

INHOMOGENEITY IN CONTINUOUSLY CAST EN AW-1050 ALUMINUM ALLOY WITH A SMALL Zr ADDITION

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Abstract

High purity 1xxx series aluminum alloys are widely valued for their excellent physical properties; however, they exhibit limited thermal stability. In this study, an experimental EN AW 1050 alloy microalloyed with Zr was produced by continuous casting and subsequently subjected to hot rolling, cold rolling, and annealing. The evolution of microstructure, precipitation behavior, and the homogeneity of mechanical properties were systematically evaluated. Microstructural characterization was carried out using light optical microscopy, scanning and (scanning) transmission electron microscopy, electron backscatter diffraction, microhardness mapping, in situ annealing inside an electron microscope and during electrical resistivity measurements. The results reveal pronounced through thickness microstructural heterogeneity originating from the continuous casting process, manifested by grain size variations and central segregation of primary intermetallic phases. Although thermomechanical processing and annealing promote recovery, partial recrystallization, and the formation of thermally stable Al_3Zr precipitates, these treatments do not ensure a fully homogenized microstructure or uniform mechanical properties. The persistent microstructural differences are reflected in microhardness variations of approximately 10–20% across the strip thickness.

Keywords: Aluminum alloys, continuous casting, Al_3Zr dispersoids, thermomechanical processing, microstructural inhomogeneity

1. INTRODUCTION

Low alloyed aluminum alloys of the 1xxx series, defined by an aluminum content exceeding 99 wt%, are widely used in industrial applications due to their excellent electrical and thermal conductivity, high corrosion resistance, and superior formability [1,2]. These attributes make them particularly suitable for electrical conductors, heat exchangers, and service in chemically aggressive environments. Despite these advantages, their relatively low mechanical strength limits their applicability at elevated temperatures. Because strengthening is primarily achieved through strain hardening introduced by cold working, exposure to temperatures approaching ~250 °C can lead to significant softening, even in previously work hardened material [3,4]. This pronounced thermal instability represents a major limitation for applications involving prolonged thermal exposure.

To mitigate this issue, minor additions of alloying elements such as Zr are commonly employed to enhance the thermal stability of 1xxx series alloys. Zirconium contributes to solid solution strengthening and, more importantly, promotes the formation of finely dispersed, thermally stable Al_3Zr precipitates. These dispersoids

effectively impede dislocation motion and act as pinning sites for grain boundaries, thereby suppressing recovery and recrystallization and improving resistance to softening at elevated temperatures [4–6].

While these alloys are traditionally produced by direct chill (DC) casting, alternative processing routes such as continuous casting (CC) have attracted increasing attention due to their higher productivity and improved energy efficiency [7,8]. A known drawback of continuous casting, however, is the tendency to develop through thickness microstructural and mechanical inhomogeneities. Such variations can lead to non uniform mechanical properties across the material thickness, potentially impairing subsequent forming operations, particularly in the production of thin sheets or thin walled components.

In the present study, an experimental EN AW 1050 alloy with a minor Zr addition was produced by continuous casting and subsequently subjected to hot rolling and cold rolling to achieve a total thickness reduction of ~74%, followed by annealing at 530 °C. Despite this extensive thermomechanical processing, the material exhibits microhardness variations of approximately 10–20% across the strip thickness. These findings indicate that neither severe plastic deformation nor subsequent high temperature exposure is sufficient to fully eliminate the microstructural heterogeneities between the surface and central regions introduced during the continuous casting process.

2. METHODS

The investigated material was an experimental EN AW 1050 aluminum alloy containing approximately 0.1 wt% Zr. The alloy exhibits low impurity levels, primarily silicon and iron, with concentrations of approximately 0.1 wt% Si and 0.3 wt% Fe.

The alloy was produced by continuous casting. During casting, the temperature of the molten metal was maintained between 705 and 710 °C. The casting speed during the continuous casting process was maintained at 12 m·min⁻¹. After solidification, the cast strip exited the casting unit at a temperature of 465–475 °C, which was also used as the processing temperature for the subsequent hot rolling operation. Hot rolling was performed immediately after casting, resulting in a total thickness reduction of ~ 62%. The hot rolled material was then subjected to cold rolling, achieving an additional thickness reduction of ~ 32%. Following cold deformation, the strips were annealed at 530 °C for homogenization.

Microstructural characterization was conducted on metallographically prepared specimens using a light optical microscope (Zeiss Axio Observer 7). Scanning transmission electron microscopy (STEM) observations were performed using a JEOL 2200FS microscope operated at 200 kV, with thin foils prepared by mechanical thinning followed by electrochemical polishing. Scanning electron microscopy (SEM) and electron backscatter diffraction analysis (EBSD) were performed on Zeiss Auriga Compact. Microhardness measurements were carried out using a QATM Qness Q10+ Vickers hardness tester with a load of 100 g and a dwell time of 10 s. Electrical resistivity measurements were performed using a four probe DC method on a system equipped with Keithley measuring instruments.

3. RESULTS AND DISCUSSION

3.1 Initial microstructure

The microstructure of the as cast strip was characterized by pronounced heterogeneity in grain size through the thickness. Representative polarized light micrographs observed in the transverse direction (TD) are shown in **Figure 1a**. A clear variation in grain size is evident between the central region of the strip and locations closer to the surface. The grains are predominantly coarse, with sizes reaching the millimetre scale. This microstructural distribution is reflected in the microhardness map, which reveals a softer region at the centre of the strip (**Figure 1c**).

Phase contrast images (**Figures 1d–f**) further reveal a pronounced central segregation zone located at the strip mid thickness (**Figure 1d**), characterized by an increased density of primary intermetallic particles. The particle density gradually decreases with increasing distance from the central plane of the strip (**Figures 1e,f**). In the remaining volume, primary particles are predominantly located along the boundaries of eutectic cells, whose characteristic dimensions are on the order of several tens of micrometers (**Figure 1d**).

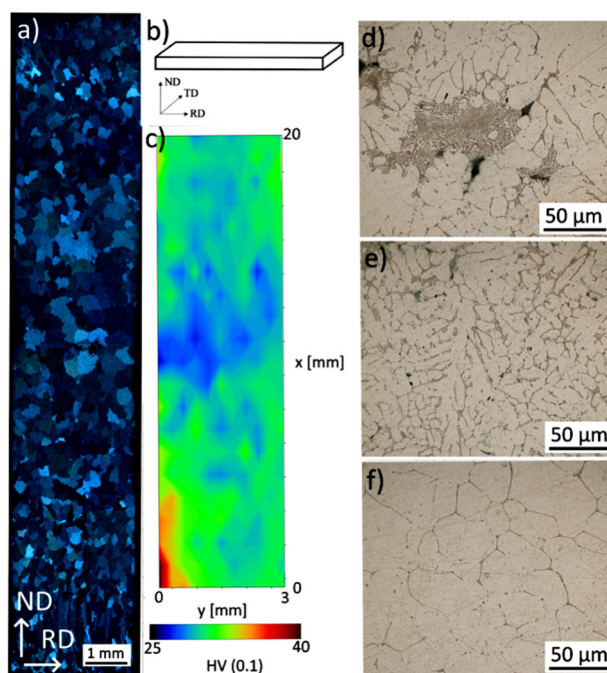


Figure 1 Initial microstructure of the as cast material a) grain structure in TD, b) principal directions of the CC strip: rolling direction (RD), transverse direction (TD), and normal direction (ND), c) microhardness map, d-f) phase contrast d) segregation zone, e) intermediate zone between central segregation zone and the surface of the strip, f) area close to the strip surface

3.2 Microstructure evolution

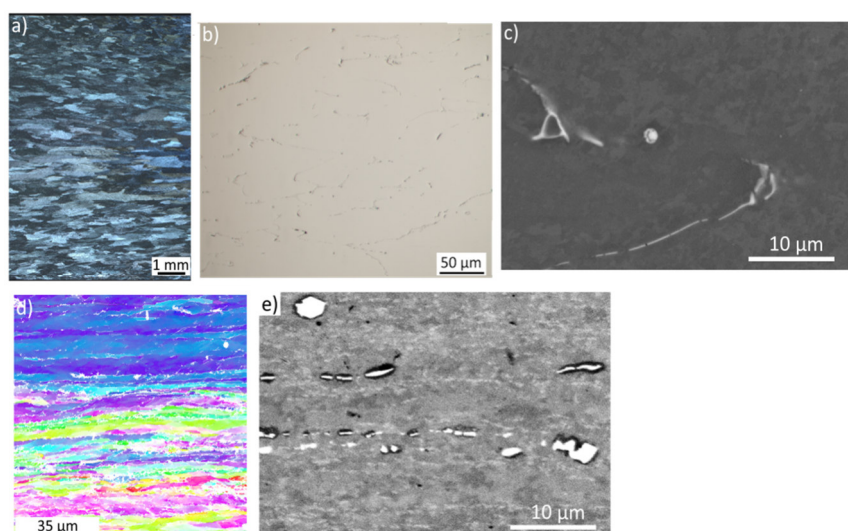


Figure 2 Microstructure of hot rolled (a-c), and cold rolled (d,e) material, a) LOM grain contrast, b) LOM phase contrast c,e) SEM BSE, d) EBSD map

The hot rolled and cold rolled states exhibit distinctly different microstructural characteristics, as shown in **Figure 2**. In the hot rolled condition, the microstructure is highly heterogeneous across the strip thickness and consists of very large grains locally reaching several millimeters in size. These grains are strongly fragmented into well developed subgrains, indicating intensive dynamic recovery with only limited indications of recrystallization (**Figure 2a**). After cold rolling, the microstructure is dominated by strongly flattened and elongated grains with a high density of low

angle grain boundaries and pronounced subgrain structures, which is characteristic of a heavily deformation induced state (**Figure 2d**). In both the hot rolled and cold rolled conditions, coarse primary intermetallic phases remain predominantly confined to the boundaries of eutectic cells (**Figure 2b,c,e**).

3.3 Al_3Zr particles

The initial as cast condition contains only a sparse population of Al_3Zr particles (**Figure 3a**). After hot rolling, fine Al_3Zr precipitates are present within the aluminum matrix, exhibiting a spatially non uniform distribution (**Figure 3b**). Subsequent annealing results in only marginal changes in the size, morphology, or spatial distribution of the Al_3Zr precipitates, indicating the high thermal stability of this phase under the applied annealing conditions (**Figure 3c**).

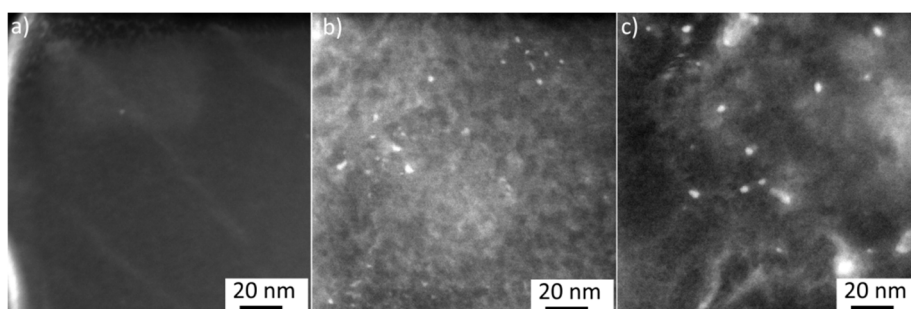


Figure 3 STEM HAADF images a) as-cast, b) hot rolled, c) cold rolled and annealed structure

3.4 Annealing of the cold-rolled structure

During annealing of the cold rolled material, the electrical resistivity exhibits an almost linear dependence on temperature, with a nearly constant derivative up to approximately 400 °C (**Figure 4a**). This behavior indicates the absence of discrete phase transformations in this temperature range. The observed evolution of resistivity is therefore attributed primarily to recovery processes, during which the deformation induced substructure is progressively eliminated. This interpretation is supported by in situ TEM annealing (**Figure 4b**), which reveals a gradual loss of subgrain contrast and a decrease in the density of low angle grain boundaries.

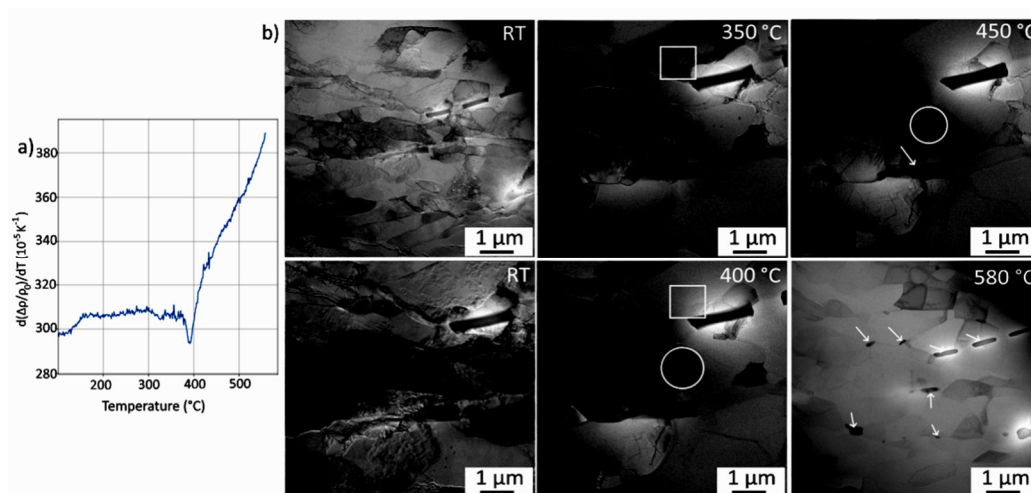


Figure 4 a) Derivative of the relative changes of electrical resistivity with respect to temperature b) STEM images of in-situ annealing of a cold rolled structure. Recovery processes, manifested by the progressive disappearance of deformation induced dislocations, are indicated by white circles and squares, while the phase transformations and the formation of new particles are indicated by white arrow

Above approximately 400 °C, a change in the resistivity trend is observed, reflecting the onset of thermally activated phase transformations and precipitation reactions that modify the solute content of the aluminum matrix. The coarse primary intermetallic phases do not fully dissolve during heat treatment and undergo only partial transformation. As a result, they continue to contribute to microstructural and property inhomogeneity even after high temperature exposure. In addition, the formation of new Fe and Si rich particles along (sub)grain boundaries further promotes depletion of the solid solution.

3.5 Final structure

Optical grain contrast microscopy and EBSD analysis of the annealed cold rolled condition (**Figures 5a,e**) consistently show that most of the material undergoes partial recrystallization, resulting in flattened and elongated grains with sizes ranging from several hundred micrometers to several millimeters. Grain boundaries are strongly pinned by primary intermetallic particles (**Figures 5b,c**). SEM observations (**Figure 5d**) indicate that transformation of the original primary intermetallic phases is limited; however, fine Fe and locally Si rich particles with sizes of approximately 300–500 nm - first observed during in situ TEM experiments - precipitate during annealing. The average microhardness (**Figure 5f**) is (27 ± 1) HV0.1, while microhardness mapping reveals a persistent inhomogeneity of approximately 10–20%, with reduced hardness in the central region. This indicates that casting induced heterogeneities are not fully eliminated by thermomechanical processing and subsequent annealing.

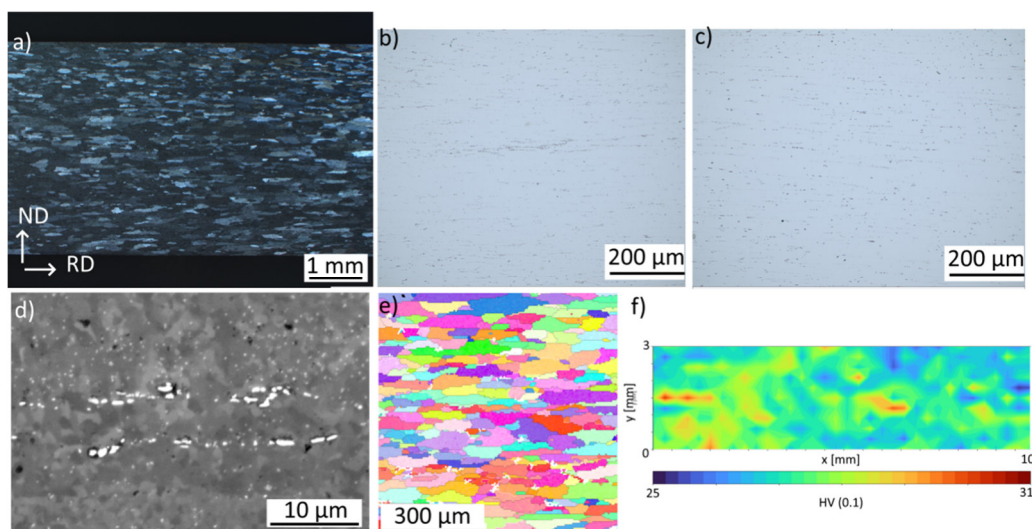


Figure 5 Final microstructure of the cold rolled and annealed strip: (a) LOM grain contrast image, (b, c) LOM phase contrast images of the central region (b) and edge region (c), (d) SEM backscattered electron image of primary intermetallic phases, (e) EBSD orientation map, and (f) microhardness map across the strip thickness

4. CONCLUSION

An EN AW 1050 aluminum alloy microalloyed with Zr was produced by continuous casting and subsequently subjected to hot rolling, cold rolling, and annealing to investigate the evolution of the microstructure and the homogeneity of mechanical properties. The results demonstrate that, although the applied thermomechanical processing substantially modifies the microstructure, it does not lead to complete homogenization of the material. Persistent through thickness microstructural features, accompanied by corresponding variations in microhardness, indicate that heterogeneities introduced during the continuous casting process remain influential even after extensive deformation and thermal treatment.

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