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Temper rolling to control texture and earing in aluminium alloy AA 5050A

Olaf Engler[1,*], and *Kristian* Knarbakk [2]

[1] Hydro Aluminium Rolled Products GmbH, Research and Development Bonn, P.O. Box 2468, D – 53014 Bonn, Germany
[2] Hydro Aluminium Rolled Products AS, Technical Customer Service Rolled Products Holmestrand, N – 3081 Holmestrand, Norway

Abstract. The development of crystallographic texture during the thermo-mechanical processing of aluminium sheet is known to result in the formation of pronounced plastic anisotropy, including the well-known earing phenomenon. In the present study we track the evolution of texture, microstructure and earing profiles in sheets of Al alloy AA 5050A during down-stream processing according to a process route resulting in temper H16 after cold rolling and temper H44 after lacquering. This process, which includes interannealing followed by a mild final pass of temper rolling, was designed for producing medium-strength sheet with low earing properties. Besides the experimental characterization of the evolution of microstructure, texture and resulting earing profiles along the process chain, means to optimize the processing by adapting the intermediate thickness are addressed.

1 Introduction

Aluminium alloy AA 5050A (ISO AlMg1.5(D)) is a medium strength Al alloy with about 1.5% Mg which is used in household applications, as tubes for automotive gas and oil lines, welded irrigation pipes and in several packaging applications [1]. Like all the AA 5xxx-series Al-Mg alloys, the strength of AA 5050A can be increased by cold working, typically by cold rolling, to the strain-hardened tempers H1x. However, work hardening of Al alloy sheet is commonly accompanied by the formation of significant plastic anisotropy. It is well documented that plastic anisotropy, including the well-known earing phenomenon, is attributed to the formation of preferred crystallographic orientation, or texture, during the thermo-mechanical production of the sheet [2–5]. The characteristic earing profiles of deep drawn cups form because the sheet texture gives rise to different radial elongations in different directions of the blank. In a rolled Al sheet with a pronounced deformation texture the ears are usually observed at the four positions ±45° to the rolling direction around the drawn cup. The height of the ears, and hence the percentage of earing, generally increase with the amount of cold rolling applied. In the soft annealed, recrystallized state ears are often found at angles of 0° and 90° to the former rolling direction.

The occurrence of earing during deep drawing of a textured sheet can cause major problems in the production of Al containers, closures or beverage cans. Hence, for such applications often low anisotropy is required, with the percentage of earing being controlled to be below 5%, and for certain critical applications even below 3%, in order to minimize material loss during trimming and prevent failure of heavily textured blanks.

In industrial practice, earing is reduced by producing mixed textures comprising both rolling and recrystallization texture components. That is to say, the respective 0°/90° and ±45° earing behaviour is superimposed, which results in low anisotropy with balanced earing profiles. This may be achieved by producing sheet in temper H14 or H16 with medium strength and very low earing properties through an intermediate annealing before a light final rolling pass, commonly referred to as temper rolling [6–9].

In the present paper it is demonstrated how texture control can be applied during industrial processing of Al alloy AA 5050A to provide low-earing grade sheet for a technical packaging application. Furthermore, means to improve earing properties through an adjustment of the processing parameters are discussed together with the resulting textural effects.

2 Experimental

The material investigated in this study was Al alloy AA 5050A, containing about 1.2% Mg and 0.1% Mn. Hot strip (or re-roll) of this alloy was produced by standard industrial routes in Hydro's rolling mill in Holmestrand, Norway, consisting of direct-chill (DC) casting of large ingots, pre-heating to 575 °C, followed by break-down and tandem hot rolling (Fig. 1). The hot strip with a thickness of 5 mm was coiled and cooled down to room temperature. Optionally, the coiled hot strip was subjected to a batch annealing treatment for 2 h at 350 °C in order to enforce recrystallization of the – non-recrystallized – hot strip (see below). Subsequently the

* Corresponding author: olaf.engler@hydro.com

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material was cold rolled in several passes to a final gauge of 0.4 mm. The medium strength H16 temper with low earing at final gauge was achieved by subjecting the material to an intermediate annealing treatment at a thickness between 0.5 and 0.6 mm. Thus, the temper rolling pass ranged from 30 to 35% thickness reduction. Finally, the final gauge sheet was coated with a thin epoxy lacquer; curing of this lacquer for about 20 s at 285 °C led to a softening to temper condition H44.

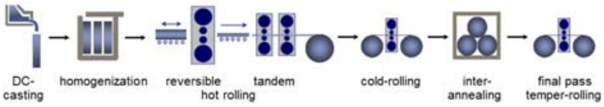

Fig. 1. Scheme of the processing of Al alloy AA 5050A sheet with low earing.

Samples for microstructural analysis and mechanical tests were taken from the hot strip, before and after intermediate annealing, and at final gauge before (H16) and after lacquering (H44). Mechanical properties of the sheets were determined by conventional tensile tests according to EN 10002-1. Cup drawing tests were performed on a hydraulic press following the guidelines of norm EN 1669. For the sheets with thicknesses in the range from 0.4 to 0.6 mm blanks with a diameter of 60 mm were deformed with a punch of 33 mm, resulting in a drawing ratio of ~1.8. From the 5 mm hot strip larger cups were produced, with a punch and blank diameter of 50 mm and 100 mm, respectively. For a quantitative assessment of the earing behaviour, the earing profiles $h(\alpha)$ were probed in steps of 1° with a mechanical set-up developed by Huxley Bertram Engineering Ltd., Cottenham, UK. Here, α indicates the angle with respect to the former sheet rolling direction. The results of two to three cups were averaged to minimize experimental scatter.

Because of the orthotropic sample symmetry of rolled strip, the earing profiles are principally symmetric with respect to the rolling direction (RD) and transverse direction (TD). Hence, the earing profile may be symmetrized (“mirrored”) with respect to the RD and TD. For better comparability of different cups (e.g. with different sheet thicknesses or different drawing ratios), the earing profiles $h(\alpha)$ were normalized by the average cup height according to:

$$h^*(\alpha) = h(\alpha) \cdot \frac{\alpha_{max}}{\sum_{\alpha} h(\alpha)\,\Delta\alpha} \tag{1}$$

For a quantitative assessment of earing often the mean earing value, Z, is determined, which is defined as:

$$Z = \frac{\bar{h}_{ears} - \bar{h}_{troughs}}{\bar{h}_{troughs}} \tag{2}$$

where the values $\bar{h}_{ears}$ and $\bar{h}_{troughs}$ correspond respectively to the average values of all ears and all troughs of a given cup profile. For mixed textures with six or eight ears the delta earing value, ΔZ, may also be useful, which is defined as:

$$\Delta Z = \frac{2\bar{h}_{45°} - (\bar{h}_{0°} + \bar{h}_{90°})}{\bar{h}_{0°} + \bar{h}_{90°}} \tag{3}$$

The microstructure of the different samples was studied by optical metallography. Longitudinal sections of the sheets were prepared and polished according to standard metallographical techniques. The grain structure was revealed by anodical oxidation and subsequent investigation under polarized light.

The crystallographic texture of the samples was analysed by means of electron back-scattered diffraction (EBSD) in a LEO 1530 field emission scanning electron microscope (SEM), equipped with a HKL NORDLYS II EBSD detector from Oxford Instruments plc. For this purpose, longitudinal sections of the sheet samples were prepared by mechanical polishing followed by electro-polishing. Areas of about 800 × 450 µm² were scanned with a step width of typically 1 µm (hot strip 2 or 3 µm). From the EBSD data of the various samples orientation distribution functions (ODF) $f(g)$ were computed by associating each orientation $g = \{\varphi_1, \Phi, \varphi_2\}$ of the orientation map with a Gauss-shaped peak with a (half) scatter width $\psi_0 = 5°$ in Euler angle space. ODFs are presented in form of iso-intensity lines in three characteristic sections through the Euler space, viz. $\varphi_2 = 45°$, 65° and 90°. With this representation we implicitly assume orthotropic sample symmetry, as given by the three orthogonal sample axes rolling direction, transverse direction and sheet normal direction. Further details of EBSD measurements, analysis and interpretation can be found in Ref. [10].

3. Experimental results

3.1 Standard processing route

The evolution of microstructure and texture during the various steps of the standard processing of low-earing grade AA 5050A sheet from hot strip to final gauge in tempers H16 before and H44 after lacquering is presented in Figs. 2 and 3. In parallel with the development of crystallographic texture during the various steps of materials processing the plastic anisotropy of the material changed as well, and Fig. 4 shows the (symmetrized and normalized) earing profiles during the various down-stream processing steps.

Fig. 2(a) shows the microstructure of the as-received AA 5050A hot strip. The material displayed a coarse, heavily layered microstructure where the grains were strongly elongated along the hot rolling direction. Evidently, the microstructure did not recrystallize during the final hot rolling passes. The texture of the hot strip is presented in Fig. 3(a), showing a pronounced texture fibre running from the Cu-orientation {112}<111> at (φ_1,Φ,φ_2) = (90°,30°,45°) through the S-orientation {123}<634> at about (57°,33°,65°) to the Bs-orientation {011}<211> at (35°,45°,90°) through orientation space. This is the typical rolling texture of Al sheet, see e.g. [3,8,9]. Furthermore, the ODF comprised weak intensities of the cube-orientation {001}<100> at (0°,0°,90°), pointing at beginning recrystallization during hot rolling or, more likely, during the subsequent cooling of the coiled hot strip to ambient temperature.

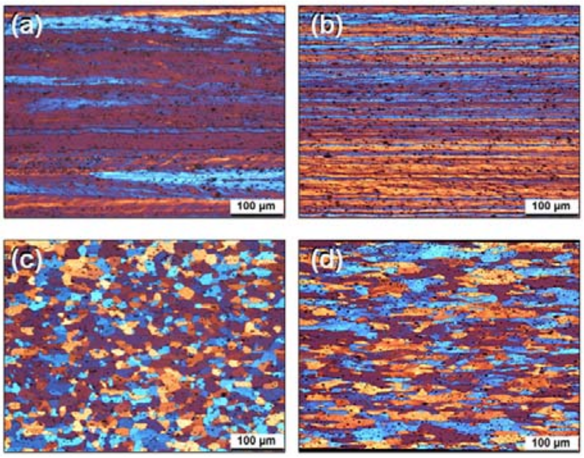

Fig. 2. Evolution of the microstructure during processing of the AA 5050A sheet; (a) hot strip, (b) cold rolled to intermediate gauge, (c) interannealed at intermediate gauge, (d) cold rolled to final gauge, i.e. temper H16 (optical metallography, longitudinal sections, magn. 200×).

From Fig. 4 it appears that the non-recrystallized hot strip had a weak eight-ear profile with ears under 0°, 45°, 90°, etc. (black curve). This earing behaviour is in accord with the observation of a mixed cube and rolling texture shown in Fig. 3(a).

Cold rolling to an intermediate gauge of 0.61 mm led to a further refinement of the elongated band structure (Fig. 2(b)), in that the thickness of the deformed bands in the through-thickness direction was significantly reduced. Simultaneously, the characteristic rolling texture orientations along the β-fibre sharpened, while the remaining orientations diminished (Fig. 3(b)). These texture changes are accompanied by an appreciable increase of the 45° ears at the expense of the original 0°/90° ears (Fig. 4, red curve), resulting in a *Z* value of as much as 8.5%.

Soft annealing at intermediate gauge gave rise to a recrystallization of the material. Fig. 2(c) shows a fully recrystallized microstructure consisting of grains with an average size of approximately 15 µm, which were slightly elongated along the former rolling direction. The resultant recrystallization texture was rather weak, consisting of the cube-orientation {001}<100> at (0°,0°,90°) and some intensities along the former S-orientation (Fig. 3(c)), which are commonly referred to as R-orientation. Such mixed cube + R textures are the typical recrystallization textures of many cold rolled, soft annealed Al alloys (e.g. [11–14]). Accordingly, the inter-annealed material showed a very smooth eight-ear profile (Fig. 4, green curve); the characteristic earing values were $Z = 1.6\%$ (see Eq. 2) and $\Delta Z = 0.6\%$ (Eq. 3).

The final temper rolling pass to final thickness led to a significant rise of the yield strength to temper H16. This temper rolling pass was again characterized by an elongation of the microstructure (Fig. 2(d)). Note that the aspect ratio of the individual grains was fairly small, about 5:1, which agrees well with the level of rolling reduction of about 35% during the temper rolling pass. Accordingly, the texture showed only minor changes, in

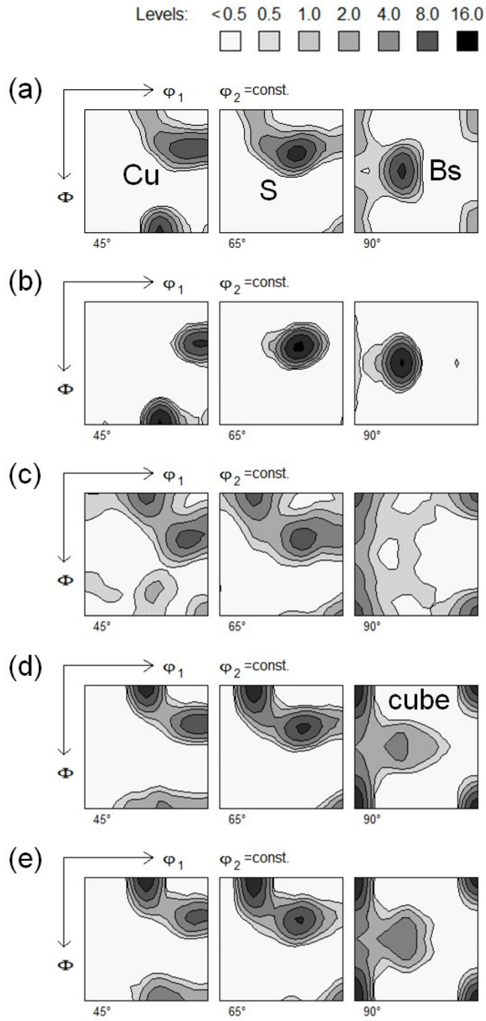

Fig. 3. Evolution of the texture during processing of the AA 5050A sheet; (a) hot strip, (b) cold rolled to intermediate gauge, (c) interannealed, (d) cold rolled to final gauge, i.e. temper H16, (e) lacquered, i.e. temper H44 (EBSD, ODF sections φ_2 = 45°, 65° and 90°).

that the former rolling texture orientation Cu, S and Bs slightly re-increased while the cube-orientation of the recrystallization texture remained largely unchanged (Fig. 3(d)). This minor sharpening of the rolling texture orientations gave rise to a slight re-increase of the 45° ears (Fig. 4, blue curve), but the overall earing remained low with the characteristic earing values *Z* and Δ*Z* of 2.7% and 2.2%, respectively.

The final lacquering operation, more specifically, the curing of the lacquer at elevated temperature, gave rise to a softening of the material to temper H44. Since recovery at these moderately elevated temperatures did not involve any grain boundary reactions, no changes in the grain structure were detected, although detailed analysis at higher magnification in the SEM or TEM will undoubtedly reveal microstructural reactions, most notably reorganization of dislocation structures into cell or subgrain structures (e.g. [15]). The texture showed a minor sharpening of the cube texture (Fig. 3(e)) with

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respect to the H16 state (Fig. 3(d)). This minor texture sharpening gave rise to a slight re-increase of the 0° and 90° ears, while the 45° ears remained roughly constant (Fig. 4, cyan curve) which, in turn, led to a decline of the value ΔZ to 0.6%, while the earing value Z remained constant at 2.7%.

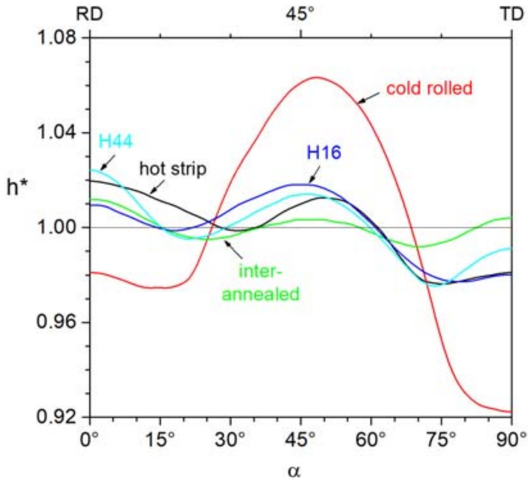

Fig. 4. Evolution of the earing profiles during processing of the AA 5050A sheet (symmetrized and normalized).

3.2 Modified processing to lower earing

The discussion of the results in the previous section has shown that the earing behaviour at final gauge – albeit being rather low – was dominated by ±45° ears. This may be seen from the positive value of ΔZ which, according to Eq. 3, implies that the height of the 45° ears exceeded that of the 0°/90° ears. Apparently, the evolution of the rolling texture orientations during the temper rolling pass could only partially be offset by the intensities of the cube+R recrystallization texture after interannealing. Hence, in order to further improve the final gauge earing behaviour two process modifications were probed, (i) lowered intermediate gauge and (ii) hot strip annealing.

In the *first trial* the intermediate thickness was lowered from 0.61 mm to 0.57 mm, i.e. the rolling reduction during the final temper rolling pass was lowered from 35% to 31%. Under the simplifying assumption that the minor increase in rolling reduction *prior to* interannealing will not affect the recrystallization texture upon interannealing, the slight reduction in temper rolling *after* interannealing should lead to lower ±45° ears and, hence, to a further improvement of the overall earing behaviour.

Fig. 5(a) shows the microstructure of the final gauge material after lacquering (i.e. temper H44), produced with the refined processing route. Obviously, in comparison to the original processing route (Fig. 2), the microstructure looks very similar, since the minor reduction in temper rolling from 35% to 31% is not discernible in the optical micrographs.

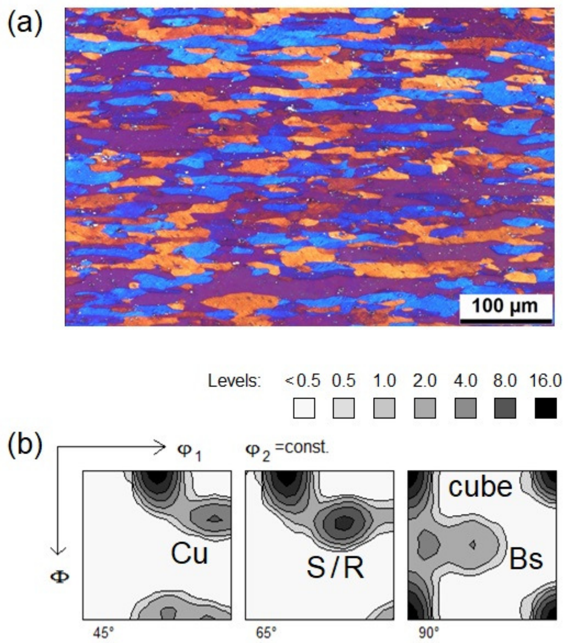

Fig. 5. (a) Microstructure and (b) texture of AA 5050A sheet at final gauge (temper H44) produced with reduced interannealing thickness.

On first sight, the final gauge texture (Fig. 5(b)) resembles the texture of the material with standard processing (Fig. 3(e)), in that both ODFs comprise mixed rolling and recrystallization texture orientations. A detailed comparison by analysing the so-called difference ODF disclosed some significant differences, however (see [16]). More specifically, the standard material revealed slightly stronger orientations of the rolling texture, i.e. Cu, Bs and, to some extent, also the S-orientation. Vice versa, the modified material had higher intensities of the cube orientation and maybe the R-orientation.

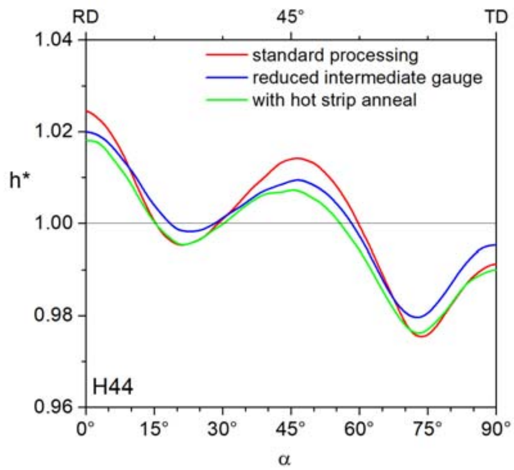

Fig. 6. Comparison of the earing profiles of AA 5050A sheet at final gauge (temper H44) produced with standard and amended processing (symmetrized and normalized).

Thus, analysis of the difference ODF revealed that the material with the modified processing comprised stronger recrystallization texture orientations but weaker rolling texture orientations. Accordingly, the earing behaviour was improved by lowering the earing profile, as apparent from Fig. 6. This diagram shows that the earing profile of the material with the modified processing (blue curve) is in all peaks and valleys closer to unity than the earing profile of the standard material (red curve). This improvement is also reflected in the characteristic earing values Z and ΔZ of 2.3% (rather than 2.7%) and 0.1% (rather than 0.6%), respectively.

In the *second trial* the non-recrystallized hot strip was subjected to an additional batch annealing treatment to enforce recrystallization, which resulted in a coarse-grained recrystallized microstructure (Fig. 7, cf. Fig. 2(a)). The hot strip texture changed from the pronounced β-fibre rolling texture of the non-recrystallized hot strip (Fig. 3(a)) to a typical cube recrystallization texture after hot strip annealing (Fig. 8(a)). Simultaneously, the 0° and 90° earing increased at the expenses of the 45° ears.

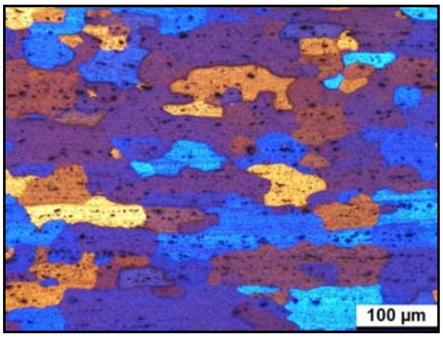

Fig. 7. Microstructure of AA 5050A hot strip after additional recrystallization anneal (optical metallography, longitudinal sections, magn. 200×).

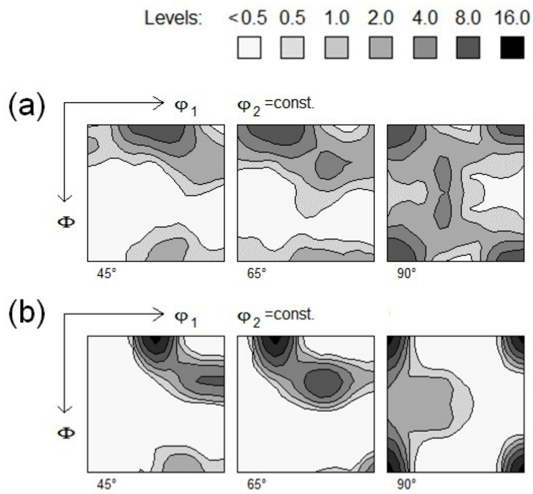

Fig. 8. Evolution of the texture during processing of the AA 5050A sheet; (a) annealed hot strip, (b) lacquered at final gauge, i.e. temper H44 (EBSD, ODF sections φ_2 = 45°, 65° and 90°).

Apparently, the higher level of recrystallization in the annealed hot strip led to larger intensities of the cube orientation throughout the entire downstream processing, although these differences diminished towards the final gauge material (Fig. 8(b)). In turn, the stronger cube texture orientations resulted in a shift of the earing profiles from 45° earing towards 0°/90° earing. Accordingly, the earing behaviour improved with respect to the original processing (Sec. 3.1), as evident from the lowered characteristic earing values of Z = 2.2% and ΔZ = 0.3% (Fig. 6, green curve).

4. Discussion

In the field of aluminium alloys, texture investigations are of great importance since texture affects a number of anisotropic materials properties, which are important for practical applications of Al sheet products. The evolution of texture and texture-related properties is strongly influenced by the various steps of thermo-mechanical processing of Al sheets – homogenization, hot and cold rolling and possible intermediate and/or final annealing (Fig. 1). In the present study it is demonstrated how texture control can be applied during industrial processing of Al alloy AA 5050A sheet in order to minimize earing through the interplay of rolling and recrystallization with the resulting textural effects.

As already mentioned in the introduction, earing in Al alloys is commonly controlled by means of producing mixed textures comprising both rolling and recrystallization texture components. That is to say, the respective 0°/90° and ±45° earing behaviour is superimposed, which results in reduced anisotropy with balanced earing profiles. In the so-called H16 route to produce sheet with minimum earing and medium strength, texture and earing are controlled through an intermediate annealing before a light final temper rolling pass (Fig. 1) [6–9].

It was shown in Sec. 3.1 that cold rolling to intermediate gauge led to the formation of a β-fibre rolling texture together with an appreciable increase of 45° earing (Figs. 2–4). During interannealing the material recrystallized, developing a fine-grained recrystallized grain structure (Fig. 2(c)) and mixed texture comprised of a cube recrystallization texture with medium intensities of a retained rolling, or R, texture (Fig. 3(c)) [11–14]. Accordingly, the interannealed sheet revealed a rather smooth eight-ear profile (Fig. 4).

Final gauge properties were achieved through a final rolling pass to medium strength (H16). This light temper rolling pass of the order of 35% thickness reduction sharpened the rolling texture orientations at the expenses of the recrystallization texture orientations (Fig. 3(d)), yet the rolling reduction was evidently not large enough to significantly degrade the latter. Lacquering of the sheet involving curing of the paint at elevated temperature led to recovery of the materials properties to temper H44, but microstructure and texture remained largely unchanged (Fig. 3(e)). Accordingly, the final gauge H44 material comprised balanced cube and rolling texture orientations and, in consequence, the desired light earing profile suitable for products requiring minimum earing (Figs. 4, 6).

In order to optimize the final gauge earing behaviour two process modifications were probed, (i) lowered intermediate gauge and (ii) hot strip annealing (Sec. 3.2). The above example has demonstrated that texture and earing properties at final gauge depend on the interplay of recrystallization during interannealing plus the deformation applied during final cold rolling. That is to say, the final gauge properties are controlled by the intermediate thickness and the resultant strain imposed upon the final temper rolling pass. In the present case the original processing route led to a weak, balanced earing profile with $Z = 2.7\%$ and $\Delta Z = 0.6\%$. According to Eq. 3 a positive value of ΔZ implies that the 45° earing exceeds the height of the 0°/90° ears, which means that the ratio between rolling and recrystallization texture orientations is shifted towards the former. Accordingly, a reduced interannealing thickness, resulting in a lowered final rolling pass, led to a slight increase in recrystallization texture orientations at the expenses of the rolling texture (Fig. 5(b)) and, in turn, an improved earing profile with $Z = 2.3\%$ and $\Delta Z = 0.1\%$ (Fig. 6, blue curve).

As an alternative, the non-recrystallized hot strip was subjected to a batch annealing treatment to enforce recrystallization. This resulted in a recrystallized microstructure (Fig. 7) with a typical cube recrystallization texture (Fig. 8(a)). Evidently, the cube texture of the annealed hot strip led to larger intensities of the cube orientation and, in consequence, to higher levels of 0°/90° earing throughout the entire process chain, although these differences diminished somewhat towards the final gauge material (Fig. 8(b)). Therefore, at final gauge, i.e. in tempers H16 and, most notably, H44, the earing behaviour was improved with respect to the original processing (see Fig. 6, green curve). With characteristic earing values of $Z = 2.2\%$ and $\Delta Z = 0.3\%$ the material was at a level approximately equal to that of the lowered intermediate thickness (see above). Thus, hot strip annealing offers an alternate processing route to improve earing properties of AA 5050A sheet, albeit at the expenses of higher processing costs.

Summary and conclusions

It is demonstrated how texture and earing can be controlled during industrial processing of sheet of the Al alloy AA 5050A (ISO AlMg1.5(D)). Furthermore, two means to improve earing properties by changing the processing parameters are addressed.

Upon industrial production of low-earing grade Al alloys the 0°/90° earing caused by the recrystallization texture and the ±45° earing due to the rolling texture orientations is superimposed in order to obtain mixed textures with a well-balanced earing profile. In the standard H16 route this is achieved by an intermediate annealing before a light final temper rolling pass.

In the present application the original processing route resulted in sheet with low earing and a positive value of ΔZ, implying that the 45° ears are slightly more pronounced than the 0°/90° ears. Thus, it appeared meaningful to further optimize earing by a strengthening of the recrystallization texture orientations at the expenses of the rolling texture orientations. This was accomplished by two different means, viz. (i) lowering the thickness of the intermediate annealing to weaken the rolling texture at final gauge or (ii) by application of an additional hot strip annealing to strengthen the cube recrystallization texture in the hot strip.

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