# Roping in 6111 aluminum alloys with various iron contents

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## Abstract

The development of surface roughness and roping after straining and its correlation with grain size and texture were investigated in AA6111 aluminum alloys with various Fe contents, using optical microscopy, scanning electron microscopy (SEM), electron back scatter diffraction (EBSD) in SEM, X-ray diffraction, and 3D non-contact profilometry. It has been demonstrated that the spatial distribution of texture components is a critical factor for roping. When the $\{0\,0\,1\}\langle1\,0\,0\rangle$ (cube) and $\{0\,1\,1\}\langle1\,0\,0\rangle$ (Goss) texture components are banded along the rolling direction (RD) and alternately distributed in the transverse direction (TD), intensive roping develops when the sheet is stretched in the TD regardless of grain size. During rolling the cube and Goss are metastable orientations in AA6111 and form cube and Goss bands along the RD. These bands are the preferred nucleation sites for recrystallization, resulting in the banded structure being retained in the final solutionised sheet. Increasing the Fe content leads to a finer grain size and lower strain induced surface roughness, but roping is insensitive to the Fe content and simply dependent on the degree of cold rolling prior to solutionising.
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## 1. Introduction

In aluminum alloy sheet, a rope-like profile parallel to the rolling direction (RD) may develop when the sheet is stretched in the transverse direction (TD). This is termed roping, or ridging, and consists of ridges and valleys of different depths (10–30 μm) and lengths (several centimeters), as shown in Fig. 1. Roping in aluminum alloys has been studied for many years, and it is generally accepted that the alignment of crystallographic texture components along the RD is the major cause for roping [1–9]. It is often observed that for a certain aluminum alloy, several specific texture components are especially important for roping behavior. For example, it has been found that the $\{0\,0\,1\}\langle1\,0\,0\rangle$ (cube) and $\{0\,1\,1\}\langle1\,0\,0\rangle$ (Goss) texture components are critical for roping in AA6111 [6,7]. When grains with cube or Goss orientations are segregated and aligned along the RD and alternately distributed in the TD, roping occurs when the sheet is stretched in the TD. Similarly, Wittridge and Knutsen [5] suggested that the cube

and $\{1\,2\,4\}\langle2\,1\,1\rangle$ (R) texture components play the same role for roping in AA3002.

Due to increasing environmental and energy saving concerns, the automobile industry tends to use lighter materials, e.g., aluminum, magnesium and composite materials, to replace heavy steels, for example, see [10]. AA6111 is an Al–Si–Mg alloy being extensively used in automotive body applications, but roping has been observed in solutionised AA6111 sheets after forming. Since roping is unacceptable for outer panel applications for cosmetic reason, it is of great interest to investigate the relationship between roping and the sheet microstructure, e.g., grain size and texture, and the possibility of preventing roping by modifying microstructure and texture. The texture in solutionised AA6111 sheet consists particularly of the cube, Goss and $\{0\,1\,1\}\langle4\,5\,5\rangle$ (P*) components [7], and the spatial distribution of the cube and Goss is critical for roping [6–9]. For a non-roping or slightly roping sheet the texture alignment is relatively short, whereas longer aggregation leads to more intensive roping. Accordingly, a processing route that reduces texture alignment or shortens its length, such as particle stimulated nucleation (PSN) [11], may reduce the tendency for roping.

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Fig. 1. Development of roping in an AA6111 sheet after a stretch of 15% elongation in the TD. The sample has been given "stoning treatment", a light sanding of the surface by a piece of carborundum with silicone dry film lubricant, to enhance the visibility of the roped surface. The RD is vertical and TD is horizontal.

In the present work, the grain structure, texture and strain induced surface roughness development, including roping, were investigated in five AA6111 alloys with different Fe contents in the range 0.06–0.75 wt.%. The relationship amongst the grain size, texture and surface roughness development as functions of the Fe content and cold rolling reduction was studied. The evolution of the spatial distribution of the cube, Goss and P*, which are the major components in the recrystallized texture in AA6111, during thermo-mechanical processing was investigated, and the grain growth kinetics of these components at 350–390 °C in a low-Fe alloy was determined. Based on the experimental results the origin of roping is considered.

## 2. Experiments

Five AA6111 alloys with different Fe contents, labeled 1–5 with chemical compositions listed in Table 1, were DC cast and hot rolled down to 6 mm thickness. They were cold rolled to different final gauges, corresponding to 63, 77, 85 and 90% thickness reductions, then solutionised at a temperature above 500 °C for a few minutes followed by a forced air quench. The grain structures and textures in different stages of the processing route, i.e., hot rolled, cold rolled and solutionised, were determined by an optical microscope and X-ray diffraction, respectively.

The spatial distribution of the cube, Goss and P* texture components in the hot rolled starting materials was determined by electron back scatter diffraction (EBSD) in a scanning electron microscope (SEM) with a field emission gun (FEG). The evolution of the spatial distribution of these texture components was investigated by EBSD in the 77% cold rolled sheets through the processing route, including

the cold rolled, partially recrystallized and solutionised conditions. The EBSD acquisition was very difficult in the 77% cold rolled sheets due to the low quality of Kikuchi patterns in the deformed structure. Hence, the as-rolled specimens were annealed at 370 °C for 10 s in a salt bath followed by water quench, resulting in a recovered structure without inception of recrystallization. At this stage, the recovered texture roughly represents the as-rolled texture, while the acquisition of EBSD patterns is much easier. Partial recrystallization was achieved by annealing the as-rolled sheets at 370 °C for 1 min in a salt bath followed by water quench.

A dedicated study of the nucleation and grain growth during recrystallization was performed in the 77% cold rolled Alloy-2. Small plates cut from the as-rolled sheets were isothermally annealed at 350, 370 and 390 °C for various times in a salt bath and water quenched. The increase of cube, Goss and P* components during recrystallization in the sheet centre were measured by EBSD, and the kinetics of grain growth of these components was calculated according to the Burke–Turnbull theory [12]. Alloy-2 was chosen because the Fe content in this alloy is relatively low such that the Kikuchi pattern is sharp and EBSD acquisition is easy. Moreover, the grain size in this alloy is not too large so that in a small EBSD–SEM scan many grains could be counted to yield statistically reliable results. The temperature was set below 400 °C because at higher temperature recrystallization is completed within a few seconds.

The global texture was measured in the sheet centre plane using a Rigaku X-ray machine with a radiation source of RU-200B rotating anode and Cr target. The orientation distribution functions (ODFs) were calculated using Van Houtte's MTM–FHM software [13]. The grain size was measured in the sheet longitudinal sections by the line intercept method in an optical microscope. The EBSD investigation was done in a Philips XL30S FEG SEM equipped with a Nordlys II detector, operated at 20 kV with 5–10 μm step sizes. The samples for EBSD were mechanically ground to the sheet centre plane, then electro-polished in a solution comprising 2% butylcellosolve, 8% $HClO_4$, 30% alcohol and 60% water with current density of 1.5 A/cm$^2$ for 30 s at −10 °C. The grain structure reconstruction and texture analysis were performed using HKL Channel 5 software. A Gaussian spread of 11° was used in the calculation of the volume fractions

Table 1
The chemical compositions (wt.%) of the five AA6111 alloys

|  | Cu | Fe | Mg | Si | Al |
|---|---|---|---|---|---|
| Alloy-1 | 0.7 | 0.06 | 0.7 | 0.7 | Balance |
| Alloy-2 | 0.8 | 0.12 | 0.8 | 0.7 | Balance |
| Alloy-3 | 0.8 | 0.29 | 0.7 | 0.7 | Balance |
| Alloy-4 | 0.8 | 0.35 | 0.7 | 0.7 | Balance |
| Alloy-5 | 0.8 | 0.75 | 0.8 | 0.7 | Balance |