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Earing Behavior and Crystallographic Texture of Aluminum Alloys during Cold Rolling

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Earing behavior and crystallographic texture during cold rolling have been investigated for two commercial can body aluminum alloys. It is found that earing behavior can be inferred from texture information. The recrystallization texture causes 90° earing, while the deformation texture results in 45° earing. A strong recrystallization texture (or a high 90° earing) of a hot band causes a later appearance of lower 45° earing in the final gauge sheet and thus is desirable for industry. The earing behavior is better indicated by the delta function, which is characterized as the intensity difference between the deformation texture and the softening texture. The results indicate that the earing behavior during cold rolling can be quantitatively monitored by the crystallographic texture. In addition, effects of the texture inhomogeneity through-thickness have also been investigated and discussed.

Keywords aluminum alloys, cold rolling, crystallographic texture, earing behavior

1. Introduction

Earing behavior of aluminum alloys has been extensively investigated either experimentally or theoretically.[1–8] It was found that earing is strongly determined by crystallographic textures. The relation between earing and texture is thus of great interest both to academia and industry. Minimizing the earing of products has always been the object of the can industry. The industry also demands the prediction of product earing based on the original hot band earing. Thus, a total understanding of earing behavior during cold rolling is a prerequisite for a satisfied prediction. A large amount of research work has been dedicated to this purpose.[9,10] It is well known that the recrystallization texture causes 90° earing and that the deformation texture results in 45° earing. With increasing cold reduction, the intensity of the recrystallization texture of the hot band decreases while that of the deformation texture increases. Correspondingly, the 90° earing of the hot band decreases with cold rolling and eventually changes to 45° earing in the final product. It is also found that a strong recrystallization texture of the hot band is good for a stable earing behavior during cold rolling.[9]

These qualitative results have been a great help in the control of the thermomechanical process and of product quality. However, a more quantitative relation is highly desired and required for automatic process control and on-line monitoring of the formability of aluminum alloys. This is usually characterized as a relation between formability parameters (*r*-value, percent earing) and orientation intensity/volume fraction[7–9] or the orientation distribution functions (ODF) coefficients W_{lmn}.[11–14] In this paper, this relation is expressed as the percent earing and the orientation intensity of the texture components. In addition, influence of the rolling process has also been investigated and discussed.

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2. Experiment Method

Two kinds of commercial can body aluminum alloys, AA3004 and AA3104, have been used for this investigation. Their chemical compositions are given in Table 1. Before cold rolling, the microstructures were obtained using optical metallography to make sure the hot bands were fully recrystallized. If not, an annealing treatment was performed. The hot bands were then cold rolled to different reductions. The rolling process was designed so that more data were obtained around the reduction at which the earing changes from 90° to 45°. Two samples were prepared for cup testing at each degree of reduction and the average of these two earing results was used. Samples were also prepared for crystallographic texture analyses with x-ray pole figures determined and ODF analyses performed.

Earing data were obtained using a Tinius-Olsen Ductometer and a Tinus-Olsen Acromat Measuring Device. Percent earing was then calculated by the equation:

$$\text{Earing} = \frac{h_{max} - h_{min}}{h_{min}}$$

Here, h_{min} is the height at the valley and h_{max} is the average height of the earing peaks.

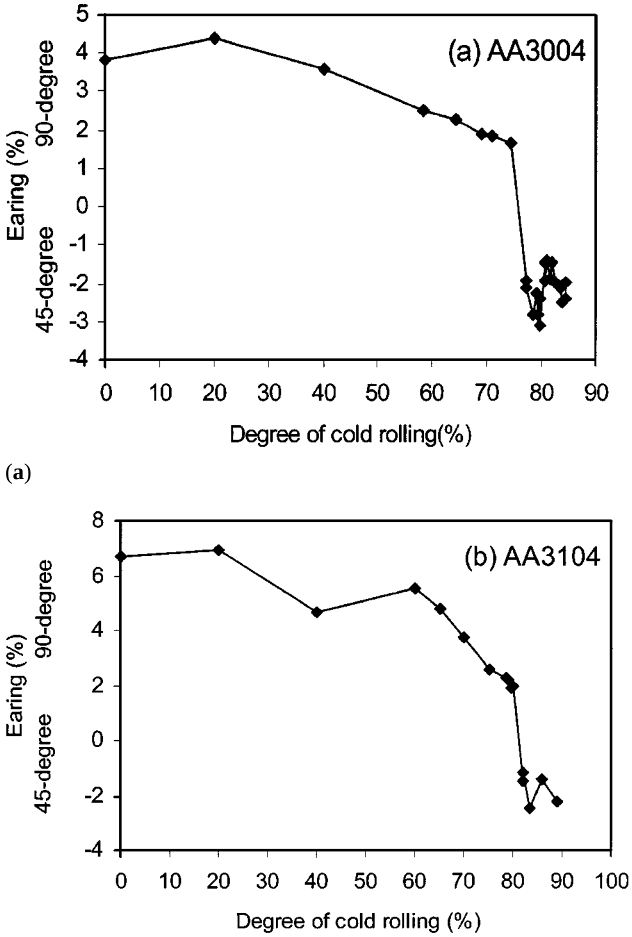
3. Results and Discussions

3.1 Earing Behavior

Figure 1(a) and (b) are the earing results of these two hot bands at different cold reductions. It is seen that the two alloys

Table 1 Chemical compositions of experimental materials

Alloys	Si	Fe	Cu	Mn	Mg
AA3004	0.174	0.375	0.135	1.094	1.043
AA3104	0.202	0.449	0.155	1.085	1.090



(**a**)

(**b**)

Fig. 1 (**a**) and (**b**) Earing behaviors during cold rolling

have similar earing behaviors during the cold rolling process. The original hot band has 90° earing, which decreases with increasing reduction and eventually changes to 45° earing after a certain degree of cold reduction (critical point). The earing decreases gradually before the critical point. However, it changes abruptly to 45° earing within a small reduction range around this critical point.

Since 90° earing is more harmful and more easily causes defects during deep drawing, the thermomechanical process is designed so that the hot band undergoes a reduction large enough to obtain a small degree of 45° earing in the final gauge sheet. Although 45° earing is better than 90° earing for deep drawing, minimizing the earing is always the object. It is generally considered that 45° earing increases with further cold deformation after the critical point. In this regard, the larger the plastic strain (%CR) at which the critical point occurs, the smaller the final earing. Theoretically, we can design thermomechanical processes so that the hot band has a suitable thickness, which only needs to undergo a slightly larger cold reduction than the critical strain point before deep drawing. However, it is difficult for industry to operate in this manner. In practice, the hot band always undergoes a reduction that is larger than the critical point before deep drawing.

Notwithstanding the general similarity of the earing behavior of the two 3xxx series alloys, there are also differences that are worth consideration. According to Fig. 1, the AA3104 hot band has a larger 90° earing (more than 6.5%) than does the AA3004 hot band (less than 4.0%). The earing of the AA3104 material changes to a 45° type at 80% cold reduction, which is also larger than that of the AA3004 (75%). It is clear that a high 90° earing of the hot band will delay the appearance of 45° earing. It is for this reason that a high 90° earing of hot bands is generally desirable for the can stock industry.

Figure 2 shows the microstructures of these two hot bands. Each of them has a fully recrystallized structure and almost the same grain size. This indicates a high degree of 90° earing of the hot bands. However, the particle size of the AA 3104 material is a little larger than that of the AA3004 material. The particle densities are almost the same. Since large particles favor the development of the cube texture, it can be inferred that the AA3104 material should have a stronger cube texture and a higher 90° earing than that of the AA3004 material. The aforementioned earing results and the texture data also confirm this conclusion.

Figure 1 also shows that the earing does not increase with further deformation after the critical point. Both of the earing behaviors present a “tilt up” phenomenon by which the earing is reduced after further cold reduction. This allows the earing to reach an acceptable level (2.0%), as prescribed by industry.

3.2 Texture Evolution

The orientation intensity of the texture components for these two alloys during cold rolling was obtained and shown in Fig. 3(a) and (b). Among the softening textures (cube, *R*-cube, and Goss), the cube component is much stronger and decreases in intensity with cold rolling. The Goss component is somewhat weak and only has a small decrease during the rolling process. The *R*-cube component is very weak and is negligible. However, all three deformation components (copper, S, and brass) have similar intensities and increase with increasing deformation.

Since the effect of textures on earing behavior is related to their type (recrystallization or deformation), it is considered desirable to use the sum of the softening components and the sum of the deformation components to further analyze the results. Figure 3 is then replotted as Fig. 4 in which the sum of the intensities of the recrystallization components and the sum of the deformation texture components were used instead of each single component. It is clear that the intensity of the sum of the softening components decreases, while that of the deformation components increases with an increase in cold rolling. It is also shown that the intensity of the cube component changes similarly with that of the sum of the softening components. It appears that the intensity of the cube component can represent the total softening component effect, at least qualitatively.

By comparison of Fig. 1 and 3, it is clear that a fully recrystallized hot band usually has a strong softening texture (especially the cube component) and yields a high 90° earing after deep drawing. The higher 90° earing of the AA3104 hot band is primarily due to its stronger softening textures. During cold rolling, the softening components decrease and the deformation components increase. These two types of textures

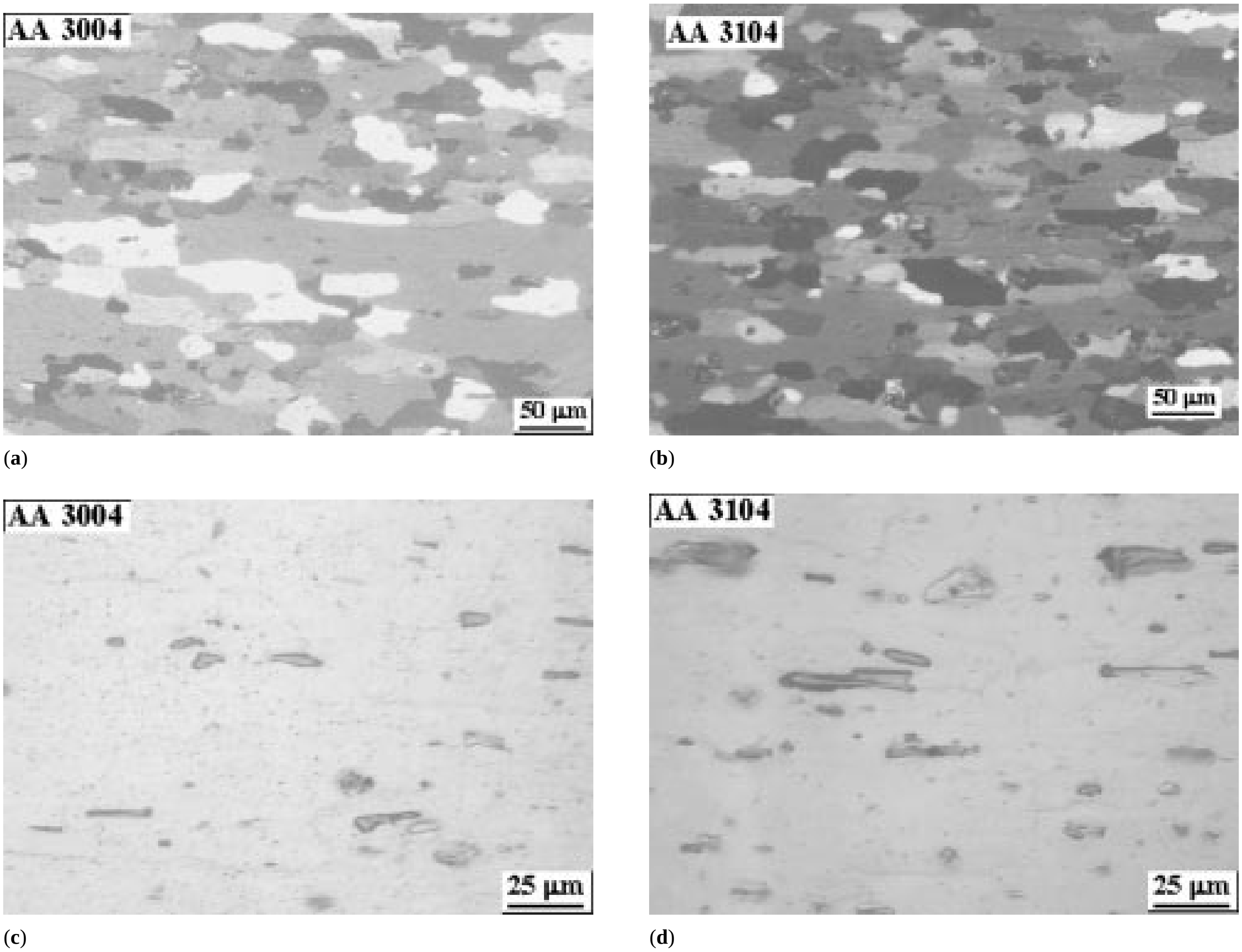


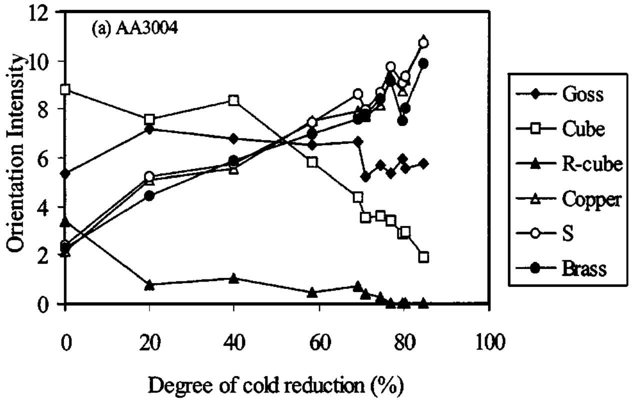
Fig. 2 (**a**) to (**d**) Microstructure of hot bands AA3004 and AA3104 aluminum alloys

interact and balance each other during cold rolling, and a corresponding earing behavior results. The interaction between these two types of textures is reflected clearly in the earing behavior. The original hot band has a strong softening texture and yields a high 90° earing. With increasing deformation, the softening textures decrease in intensity and the deformation textures increase and eventually become the dominating type at which point 45° earing appears. A higher intensity of the original softening textures will maintain a dominating role to a higher plastic strain (reduction) or to a larger critical strain point. In the measurements of 90° earing, we also found that the two peaks along the rolling direction are smaller to those in the perpendicular (transverse) direction. The Goss component contributes significantly to 0/180° (rolling direction) earing.[15] Figure 3 indicates that the Goss component is weak compared to the cube component and is almost constant during the rolling process.

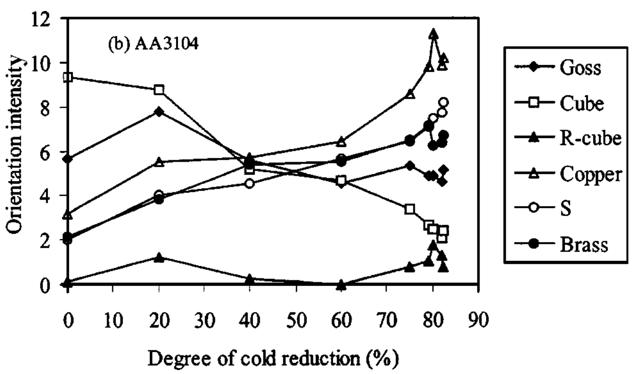
3.3 Delta Function

Recent work[9] has shown that the delta function gives a very good quantitative description of the relation between earing and texture. Here, the delta function is used as the intensity difference of the deformation components and the softening components.

Figure 5 shows the earing behavior as a function of the delta function. The striking point is that the earing behavior is very similar either drawn as a function of the delta function or as a function of the degree of cold reduction (Fig. 1). A linear relationship between the delta function and cold reduction is also observed up to the critical strain and is shown in Fig. 6. In fact, there are two linear relations with different slopes that change exactly at the critical points. That is, the linear relation between the delta function and cold reduction depends on the type of earing (90 or 45°). We can see that the slope of this plot for the AA3104 material (1/4) is smaller than that for the AA3004 material (1/3). This indicates the dominating role of the softening texture components for both AA3104 and AA3004. The degree of this dominance, however, is different for the two alloys. The aforementioned behavior suggests that there is a certain quantitative relation between the percent earing and the resultant texture intensity. This means that it is possible to predict the earing behavior from texture information alone.

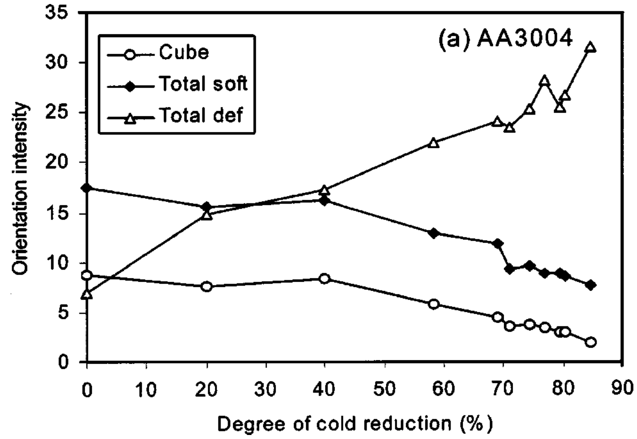


(a)

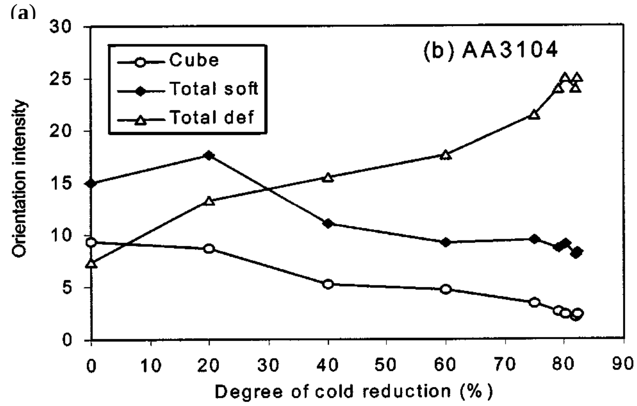


(b)

Fig. 3 (**a**) and (**b**) Texture evolution during cold rolling



(a)



(b)

Fig. 4 (**a**) and (**b**) Orientation intensity of total softening and total deformation components as well as the cube component

This is very encouraging for the can industry and for the concept of online texture monitoring of can stock material.

3.4 Texture Inhomogeneity between Surface and Midplane

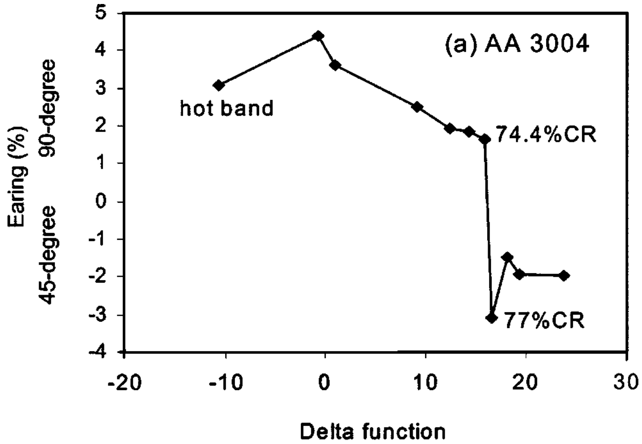
The texture inhomogeneity between surface and midplane has been widely observed in aluminum sheet and plate material.[16–19] Since x-ray diffraction only provides information from material near the surface, it is usually hard to decide which information (surface, midplane, or their average texture results) best reflects the real texture of the hot band. All three kinds of texture results are found in the literature. Table 2 shows the orientation intensity of different texture components at the surface and the midplane during cold rolling. The texture difference between the surface and midplane is obvious. Figure 7(a) replots these results as the sum of the intensity of the softening texture components and the sum of the intensity of the deformation texture components. The texture inhomogeniety through the thickness is small for the deformation components, but it is greater for the softening components.

Because of the difficulty in determining the texture at the midplane when the thickness of the sample becomes small, we were unable to evaluate whether the texture results from the surface and midplane eventually converge at some critical thickness.

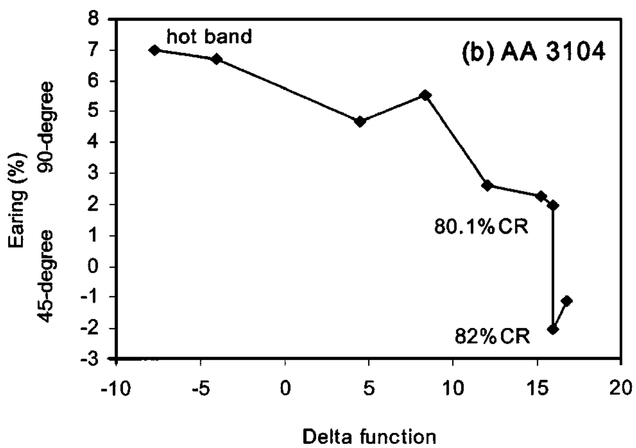
Figure 7(b) is a plot of delta function for the surface and midplane positions as a function of cold reduction. All the data are found to fall on two straight lines that are almost parallel to each other. It is obvious that their averages would also fall on a straight line that exists between these two lines. These results suggest that either the data from the surface or from the midplane, or their average, could be used as a good indication for the earing behavior during cold rolling. However, mixing of these data could cause some erroneous conclusions.

3.5 Effect of Rolling Direction

Figure 8 shows the effect of rolling direction on the earing behavior during cold rolling. One set of the samples is cold rolled without changing the sample forwarding direction, and the other set of samples is cold rolled by reversing the sample forwarding direction for each step. We can see that the earing behavior before the critical point is a little bit different. The earing of the samples after reverse rolling is a little larger than that without changing the direction. This is because reverse rolling will cause recovery or decrease the intensity of the deformation structure due to the prior rolling step. Thus, each reverse rolling will decrease to some degree the former deformation structure and delay the deformation texture evolution compared to straight rolling. The effective strain of reverse rolling is smaller than that of straight rolling at the same degree of cold

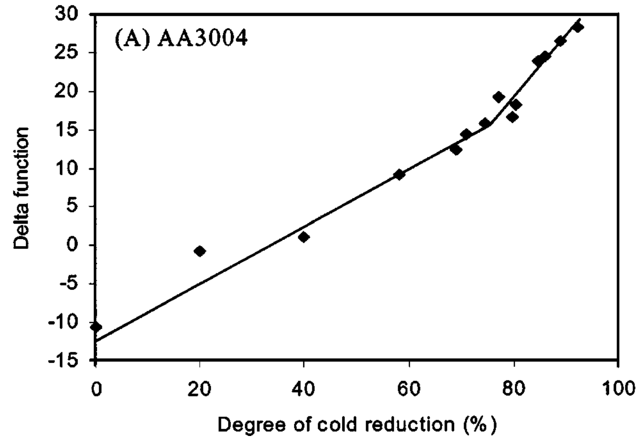


(**a**)

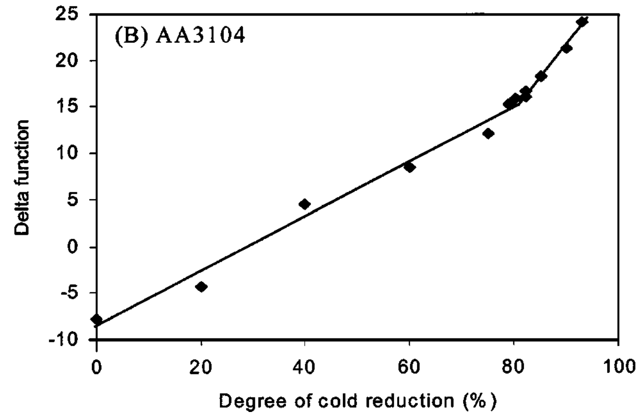


(**b**)

Fig. 5 (**a**) and (**b**) Earing behaviors with delta function during cold rolling



(**a**)



(**b**)

Fig. 6 (**a**) and (**b**) The relation between delta function and degree of cold reduction

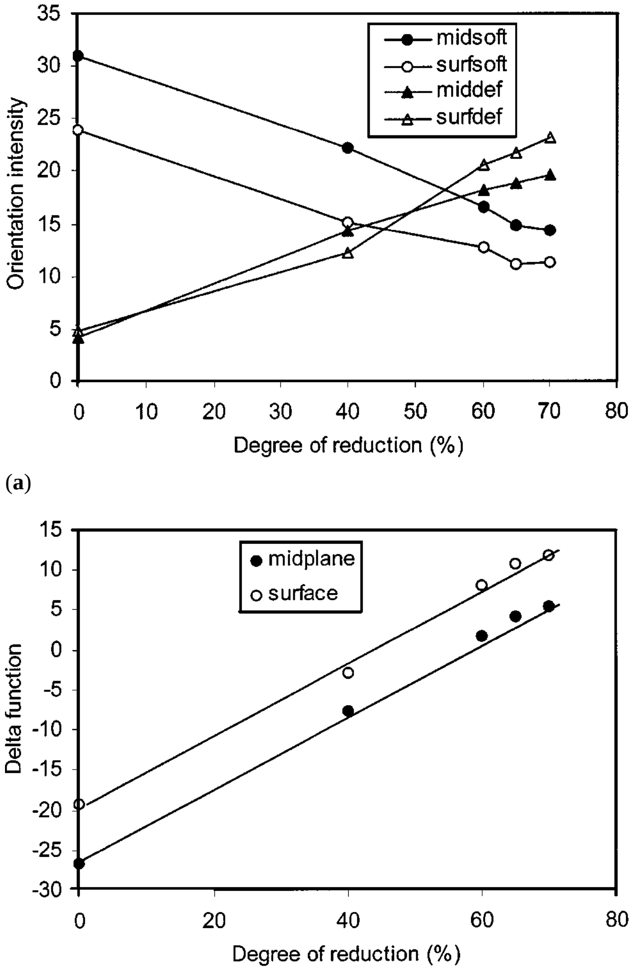
Table 2 Comparison of texture intensity between surface and midplane during cold rolling

Cold Reduction	Position	Goss	Cube	R-cube	Copper	S	Brass
HB	Surface	4.2930	16.3738	3.3176	1.6386	2.4477	0.7330
0%	Midplane	9.5923	19.4306	1.9668	1.6298	2.0754	0.5464
40%	Surface	3.7312	9.8964	1.5339	3.4615	4.3490	4.3421
	Midplane	9.4696	10.0498	2.6559	3.2537	4.5919	6.5230
60%	Surface	3.7846	7.8268	1.0149	5.3782	7.9743	7.1918
	Midplane	8.7300	6.5429	1.3429	4.7513	5.7823	7.6739
65%	Surface	3.9915	6.3290	0.7257	5.4474	8.5474	7.6693
	Midplane	9.2567	4.4359	1.0524	4.9553	5.5317	8.2396
70%	Surface	4.1577	6.7509	0.3933	6.4554	8.5839	8.0434
	Midplane	8.4093	4.8747	1.0711	5.0913	6.5130	7.9654

reduction. As a result, more of a softened or recrystallization structure remains and thus a higher intensity of 90° earing.

4. Conclusions

- The earing behavior of aluminum alloys during cold rolling is determined both by the texture of the original hot band and by the details of the rolling process and can be explained by its crystallographic texture. It is found that the high 90° earing (or strong cube component) of the hot band causes the later appearance of 45° earing after a critical amount of cold work and the resulting low 45° earing desirable for subsequent formability.
- The delta function yields a similar behavior as earing during cold rolling and could be used as a good indication of the



(**a**)

(**b**)

Fig. 7 (**a**) and (**b**) Comparison of texture between surface and midplane of aluminum alloy during cold rolling

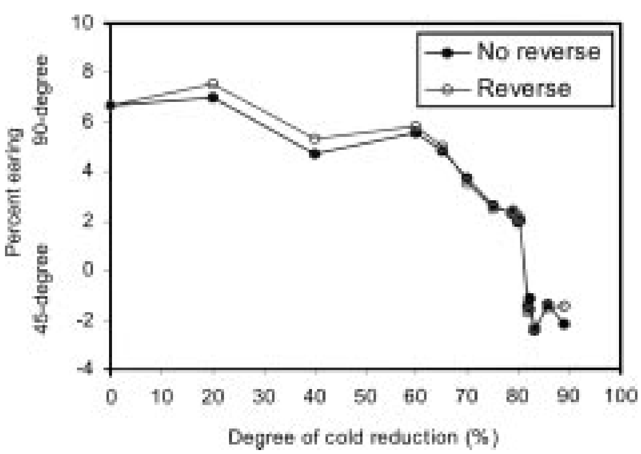


Fig. 8 Comparison of delta functions between surface and midplane

earing behavior in this process. Despite certain differences that exist concerning the earing behaviors of these two alloys, their critical earing points correspond to a very close value of the delta function, which is 15.7536 for the AA3004 aluminum alloy and 15.9344 for the AA3104 alloy.

- The linear relation between the delta function and cold reduction depends on the earing types. The slopes of these lines are different for 90° earing and for 45° earing. The slopes change exactly at the critical point, which indicates the possibility of the description of the earing behavior from textures.
- Texture inhomogeneity through the thickness exists even up to 70% cold reduction. No information on the effect of further reduction has been obtained due to the difficulty of evaluating texture at the midplane. However, as long as the earing behavior is the prime consideration, it appears that texture data from the surface, the midplane, or their average present a good correlation with earing.

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