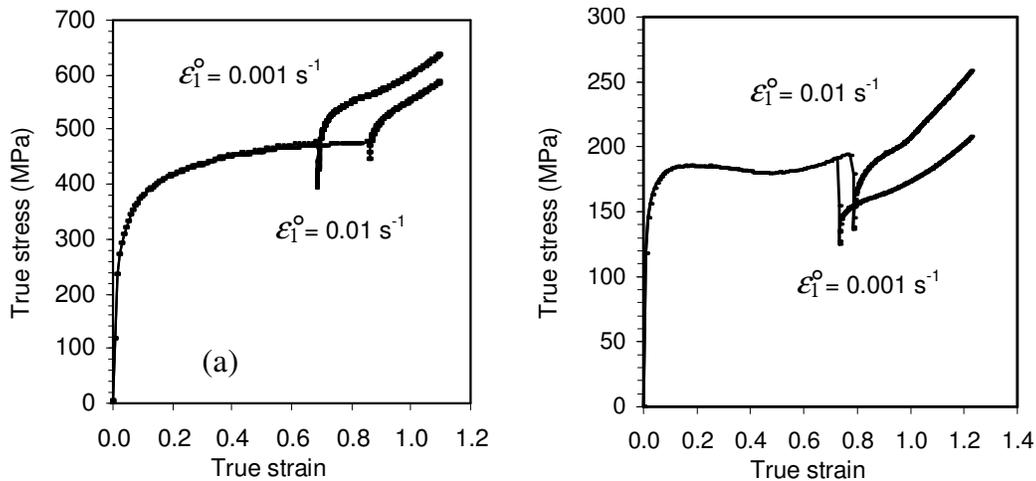
and forging, sequential passes may also take place at different temperatures and strain rates. By contrast, laboratory tests are usually carried out under constant deformation conditions to obtain relationships between flow stress and the strain (Furu et al., 2006). From such tests, constitutive relationships have been proposed and have been used to derive working forces for the hot working operations by considering the mean strain rate and temperature (Gil et al., 2002). Present models, however, have no predictive power outside their experimentally established range of application. They can not be applied to the complex temperature and strain rate transients encountered during thermo-mechanical processing. In order to progress further and improve knowledge of the link between deformation structures and re-crystallization kinetics a better understanding of the evolution of microstructure during transient deformation conditions is required (Shahani, 2005).

The key variables that describe a deformed structure are the subgrain size, the misorientation between neighbouring subgrains and the internal dislocation density of the subgrains. These influence flow stress and stored energy. The microstructural evolution during cold deformation of metals and alloys has been the subject of many studies over the last three decades (Ricks et al., 1994). Fewer studies have investigated the micro-structural evolution in aluminum alloys at high

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**Table 1.** Chemical composition of the AA2024 alloy.

Element	Cu	Mg	Mn	Fe	Si	Ti	Zn	Al
Wt%	3.9	1.5	0.2	0.5	0.6	0.1	0.9	Base

**Figure 1.** True stress-true strain curves for super saturated specimens deformed at, (a) 200°C and (b) 300°C to a strain of 1, at strain rate of 0.1 s<sup>-1</sup>.

deformation temperatures (Nes et al., 2001).

During thermo-mechanical processing, the re-crystallization behaviour of a material is influenced by the chemical composition, strain rate and temperature of deformation. The latter parameters can be controlled during processing but rarely, if ever, are constant deformation conditions produced. Current models rely on data which have been obtained from laboratory experiments carried out under nominally constant deformation conditions. The tests involves simple deformation paths that reproduce the main characteristics of hot rolling and can be performed at both constant and varying strain rates.

The alloy that is chosen for these investigations is a AA2024 aluminum alloy. The present study is aimed to examine the grain refinement in an extrude AA2024 aluminum alloy using hot compression testing in the temperature range of 200 - 300°C.

#### MATERIAL AND EXPERIMENTAL PROCEDURE

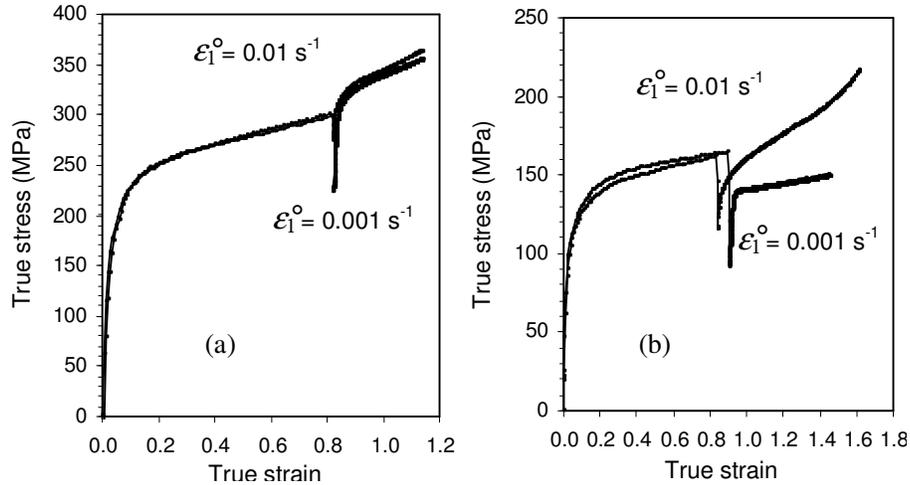
The material used in the present work is a AA2024 aluminum alloy. The composition is given in Table 1. Cylindrical compression specimens which is 8 mm in diameter and 12 mm length were machined parallel to the extrude axis. The samples were homogenized at 300°C for 12 h ( $T_1$ ). The initial microstructure is composed of dendrite lamellas lying parallel to the billet axis. 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  $\epsilon = 0.2$  with the constant strain rate of 0.1 s<sup>-1</sup>, where steady-state flow was achieved and rapidly decreasing strain rate from 0.1 s<sup>-1</sup> to 0.01, 0.001 and 0.0001 s<sup>-1</sup>, respectively. The time between the two tests was less than 1 s. 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.

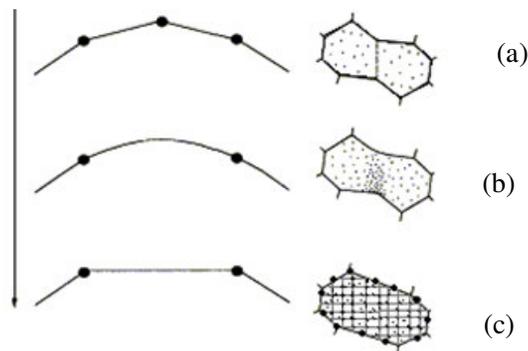
#### EXPERIMENTAL RESULTS AND DISCUSSION

The true stress-true strain curves of specimens subjected to a strain rate drop are shown in Figures 1 and 2 for specimens of super saturated and annealed, respectively. In the second test at 300°C, the flow stress decreases with further straining and, after reaching its maximum value, it is reduced (Figure 1b). 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 stable constant.

At low second strain rate (0.0001 s<sup>-1</sup>), the strain value reaches to a steady-state of  $\sim 0.1$ . In this condition, dynamic softening occurs but at higher second strain rate (0.01 s<sup>-1</sup>) before reaching to a new steady-state work, hardening is produced. It is clearly shown that three typical features exist during multistage hot deformation of aluminum alloys, namely flow stress which increases directly with increasing strain (AA2024 alloy at 300°C), keeps constant with increasing strain and exhibits a peak



**Figure 2.** True stress-true strain curves for annealed specimen deformed at, (a) 200°C and (b) 300°C to a strain of 1, at strain rate of 0.1 s<sup>-1</sup>.



**Figure 3.** Schematic of the dissociation of a subgrain (microband) boundary to give increased subgrain size.

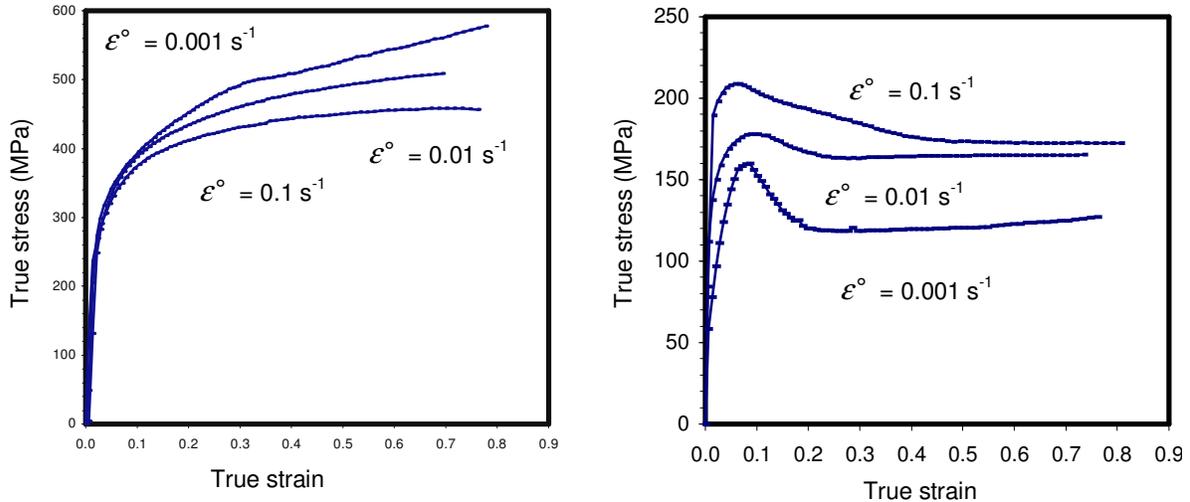
with a gradual decline with increasing. The stress-strain curves show considerable dynamic softening after reaching the peak at each stage.

Part of this softening, especially at higher deformation temperature, could be due to the dynamic recovery and re-crystallization during deformation. In order to quantify this dynamic softening, Sellars et al. (1994) have considered the relative difference between the value of the peak stress and the value of the stress taken at a strain of 0.25 beyond the peak. Dynamic recovery (DRV) and re-crystallization (DRX) are softening mechanisms that have distinctive effects on shaping the flow curve and retarding fissure formation to raise the hot ductility.

It is concluded that the flow softening of Al-5Mg coincides with the transformation of the dislocation wall structure into subgrains and is not related to dynamic recrystallization. It is found that grain boundary sliding takes place frequently during deformation and the flow softening in the regions of localized deformation results

from the apparent grain refinement based on the folding of pancake-shaped grain structures and grain boundary sliding. In addition, the flow stress value at the second deformation seems to be a little smaller than the first deformation value due to the effect of the friction and inhomogeneous deformation at strain > 0.6, and a little dependence on the delay times for the same alloy at the same deformation temperature and strain rate during multistage hot deformation.

The consequences of a subgrain boundary dissociating are illustrated schematically in Figure 3. The initial structure is shown in Figure 3a, with dissociation of the central boundary occurring in Figure 3b and resulting in ejection into the adjacent subgrains of the geometrically necessary dislocations to retain the curvature. This gives an increase in subgrain size and a high internal dislocation density. These dislocations are of the same burgers vector, so they can not annihilate either mutually or to a significant extent with dislocations in the random



**Figure 4.** True stress-true strain curves for super saturated aluminum alloy AA2024 deformed at, (a) 200°C and (b) 300°C with a constant strain rate.

three-dimensional internal network. With increasing strain, these geometrically necessary dislocations can join the adjacent subgrain boundaries to increase their misorientation and so retain the overall local lattice curvature.

This schematic change in internal dislocation density is clearly consistent with the experimental observations after a decrease in strain rate. This important role of microbands is consistent with observations on the effects of reversing the direction of straining.

Figure 4 shows the behavior of hot deformation samples in 200 and 300°C at strain rate of  $0.5 \text{ s}^{-1}$ . It is clearly shown that in strain less than 0.8, the behavior of hot deformed samples are different. As it can be seen with decreasing strain rate, there is some factors in the structure which cause dynamical behavior changes. The flow stress is increased with further straining at 300°C and after reaching the maximum value, it is reduced. The work softening is due to solute depletion, particle coalescence and enhancement of dynamic recovery. At low second strain rate dynamic softening occurs.

## Conclusion

The interaction between the microstructural variables subgrain size, subgrain misorientation and dislocation density within the subgrains have been examined. For deformation at constant strain rate, the subgrain size decrease with strain until a steady-state size is reached. It is also shown that the misorientation between microbands and subgrains increases with strain to a

steady state value. The dislocation density within the grains also increases with strain until a steady state value is reached. Under transient conditions of reducing strain rate to 1, the subgrain size and misorientation are smaller than in steady-state. During deformation at constant strain rate after the transient, the subgrains grow by a process of dissociation of subgrain boundaries which produces a larger number of dislocations in the subgrains until the values characteristic of steady-state are eventually achieved.

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