Evaluation of $r$-value of steels using Vickers hardness test

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Abstract. The plastic strain ratio (Lankford value, $r$-value) is an index of mechanical anisotropy of sheet metals. The Vickers hardness is measured to determine the $r$-value. Tensile and indentation tests of three kinds of commercial steel sheets are conducted in directions 0°, 45° and 90° to the rolling direction. A relationship is found between the $r$-value and impression aspect ratio by a hardness tester. The aspect ratio is defined as the ratio of the diagonal length in the longitudinal direction to that in the thickness direction.

1. Introduction

Many parts for automobiles and home electric appliances are made of steel sheets. In sheet metal forming processes, the $r$-value is an index of mechanical anisotropy [1] that shows good correlation with deep drawability [2,3]. Accurate measurement of $r$-values enables more precise control of processes and results in many benefits such as an improvement in yield efficiency in machining processes and a decrease in loss of material. The $r$-value is defined as the strain ratio (width strain/thickness strain) in tensile tests. The $r$-value is unity for isotropic materials because strains in both directions are equal. The $r$-value is higher than unity for anisotropic materials, which deform more in the width direction than in the thickness direction. It is known that the $r$-value is governed mainly by crystallographic texture. The $r$-value increases with $<111>$/ND texture components and decreases with $<100>$/ND texture components [1,4,5]. Therefore, sheet metals with high $r$-values for deep drawing are often cold-rolled under well-lubricated conditions to develop $\gamma$-fibers ($<111>$/ND).

The $r$-value, generally measured by tensile tests, reflects only the average anisotropy through the thickness. However, the $r$-value near the surface seems to be lower than that around the center owing to shear texture formed in the rolling process. For tensile tests, the materials tested should be a particular shape of flat sheet. It is important to evaluate the distribution of $r$-values in a tailored sheet or a sheet with a graded microstructure. Thus, establishment of other methods to measure the $r$-value is strongly desired.

A Vickers hardness test gives local mechanical information because the impression after the test has a micrometer size. The shape of the impression is normally independent of applied load. The test provides a hardness value that corresponds to the yield stress or the strength. Nakamura and Tozawa proposed that anisotropic information on materials can be obtained from the shape of the impression made by the indenter, mainly for silicon steels [6]. However, this could also be applied to other steels.

The two diagonal lengths of the impression after indentation are equal for isotropic materials, but not for anisotropic ones. The shape of the impression should be affected by anisotropy in flow stress. The shape of a micrometer-sized impression is influenced by the texture. In this study, three kinds of
commercial steel sheets for deep drawing were tested to provide an estimation of the $r$-value of steel sheet from the shape of the impression formed by a Vickers hardness test.

2. Experimental procedure

2.1. Observation of microstructure

Three kinds of commercial cold-rolled steel sheets were used, (a) extra-low carbon steel, (b) ultra-low carbon steel, and (c) low carbon steel. The chemical compositions are shown in Table 1. Electron Back Scattering Diffraction analysis was conducted in a 200 µm x 200 µm area on the TD plane, by a field emission scanning electron microscope (FE-SEM; Japan Electro Optical Laboratory, JSM-6500F) with a slow-scan CCD camera. Specimens were sampled in 10 mm lengths. In the SEM observations, the accelerating voltage was 15 kV, the exposure current was 16 nA and the scanning pitch was 0.5 µm. An EDAX system (OIM Data Collection ver.5.2 and Analysis ver.5.2) was used.

| Sheet | JIS | C  | Si  | Mn  | P   | S    | Fe   |
|-------|-----|----|-----|-----|-----|------|------|
| A     | SPC270C | 0.019 | 0.01 | 0.14 | 0.012 | 0.0068 | Bal. |
| B     | SPC270D | 0.0018 | 0.02 | 0.17 | 0.014 | 0.005 | Bal. |
| C     | SPC440  | 0.172 | 0.01 | 0.76 | 0.014 | 0.003 | Bal. |

2.2. Measurement of $r$-value by tensile test

Specimens for tensile tests were prepared so that the tensile axis was parallel to the rolling, transverse and diagonal directions of the three steel sheets. The gauge length and width were 20 mm and 10 mm, respectively. Uniaxial tensile tests were conducted with a cross-head speed of 1 mm/min. After uniform straining of 15% in tension, the specimen was unloaded and the $r$-value was calculated. The $r$-value is defined as the strain ratio (width strain/thickness strain)

$$r = \frac{\ln(w_1 / w_0)}{\ln(l_1 / l_0)},$$

where $w_0$ and $l_0$ are the initial width and thickness of the gauge, respectively. $w_1$ and $l_1$ are the width and thickness of the gauge after deformation, respectively. As it is difficult to measure the strain in the thickness direction of a thin sheet accurately, it was calculated from the strains in the longitudinal and width directions using the volume constancy [7].

$$l_0w_0d_0 - l_1w_1l_1 = 0$$

Hence, the $r$-value was calculated by

$$r = \frac{\ln(w_1 / w_0)}{\ln(w_1 \cdot l_1 / w_0 \cdot l_0)}.$$  

The planar average $r$-value is defined by $r_0$, $r_90$ and $r_{45}$ for a tensile axis along the rolling, transverse and diagonal directions, respectively, of the sheets.

$$r = \frac{r_0 + r_90 + 2r_{45}}{4}$$

The specimens were reloaded to measure the tensile strength and elongation. Mechanical properties of the steel sheets are shown in Table 2.

2.3. Vickers hardness test

Three faces of the initial sheets shown in Figure 1 were sectioned and polished to a mirror finish. After polishing, a Vickers hardness test was conducted with an indentation load of 100 gf and a duration of 15 s (number of tests: 20). The diagonal length of the impression in the thickness direction $d_{t}(d_{ND})$ and
that in the longitudinal (rolling / transverse / diagonal) direction \(d_2(d_{RD}, d_{TD}, d_{DD})\) were measured. The Vickers hardness (HV) is defined as

\[
H = 1.854 \frac{F}{d^2}.
\]

\(F\) is the indentation load (kgf) and \(d\) is the diagonal length (mm). \(d\) is generally an average of \(d_1\) and \(d_2\). To estimate the anisotropy, the aspect ratio \(\alpha\) is defined as the ratio of the two diagonal lengths.

\[
\alpha = \frac{d_2}{d_1}.
\]

The aspect ratio \(\alpha\) is unity in isotropic materials and higher than unity in anisotropic materials that deform more in the longitudinal direction than in the thickness direction. To estimate the planar anisotropy of the aspect ratios, \(\alpha_0, \alpha_{90}\) and \(\alpha_{45}\) were defined as aspect ratios in the rolling plane, transverse plane and diagonal plane, respectively. The planar average of the aspect ratio is defined as

\[
\frac{\alpha}{4} = \frac{\alpha_0 + \alpha_{90} + 2\alpha_{45}}{4}.
\]

### Results

#### 3.1. Crystallographic texture

Inverse pole figure maps on TD sections of initial sheets are shown in Figure 2. Sheets A and B have equiaxed microstructure with a mean grain size of 15.6 µm and 13.8 µm, respectively. The grain size of sheet C was 4.8 µm with a random preferred orientation.

It is possible to determine texture quantitatively in Bunge ODF sections for \(\phi_2 = 45\)(deg.), as shown in Figure 3. The major texture components in sheet A are \{111\}<211> and the sub-components are \{112\}<110>. The major texture components in sheet B are \{111\}<110>. The major texture components in sheet C are \{112\}<110>, although the intensity is low. <111>//ND (\(=\) γ-fiber)

![Figure 1. Indentation directions of Vickers hardness tests.](image)

### Table 2. Mechanical properties of the steel sheets used.

| Sheet | Angle to RD (deg.) | 0.2% proof stress /MPa | UTS /MPa | Elongation (%) |
|-------|--------------------|------------------------|----------|---------------|
| A     | 0                  | 246.5                  | 336.4    | 49.2          |
|       | 45                 | 260.3                  | 352.7    | 42.3          |
|       | 90                 | 258.5                  | 342.0    | 52.0          |
| B     | 0                  | 163.7                  | 290.6    | 62.3          |
|       | 45                 | 166.1                  | 298.6    | 60.3          |
|       | 90                 | 163.8                  | 291.9    | 62.7          |
| C     | 0                  | 319.2                  | 462.5    | 44.9          |
|       | 45                 | 335.5                  | 473.9    | 43.8          |
|       | 90                 | 317.8                  | 461.6    | 44.6          |
components, which increase the deep drawability, are strongly developed in sheets B and A, showing strong intensity. The proportion of \( <110>/RD (= \alpha\text{-fiber}) \), which increases the planar anisotropy, is relatively low in sheet B.

3.2. \( r \)-value obtained by tensile test
Sheet B has the highest \( r \)-value, and sheet C has the lowest among the three sheets in Figure 4. This is reasonable if the intensities of \( \gamma \)-fibers in the ODF are considered. The \( r \)-value shows high planar anisotropy as in Figure 4. The planar anisotropy of the \( r \)-value in sheets A and C is higher than that in sheet B. This is in good agreement with the intensities of \( \alpha \)-fibers from the ODF results.

3.3. Vickers hardness
In Figure 5, the Vickers hardness shows lower planar anisotropy. The Vickers hardnesses of sheets A, B and C were 116HV, 100HV and 151HV, respectively. The average diagonal length calculated by Eq. (6) with these hardness values were 40.0 \( \mu \)m, 43.1 \( \mu \)m and 35.0 \( \mu \)m, respectively. The diagonal lengths
are larger than the mean grain sizes of the sheets in Figure 2. The hardness reflects averaged mechanical properties of grains under the indenter.

The aspect ratio $\alpha$ shows high planar anisotropy in Figure 6. In sheets A and C, $\alpha_{0}$ and $\alpha_{90}$ are higher than $\alpha_{45}$. In sheet B, the aspect ratios are higher than unity in all directions. This result indicates that sheet B deformed more in the longitudinal direction.

4. Discussion

There is high planar anisotropy in the $r$-value and aspect ratio, but not in the Vickers hardness. The Vickers hardness defined by Eq. (6) is calculated from the average of $d_1$ and $d_2$. The diagonal lengths $d_1$ and $d_2$ may have low planar anisotropy because it reflects a property either in the thickness direction or another direction. It is supposed that flow stress in the thickness direction is much higher than in either direction on the rolling plane. To estimate the $r$-value, a parameter having a high dependence on anisotropy is required, such as the aspect ratio $\alpha$ defined by Eq. (7).

In this study, $\alpha^2$ is used as the parameter that corresponds to the ratio of two hardness values calculated using only the diagonal length in the thickness direction and only in the longitudinal direction. Figure 7 shows the relationship between $\tilde{r}$, the planar average $r$-value measured by the tensile test and $\tilde{\alpha}^2$, the square of the planar average of the aspect ratio obtained by the Vickers hardness test. The coefficient of correlation between $\tilde{r}$ and $\tilde{\alpha}^2$ is 1.00. There is a good relationship between $\tilde{r}$ and the impression geometry.

The $r$-value measured from the tensile test and the aspect ratio $\alpha$ obtained from the Vickers hardness test show high planar anisotropy, and as has been mentioned, seem to have some relationship. To discuss this relationship in more detail, the $r$-values, $r_0$, $r_{45}$ and $r_{90}$ are compared with the aspect ratios, $\alpha_{0}$, $\alpha_{45}$ and $\alpha_{90}$, respectively, under the condition that the indentation plane is normal to the tensile axis. From Figure 8, a linear relationship between the $r$-value determined from the tensile test and the aspect ratio $\alpha$ obtained from the Vickers hardness test is found as

$$r = 15.1\alpha^2 - 13.8.$$  

(9)

The deformation in the thickness direction decreases with increasing $r$-value and with higher $\alpha$ as the shape of the impression becomes more rhombic, that is, the impression is longer in the longitudinal direction than in the thickness direction. Eq. (9) gives a better correlation than Nakamura’s nonlinear
relationship plotted as a curved line in Figures 7 and 8. Nakamura and Tozawa [6] proposed a nonlinear relationship between the $r$-value and the ratio of two Vickers hardness values calculated using the diagonal lengths in the thickness and width directions. They mainly used silicon steels with a relatively low $r$-value, so the equation deviates at high $r$-values.

In Figure 8, Eq. (9) does not pass through the point where both the $r$-value and aspect ratio are unity. This result is unexpected considering that both the $r$-value and aspect ratio should be unity for isotropic materials. This may be because the $r$-value may have a distribution through the thickness of the sheet. In this study, the $r$-value was determined by the tensile test, while the Vickers hardness test was conducted only around the midplane. Additionally, this might be attributed to experimental errors caused by loose guiding in the rolling operation, sectioning of the specimen or tilting of the specimen in hardness test.

![Figure 7](image1.png)

**Figure 7.** Relationship between planar average $r$-value obtained by tensile test and planar average aspect ratio obtained by Vickers hardness test.

![Figure 8](image2.png)

**Figure 8.** Relationship between $r$-value obtained by tensile test and aspect ratio obtained by Vickers hardness test.

### 5. Conclusions

Tensile and indentation tests of three kinds of commercial steel sheets were conducted in directions 0°, 45° and 90° to the rolling direction. A good linear relationship between the $r$-values determined by the tensile test and the aspect ratio $\alpha$ of the Vickers hardness test is found as $r = 15.1\alpha^2 - 13.8$. The aspect ratio $\alpha$ is defined as the ratio of the two diagonal lengths of the diamond-shaped impression.

By taking advantage of this equation, the $r$-value of steel can be locally evaluated.

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