STRAIN-DEPENDENCE OF PLASTIC STRAIN RATIO OF DEEP-DRAWING ALUMINIUM-KILLED STEEL SHEET①

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ABSTRACT The change of width and length of an aluminium-killed(AK) steel sheet was measured in detail at various tensile strain levels. The effects of tensile strain on the conventional strain ratio, r^c-value, and the instantaneous strain ratio, r^i-value, were analyzed. It was shown that the strain ratio of the AK steel sheet had obvious strain-dependency. The individual r^c-values for all tested directions tended to unity with increasing strain so that the planar anisotropy decreased with increasing strain. The r^i-value had overall strain-denpendency similar to that of r^c-value, though it was overly sensitive to the experimental errors and showed significant variation with strain. In the representation of average strain ratio, the linear regression strain ratio, r^r-value, which was obtained by fitting a straight line to the ε_W vs ε_T curve, is preferable to the r^c-value measured at some specfic extension.

Key words plastic strain ratio anisotropy tension

1 INTRODUCTION

The plastic strain ratio has been widely used as a measure of plastic anisotropy and deep drawability for many years. Recent years have, however, uncovered a problem of strain-dependency of strain ratio, i. e. the effect of tensile strain on the strain ratio. The strain ratio originally introduced by Lankford *et al*[1] was designated as conventional strain ratio, i. e. r^c-value in the present study, and defined as

$$r^c = \frac{\varepsilon_W}{\varepsilon_T} = \frac{\ln(W/W_0)}{\ln(T/T_0)} \quad (1)$$

Assuming constancy of volume ($\varepsilon_L + \varepsilon_W + \varepsilon_T = 0$), the r^c-value can then be expressed indirectly as

$$r^c = \frac{\varepsilon_W}{-(\varepsilon_W + \varepsilon_L)} = -\frac{\ln(W/W_0)}{\ln(W/W_0) + \ln(L/L_0)} \quad (2)$$

where ε_L, ε_W, and ε_T are the true strains in the length, width, and thickness of a tension sample; L_0, W_0, T_0 and L, W, T are the length, width, and thickness of the sample before and after tension, respectively. The r^c-value is generally believed to be independent of the level of tensile strain, and the r^c-value measured at a given elongation has been used as an indicator of plastic anisotropy and drawability. However, the observations of Hu[2] and Truszkowski[3] showed that the r^c-values measured at various elongations were usually different.

Alternatively, in the theory of anisotropy yield criterion proposed by Hill[4], the instantaneous strain ratio was adopted and defined as

$$r^i = d\varepsilon_W / d\varepsilon_T \quad (3)$$

It can be used to describe the instantaneous plastic anisotropy, while the r^c-value is dependent only on the final state. In the original publication[4], Hill considered that the r^i-value varied with strain, but in the treatments

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of his theory it was generally assumed that in cubic structure the r^i-value was independent of strain[5]. Arthey and Hutchinson[6] observed that, for both aluminium-killed steel and titanium stabilized steel, the r^i-value was invariant with strain except for the initial period of discontinuous yielding. Liu and Johnson[7] also concluded from the measurements of four steels that r^i-value is independent of strain and attributed the initial variation of r^i-value to the experimental error. However, Lake *et al*[8] proposed that it's incorrect to consider that r^i-value is constant with strain though the discontinuous yielding and experiment error may be the reason for obvious variation of the r^i-value at low strains.

For the observations and analyses on the strain-dependency of both r^c-value and r^i-value are very disputable, it is the purpose of the present study to clarify this discrepancy on the basis of detailed measurements and calculations of these strain ratio terms of an AK steel sheet.

2 EXPERIMENTAL

2.1 *Material and Mechanical Properties*

Material used in the present investigation was a 2.0 mm thick AK steel sheet obtained from a commercial source. The chemical composition(%) was C-0.07, Mn-0.30, Si-0.04, Al-0.05, P-0.01, S-0.02. Its mechanical properties are listed in Table 1.

Table 1 Mechanical properties of the material used

Angle to RD/(°)	σ_s /MPa	σ_b /MPa	UE /%	TE /%
0	211	287	31.0	34.6
22.5	215	298	30.8	33.6
45	221	299	29.7	34.6
67.5	218	296	27.4	28.4
90	202	291	28.6	30.5

2.2 *Experimental Procedures*

The tapered tension specimens with length direction 0, 22.5, 45, 67.5, and 90° to the rolling direction (RD)were prepared as describled in ASTM Standand E517. The gage length was 50 mm. Due to the slight difference in width, a strain gradient existed along the specimen length, thus at least five transverse lines were scribed equally spaced within the gage length and the average width strain were calculated based on the widths measured individually at these lines.

An interrupted tensile test schedule was adopted in the present study. From the data on uniform elongation(UE) listed in Table 1, a more or less equally spaced interval in ε_L was made on a given specimen. When the specimen was stretched to a pre-determined strain level, the test was arrested, the load was removed by releasing the lower grip, and the widths were measured at the scribed lines with a micrometer and the length strain was measured by the extensometer automatically. The specimen was then gripped again, and pulled to the next increment of strain, and so on up to or beyond the end of uniform elongation. All tests were carried out on an Instron-8032 electronic tensile machine at a crosshead speed of 5 mm/min. The typical load-extension curve was illustrated in Fig. 1.

3 RESULTS AND DISCUSSION

3.1 *Conventional Strain Ratio*

The conventional strain ratio, r^c-value, was calculated using Eq. (2), and was shown in Fig. 2. It can be seen that, the r^c-values changed with the length strain obviously, in which, the r^c-values of 0, 22.5, and 45° from RD were smaller than 1 and increased with the length strain, the r^c-values for 67.5 and 90° to RD were larger than 1 and decreased with the length strain. Therefore, the r^c-values for all tested directions tended to unity with increasing strain. In addition, the r^c-values at low strains for 67.5 and 90° directions were relatively small and unidentical to the overall tendencies of strain-dependency. This can be attributed to the discontinuous yielding in the range of Lüders strain and experimental error

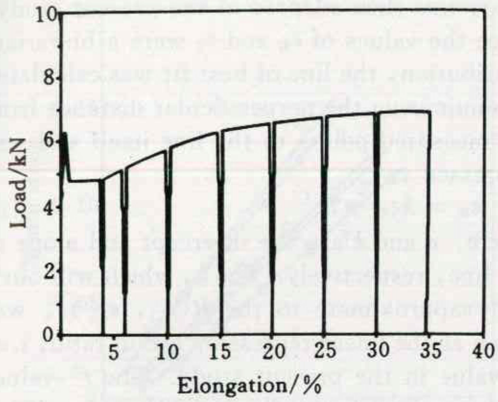

Fig. 1 Typical load-elongation curve of the tensile testing sequence

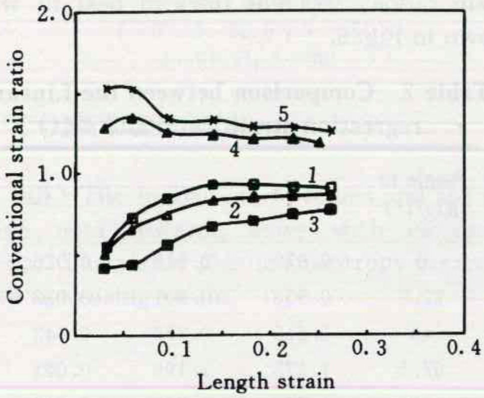

Fig. 2 Variation of measured r^c -values with strain level

1—0°; 2—22. 5°; 3—45°; 4—67. 5°; 5—90°

which is most influential at low strains. For the texture development in tension observed by Daniel *et al*[9] in an AK steel showed that it was at low strain that the texture changed significantly, therefore, the obvious change of texture in tension should be the main reason for the significant variation and instability of r^c -value at low strains. The normal anisotropy, r_m -value, and planar anisotropy, Δr -value, at various extensions were also calculated, in which

$$r_m = (r_0^c + 2r_{22.5}^c + 2r_{45}^c + 2r_{67.5}^c + r_{90}^c)/8 \quad (4)$$

$$\Delta r = (r_0^c + r_{90}^c \quad 2r_{45}^c)/2 \quad (5)$$

The results were shown in Fig. 3. As can be expected, the r_m -value also tended to unity with the strain, and the Δr -value decreased with the strain.

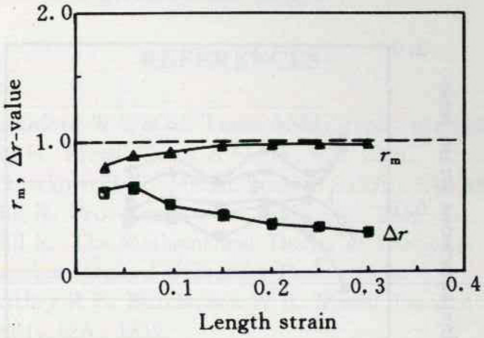

Fig. 3 Variation of r_m -value and Δr-value with strain level

3. 2 *Instantaneous Strain Ratio*

The calculation of instantaneous strain ratio, r^i -value, was based on the difference between the length strain and width strain for two successive measurements, i. e.

$$r^i = -\frac{\ln(W_{k+1}/W_k)}{\ln(W_{k+1}/W_k) + \ln(L_{k+1}/L_k)} \quad (6)$$

where W_k, L_k and W_{k+1}, L_{k+1} are the width and length of the sample for step k and step $k+1$, respectively. The r^i -value so determined was taken as the value for a strain mid-way between the two steps. The r^i -values calculated as Eq. (6) at different length strains for the directions tested were shown in Fig. 4. It can be seen that the change of r^i -value with the length strain was similar to that of r^c -value, though more significant it was.

By differentiating both sides of Eq. (1), the following relationship between r^i and r^c is obtained:

$$r^i = r^c + \varepsilon_T \frac{dr^c}{d\varepsilon_T} \quad (7)$$

It clearly shows that $r^i = r^c$ only when $dr^c/d\varepsilon_T = 0$, i. e. the r^c-value is independent of strain, and that the r^i -value is more obviously influenced by experimental error than the r^c. The significant variation of r^i -value with strain can therefore be attributed to the influence of experiment error and the large step of strain, which was about 5% in the present study. It is expected that a high degree of precision in measuring the r^i-value is feasible if smaller steps of tension strain are adopted.

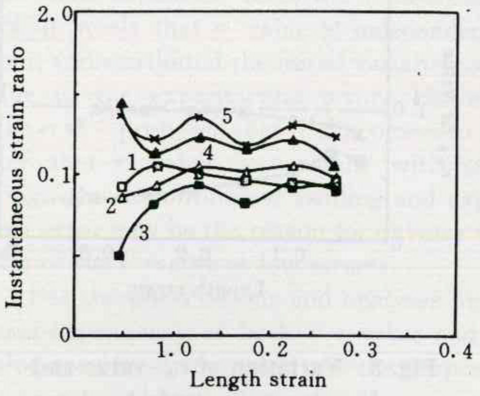

Fig. 4 Variation of measured r^i-values with strain level

1—0°; 2—22.5°; 3—45°; 4—67.5°; 5—90°

3.3 *Linear Regression Strain Ratio*

A single-valued parameter representive of the average strain ratio over a given strain range is usually required for those concerned with the formability of sheet at an industrial level. However, the r^c-value and the r^i-value dependent on the final and instantaneous state, respectively, are both undesirable. The direct way to achieve this is to integrate the r^i-value over the required strain range[10], i.e.

$$R(\varepsilon_{L1}, \varepsilon_{L2}) = \frac{1}{\varepsilon_{L2} - \varepsilon_{L1}} \int_{\varepsilon_{L1}}^{\varepsilon_{L2}} r^i(\varepsilon_L) d\varepsilon_L \quad (8)$$

where ε_{L1} and ε_{L2} are the length strains of initial and final state, respectively. The $R(\varepsilon_{L1}, \varepsilon_{L2})$ so determined is a true integal value and takes into account any change over the strain path of the sample.

For this integration is time-consuming and unsuitable for the rapid assessment of the average strain ratio, another way, which is to use linear regression technique to get a straight line fit to the ε_W *vs* ε_T curve and take the slope of this fit line as the average strain ratio, was then adopted in the present study. Since the values of ε_W and ε_T were a bi-variate distribution, the line of best fit was calculated by minimizing the perpendicular distance from the measured points to the line itself and was expressed as

$$\varepsilon_W = k\varepsilon_T + a \quad (9)$$

where a and k are the intercept and slope of the line, respectively. The k, which will obviously approximate to the $R(\varepsilon_{L1}, \varepsilon_{L2})$, was taken as the linear regression strain ratio, i.e, r^r-value in the present study. The r^r-values so determined from initial yielding to uniform elongation for the five directions were listed in Table 2 and compared with the r^c_{UE}-values which were generally recommended as average strain ratios[1,11]. The lines of best fit were shown in Fig. 5.

Table 2 Comparison between the Linear regression strain ratio and r^c_{UE}

Angle to RD/(°)	r^i or k	r^c_{UE}	$\|r^i - r^c_{UE}\|$
0	0.939	0.913	0.026
22.5	0.933	0.901	0.032
45	0.815	0.773	0.042
67.5	1.175	1.196	0.021
90	1.282	1.263	0.019

From Table 2, it can be seen that $|r^r - r^c_{UE}| < 0.05$ for all the directions tested, it then appeared that for the AK steel tested in the present study the r^c_{UE}-values were close to the r^r-values and can also be used to represent the average strain ratio over the total region of uniform strain. However, the r^r-values calculated by Lake *et al*[8] in low-carbon steels, which showed more obvious strain dependency of r^c-value than that of the present material, were close to the conventional strain ratios at 15% extension. Therefore, it can be concluded that the r^r-value may close to r^c-value at different strain levels for different materials, and that in the representation of average strain ratio the r^r-value is preferable to the r^c-value measured at some specific extension.

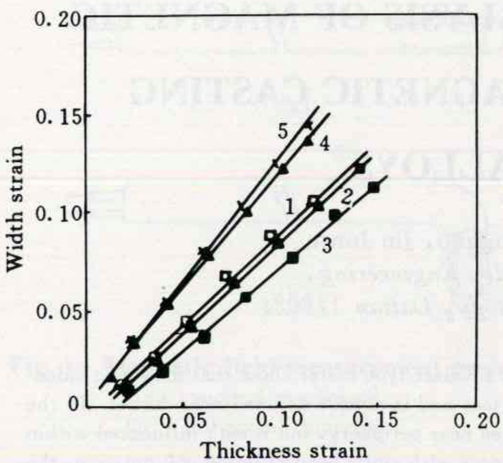

Fig. 5 Linear regression of the ε_W, ε_T data set

1—0°; 2—22.5°; 3—45°; 4—67.5°; 5—90°

4 CONCLUSIONS

(1) The individual r^c-values and the r^c_m-value tend towards unity with increasing strain. The planar plastic anisotropy decreases with increasing strain.

(2) The r^i-value shows significant variation with strain and is overly sensitive to measuremental errors, though its overall strain-dependency is similar to that of the r^c-value.

(3) The r^r-value is preferable to the r^c-value in the representation of average strain ratio over a given strain range.

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