Formability of Sn-containing ferrite stainless steel sheet

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Abstract

The effect of annealing treatment on the deep drawability and ridging resistance in a Sn-containing ferritic stainless steel was studied by average plasticity strain ratio r-value measuring, X-ray diffraction (XRD) and electron back scatter diffraction (EBSD) analysis after carried out tensile tests. The results indicate that the average plastic strain ratio (r-value) increased as the annealing temperature and keeping time increased, which reached up to 1.82 after annealing treated at 900 °C for 4 min. However, ridges became obvious as the temperature increased. When the annealing temperature increased from 860 to 920°C for 2 min, the fraction of the recrystallization texture component of γ-fiber in the center of the tested sheet increased from 40% to 70%, while the root-mean-square deviation of the profile (Rq value) increased from 1.179 to 1.783 μm. In the tensile tests of the annealed samples with half-thickness of the sheet, the ridging morphology in the center was more obvious than that on the surface. The experiments show that the inhomogeneous distribution of grain clusters of γ-fiber texture formed during recrystallization in the center layer of the sheet is a significant cause of ridging in the sheet, the textures on the surface distributes homogeneously relatively, which is beneficial to reduce the manifestation of ridging.

1. Introduction

Ferritic stainless steel is widely used due to its low cost and excellent performances such as high strength and...
high resistance to chloride stress corrosion. Hiraide et al. (2013) and Abratis et al. (2013) added Sn to ferritic stainless steel to improve the corrosion resistance of ferritic stainless steel. Han et al. (2013) studied the effect of Sn on the ferritic stainless steel. As a new type Cr-saving stainless steel, the Sn-containing ferritic stainless steel is expect to be employed as stampings such as kitchen equipments, home appliances and automotive assembly parts. So the deep drawing performance plays a decisive role on its application prospects. Thus, to get a product with excellent deep drawability and perfect surface is the objective of deep drawing works (Du et al., 2012).

As is well known, plastic strain ratio (r-value) is an important index to reflect the maximum deformation degree during metal sheet forming process. However, even though the annealed sheet has a high r-value and good stamping performance, ridging still appears on the surface after stamping. Since 1960s, researchers have begun to study the mechanism of ridging in ferritic stainless steels during the sheet forming (Takechi et al., 1967). It is now accepted that the ridging phenomenon results from the different plastic flow of different texture components. In this paper we will investigate the influence of annealing process on the formability of the Sn-containing stainless steel and mechanism of the ridging phenomenon.

2. Experimental procedure

The tested material was the cold-rolled ferritic stainless steel sheet with 0.6mm thickness, the chemical composition of which is shown in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>N</th>
<th>Sn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass %</td>
<td>0.01</td>
<td>0.58</td>
<td>0.17</td>
<td>0.001</td>
<td>0.019</td>
<td>16.51</td>
<td>0.008</td>
<td>0.09</td>
<td>Bal</td>
</tr>
</tbody>
</table>

The tested sheet was annealed at 840, 860, 880, 900 and 920 °C for 2 or 4 min. Dog-bone samples were cut from the annealed sheets at 0º, 45º and 90º with respect to the rolling direction. Two samples were taken for each direction and the average value were calculated to be employed. The samples were drawn to 15% on MTS810 material testing machine. The r-value of each direction was determined as the ratio of the width and thickness plastic strain, and the average plastic strain ratio were calculated by $r=(r_{00}+2×r_{45}+r_{90})/4$. The orientation distribution function (ODF) that reflected macro-texture was determined by X-Ray Diffraction, and the Root-mean-square deviation of the profile (Rq value) that reflected the surface roughness of the tensile samples was measured on surface profile Dektak machine.

In order to investigate the difference of ridging morphologies, recrystallizations and textures between the surface and center of the sheets, the sheets were annealed at 860 °C for 2 min, 860 °C for 4 min and 920 °C for 2 min and then were grinded and mechanically polished to the mid-thickness of the sheet. The half-thickness samples were drawn to 20% elongation and the surface roughnesses were detected by Dekktak machine. The micro-orientation distribution function sections on the original surface and the new surface (the original center of the sheet) were investigated by electron back scatter diffraction (EBSD) analysis, respectively. The measurement were carried out in a scanning electron microscopy (SEM) equipped with HKL-channel-5 system.

3. Results and discussion

3.1. r-value and Rq value

Table 2 shows the average plastic strain ratio, r-value and the surface roughness, Rq value of the annealed Sn-containing stainless steel sheets after 15% tensile. It can be seen that for both keeping time of 2 min and 4 min, the r-value exhibits a rising trend basically when the annealing temperature was below 900 °C. When the annealing temperature exceeded 900°C, r-value changed to decrease oppositely. The highest r-value appeared at 900 °C for 4 min, which was 1.82. The variety of Rq value exhibits approximately the same tend as that of r-value. It means that increase of r-value caused the increase of Rq value with the temperature rising and keeping time extension.
Table 2. \( r \) and \( R_q \) values of tested sheet after different annealing treatments.

<table>
<thead>
<tr>
<th>Annealing processes</th>
<th>2 min</th>
<th>4 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>840 °C</td>
<td>860 °C</td>
</tr>
<tr>
<td>( r )</td>
<td>1.4158</td>
<td>1.6632</td>
</tr>
<tr>
<td>( R_q (\mu m) )</td>
<td>1.179</td>
<td>1.182</td>
</tr>
</tbody>
</table>

3.2. Macro-texture

The orientation distribution function sectional views of the tested steel with constant \( \Omega_2=45^\circ \) were plotted, as shown in Fig.1. The cold rolled sheet presents a strong \( \alpha \)-fiber \(<110>/\text{Rolling Direction}\) texture, especially \{112\} <110> texture had the maximum density of 6.5, and the second one was \{001\} <110> texture with a density of 4.0. The \( \gamma \)-fiber \(<111>/\text{Normal Direction}\) texture could be seen however its density was only 3.0 under the cold rolled state. Annealing treatment conducd to the vanishing of the \( \alpha \)-fiber and strengthening of the \( \gamma \)-fiber, which is adequate for deep drawing operations. In the tested temperature range from 840°C to 900°C, as the temperature was promoted, the intensity of the \( \gamma \)-fiber texture increased, i.e. the intensity of \( \gamma \)-fiber reached the highest 8.8 at 900°C, which was \{111\}<112> texture. It can be concluded that there is a close correspondence between the \( r \)-value and the intensity of \( \gamma \)-fiber.

![Fig. 1](image-url)

For metals and alloys with bcc crystal structure, the \( r \)-value that can evaluate deep drawability has a close relation with density of \( \gamma \)-fiber texture. The higher the intensity of \{111\} texture is, the greater the \( r \)-value is. The result indicates that the \( \gamma \)-fiber texture strengthened and \( r \)-value increased as the recrystallization proceeds further.
When the temperature increased to 920°C, the γ-fiber texture strengthened furthermore, however, the r-value, in other words, the deep drawability decreased. It can be attributed to the grain coarsen. When annealed exceeded 920°C, recrystallization had been completed, but grains still grew up. Researches indicated that some grain boundary with special orientation has very large movement speed, so grains relate to this grain boundary priority to grow at high speed. According to the reference (Rajib et al., 2007), there are many special grain boundary between grains with \{111\}<112> orientation and \{111\}<110> orientation.

3.3. Recrystallization and grain size

Fig. 2 shows the degrees of recrystallization on the surface and in the center of the Sn-containing stainless steel sheet after annealed at 860°C for 2min and 4min and 920°C for 2min, which were identified as deformed, substructured or recrystallized according to the misorientation in each grain. The red, yellow or blue represents the grain or the region is deformed, substructured or recrystallized, respectively. It can be seen that the degrees of recrystallization increased with the increase of annealing temperature and extension of keeping time both on the surface and in the center of the tested sheet.

It is notable that the recrystallization proceeded faster in the center than on the surface. It can be attributed to the influence of combination of strain stored energy of differently orientated grains \(E\{110\}<001> <E\{001\}<110> <E\{112\}<uvw> <E\{111\}<112> <E\{111\}<110>\) (Sinclair et al., 2003) and the different texture on the surface and in the center of the tested sheet. The strain stored energy of the texture components in the center was higher than that on the surface so that it provided a higher driving force and results in a deeper and completer degree of recrystallization.

3.4. Micro-texture

The distribution of α-fiber and γ-fiber texture in the Sn-containing stainless steel sheet, which annealed at 860°C for 2min and 4min and 920°C for 2min, are shown in Fig.3, in which the dark red grains and blue grains represent the grains with α-fiber and γ-fiber texture, respectively, and the white ones are the grains with other orientations. The orientation was highlighted with a 15° tolerance. It can be seen that the blue γ-fiber texture components increase with the increase of annealing temperature and extension of keeping time, especially in the center of sheet. In addition, the grains with the orientation of γ-fiber texture gathered together to form clusters.
It also can be seen that the grains with the orientation of γ-fiber texture clustered more severely in the center than on the surface of the tested sheet in Fig.3.

Fig.4 shows the distribution of misorientation along the line of AB, CD, EF in of Fig.3(b), (d) and (f) respectively. The datum point of orientating in each line is A, C, E, respectively. As is shown in Fig.4, it is obvious that the misorientation between the grains in clusters with γ-fiber texture decreased gradually with the increase of annealing temperature and extension of keeping time in the center of the tested sheets. The results indicate that the increase in the number and size of γ-fiber texture clusters as well as the decrease of misorientation in γ-fiber texture clusters should be the reason why the intensity of γ-fiber texture increases as the recrystallization proceeds further.

Similar to the conclusion of Du et al. (2012) and Gao et al. (2012), the result indicates that the proceeding of recrystallization is beneficial to the development of γ-fiber texture, but it will lead to the increase in the number of coarse grains and inhomogeneous distribution of grains with different sizes, which disturbs the random distribution of grain orientations. Harase et al. (1991) and Raabe et al. (1995) have indicated that the strong γ-fiber texture in the steel product can result in high surface quality during the sheet metal forming. Szpunar et al. (1994) also

Fig. 3. Distribution of α-fiber and γ-fiber texture (a), (c) and (e) on surface and (b), (d) and (f) in center of the tested sheet after annealed at (a), (b) 860°C for 2 min, (c), (d) 860°C for 4 min and (e), (f) 920°C for 2 min.

Fig. 4. Misorientation distribution in γ-fiber texture cluster marked in Fig. 3.
reported that strong γ-fiber texture component \{111\}<112> may not reduce the ridging morphology of the steel product. Furthermore, Vlad et al. (1988) found that ridging occurred in the ferritic stainless steel with only \{111\}<112> texture and fine grain structure. Similar to the result of Verbeken et al. (2003) and Chen et al. (2010), the samples annealed at 920°C for 2 minutes showed high r-value resulting from the coarse γ-fiber grain clusters. The result in this study proves that there is a nearly opposite relationship between the deep drawability and the ridging resistance of the tested sheets. In other words, a strong γ-fiber texture can lead to an excellent deep drawability while it does not certainly lead to high ridging resistance ability.

4. Conclusion

(1) In the Sn-containing ferritic stainless steel, the r-value increases with the proceeding of recrystallization and the highest r-value appears after annealing at 900°C for 4 min.
(2) The inhomogeneously-distributed strong γ-fiber texture in the center of the sheet leads to more severe ridging morphology than on the surface. The homogeneous texture components on the surface are beneficial to reduce the ridging.
(3) There is a nearly opposite relationship between the plastic stain ratio r-value and the ridging resistance in Sn-containing ferritic stainless steel sheet. A strong γ-fiber texture can lead to an excellent deep drawability while it does not certainly lead to high ridging resistance ability.

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References