TEXTURE AND PRESS FORMABILITY OF DUAL-PHASE STAINLESS STEEL SHEET

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ABSTRACT

The press formability of a dual-phase stainless steel sheet consisting of ferrite and austenite phases was estimated from a viewpoint of texture using plastic strain ratios ($r$-values). From the comparison of the mechanically obtained $r$-values by tensile test and the $r$-values calculated from the crystal orientation distribution functions (ODFs) of each phase, we found the ferrite phase contributed more to the transformation of the dual-phase stainless steel than the austenite phase.

INTRODUCTION

A dual-phase stainless steel consists of equal quantities of ferrite and austenite phases. Because the stainless steel shows excellent corrosion resistance and high strength, it is widely used for various chemical industrial equipments or devices. However, the press formability of the material is limited by low-ductility at room temperature. It is known that the ductility is closely related to crystal orientation distribution [1]. When the press formability of the dual-phase stainless steel is improved, it is very important to control the crystal orientation distribution (texture) of the phase which greatly contributes to the ductility.

In this study, the influence ratio of each phase to the ductility was investigated using plastic strain ratios ($r$-values). The $r$-value is obtained by dividing the logarithmic strain of the transverse direction of a specimen by that of the normal stain in a tensile test, and can be used to evaluate the press formability. The material with higher $r$-value shows better press formability. Theoretical $r$-values of each phase, calculated from crystal orientation distribution functions (ODFs) based on Taylor theory, have been compared with experimentally measured $r$-values. The ODFs of each phase were separately calculated from the pole density data of complete pole figures obtained by a pole figure measurement using an imaging plate (IP). As the result, it became clear that the ferrite phase greatly contributes to the ductility of the dual-phase stainless steel and the ductility is under the influence of the crystal orientation distribution in this phase.

POLE FIGURE MEASUREMENT USING IMAGING PLATE AND CALCULATION OF ODF

In the pole figure measurement using the IP [2], an entire Debye-Scherrer ring can be measured.
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In the measurement of Debye-Scherrer rings, by turning a disk specimen at regular intervals (β-rotation), as shown in Fig. 1, the pole density distribution along the circular paths of loci (locus circles) on a pole figure shown in Fig. 2 can be obtained. In the ODF analysis by Bunge’s method [3], the pole density data of three or more complete pole figures are needed. In the pole figure measurement, complete pole figures are obtained by measuring two incomplete pole figures at two different X-ray incident angles $\psi_1$ and $\psi_2$ by a back-reflection method and combining them. It is the advantage of the measurement method that the average crystal orientation distribution in the normal direction of the sheet can be measured, because X-rays are irradiated to the slope part of the specimen (the section of the sheet) as shown in Fig. 1.

**CALCULATION METHOD OF R-VALUE FROM ODF BASED ON TAYLOR THEORY**

According to Taylor theory, the strain of an individual grain in a polycrystalline material is equal to the macroscopic strain of the polycrystalline material due to the continuity between the grains. To satisfy this assumption, five or more independent slip systems must act in each grain. The method to obtain r-values of the polycrystalline material from the ODF is proposed based on this theory [4].

Assuming that individual grain receives the same uniform strain as the sample to keep the continuity of the strain at grain boundaries in the polycrystalline materials, strain tensor of the sample coordinate system $E_s$ can be transformed into strain tensor of the crystal coordinate system $E_c$. $R$ is a transformation matrix that transforms the strain from the sample coordinate system to the crystal coordinate system:

$$ E_s = \varepsilon \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & -q & 0 \\ 0 & 0 & -(1-q) \end{bmatrix} , $$

$$ E_c = R \cdot E_s' R' , $$

where, $q$ is the contraction ratio of the transverse direction of a specimen. Moreover, to select five...
active slip systems from twelve slip systems, the principle of minimum work is introduced. The combination of shear strain $\beta$, which minimizes the energy consumed by the slip transformation, is chosen:

$$M = \text{Min} \sum_{n=1}^{\lambda} |b_n|,$$

where, $M$, called Taylor factor, is the function of $\varphi$ and the crystal orientation $g$ described by Eulerian angles $(\varphi_1, \Phi, \varphi_2)$. When the Taylor factor $M$ is calculated at every crystal orientation under the constant $\varphi$, the relation between $M$ and $g$ is obtained. Moreover, to calculate easily, $M$ is approximated by a generalized spherical harmonic function $T_i^{\mu\nu}(g)$:

$$M(q, g) = \sum_{\ell=0}^{L} \sum_{\mu=1}^{M(\ell)} \sum_{\nu=1}^{N(\ell)} m^{\mu\nu}_t(q) \cdot T_i^{\mu\nu}(g),$$

where, $m^{\mu\nu}_t(q)$ is the expansion coefficient of $T_i^{\mu\nu}(g)$ and the function of $q$. Actually, it is calculated from $q=0$ to $q=1$ at 0.1 intervals. The average value of Taylor factor $\bar{M}$ of the entire sample can be calculated by the next equation:

$$\bar{M}(q) = \int M(q, g) \cdot f(g) dg,$$

where, $f(g)$ is the experimentally obtained crystal orientation distribution function. $\bar{M}$ can be expressed by using the Eq. (4) and expansion coefficient $C_i^{\mu\nu}$ of the crystal orientation distribution function:

$$\bar{M}(q) = \sum_{\ell=0}^{L} \sum_{\mu=1}^{M(\ell)} \sum_{\nu=1}^{N(\ell)} m^{\mu\nu}_t(q) \cdot C_i^{\mu\nu} \cdot \frac{\sin(2\nu-1)\alpha}{2\ell+1},$$

In the case of a tensile specimen which tensile axis parallels to the rolling plane of a sheet and inclines from the rolling direction of the sheet by $\alpha$ degrees, the Taylor factor of the direction of the tensile axis ($\alpha$ direction) is expressed by the next equation:

$$\bar{M}(q, \alpha) = \sum_{\ell=0}^{L} \sum_{\mu=1}^{M(\ell)} \sum_{\nu=1}^{N(\ell)} m^{\mu\nu}_t(q) \cdot C_i^{\mu\nu} \cdot \frac{\cos(\nu-1)\alpha}{2\ell+1}.$$
Conditions of Pole Figure Measurements and ODF Calculation

The specimen used for pole figure measurement was cut from the sheet by a wire-electrodischarge machine. The maximum diameter of the specimen was 12mm. The slope part of the specimen was finished by electrolytic polishing after buffing and emery polishing.

\{100\}, \{110\} and \{211\} complete pole figures were used to analyze ODF of the ferrite phase. Similarly, \{110\}, \{111\} and \{311\} complete pole figures were used for the analysis of austenite phase. The \{211\}, \{110\} \{311\} and \{111\} pole figures were obtained by Co-K\(\alpha\) characteristic X-rays. The \{100\} and \{110\} pole figures were obtained using Cr-K\(\alpha\) characteristic X-rays.

Conditions to Obtain R-values

To calculate \(r\)-values from the ODF, five active slip systems were selected from twelve \{110\}<111> slip systems in the calculation of the ferrite phase. Similarly, the five active \{111\}<110> slip systems were selected in the calculation of the austenite phase.

The \(r\)-values were also experimentally measured by tensile tests. The specimen shown in Fig.3 was used in the tests. The tensile axis was parallel to the rolling plane and inclined from the rolling direction of the sheet by \(\alpha\) degrees. Seven specimens of \(\alpha=0, 15, 30, 45, 60, 75\) and 90 degrees were tested.

Fig.3. Tensile specimen to obtain \(r\)-values experimentally.

Fig.4. Results of ODF of dual-phase stainless steel sheet.
Fig. 5. Mechanically obtained and calculated \( r \)-values of dual-phase stainless steel sheet of 6.0mm thick.

were prepared. The width and thickness of the specimen were measured by a micrometer before and after the expansion to 30%, and the \( r \)-value was calculated from the next equation:

\[
 r = \frac{\varepsilon_w}{\varepsilon_t}
\]  

(9)

where, \( \varepsilon_w \) and \( \varepsilon_t \) are strains of width-direction and thickness-direction of the specimen, respectively.

RESULTS AND DISCUSSIONS

Texture of Dual-Phase Stainless Steel Sheet

Figure 4 shows the results of the ODF of the ferrite and austenite phases of the dual-phase stainless steel sheet of 6.0 mm thick. The result of the ferrite phase shows the orientation density distribution about \( \varphi_2 = 45 \) degrees section of Eulerian space. Similarly, the result of the austenite phase shows the orientation density distributions about \( \varphi_2 = 0, 45 \) and 65 degrees sections. Ideal preferred orientations of cubic materials which appear in these sections are also shown in the figure. From the comparison between them, it is judged that the ferrite phase has mainly \( \{001\}<110> \) texture. Similarly, it is judged that the austenite phase has mainly \( \{011\}<112> \) and \( \{123\}<634> \) textures. Here, \( \{hkl\} \) and \( \langleuvw\rangle \) mean the crystal plane and crystal axis parallel to the rolling direction of the sheet, respectively. The results of the sheet of 1.5mm thick sheet was similar to the above results.
Mechanically Obtained R-values and Theoretically Calculated R-values

Figure 5 shows mechanically obtained r-values and theoretically calculated r-values from the ODFs of the ferrite and austenite phases shown in Fig.4. To obtain good press formability, it is necessary to obtain higher r-values than 1 in all \( \alpha \) directions.

All curves have a maximum r-value at about \( \alpha =50 \) degrees. The r-values of the austenite phase were higher values than 1 at most \( \alpha \) directions. On the other hand, mechanically obtained r-values and r-values of the ferrite phase were generally low at all \( \alpha \) directions. As the results, it was considered that the ferrite phase inhibits the press formability of the dual-phase stainless steel because the curve of the phase and the curve of mechanically obtained r-value are very similar.

Influence of Texture State of Ferrite Phase on Mechanically Obtained R-values

As mentioned above, it has become clear that the ferrite phase greatly contributes to the mechanically obtained r-values of the dual-phase stainless steel. Next, the influences of texture state of the ferrite phase on mechanically obtained r-values were examined.

Figure 6 shows orientation density distribution of continues orientations which reaches to \{111\}<110> from \{001\}<110> through \{112\}<110> of the sheets of 6.0mm and 1.5mm thick. There is almost no difference in \{111\}<110> orientation density which improves the r-value, however there is a difference in \{001\}<110> orientation density which depraves the r-value [1].

Figure 7 shows the mechanically obtained r-values of 6.0 and 1.5mm thick. The r-values of the sheet of 1.5mm thick shows higher values at near \( \alpha =0 \) and 90 degrees direction than 6mm thick. As the result, it is considered that the press formability of the dual-phase stainless steel can be improved by mainly controlling the texture of the ferrite phase. In that case, it is effective to increase \{111\}<110> orientation density.

CONCLUSIONS

(1) The ferrite phase greatly contributes to the mechanically obtained r-values.
(2) The press formability of the dual-phase stainless steel can be improved by mainly controlling the texture of the ferrite phase.

REFERENCES