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EARING IN DEEP-DRAWING STEELS

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The variations of the fourth-order coefficients of the crystallite orientation distribution function, with rolling reduction have been determined after cold-rolling and annealing for a deep-drawing quality rimming steel and an aluminium-killed steel. These coefficients influence drawability and earing behaviour and by the manipulation of the coefficients in the distribution function of a 60% cold-rolled and annealed rimming steel, a hypothetical non-earing sheet texture has been derived. By comparison with the actual sheet texture those textural components which most affect earing behaviour are identified.

INTRODUCTION

The effects of normal and planar anisotropy of mechanical properties on the deep-drawing performance of sheet metals have been variously reported.[1–5] In particular, the relationship between anisotropy and the appearance of "earing" has attracted considerable attention. The earing phenomenon has been reviewed by Wright[6] and by Grewen.[7] Although earing in sheet metal is known to be determined by mechanical anisotropy attributable to the existence of crystallographic preferred orientation (texture) in the sheet, there are few quantitative treatments available.[5,8,9] One of the most important aspects of texture study is the development of methods for changing the texture towards the ideal. For control of earing this requires clear identification of the textural components contributing most strongly to the mechanical anisotropy. Although empirical methods have been developed with some success,[5,7] fundamental analyses are still needed.

The application of spherical harmonic analysis methods in texture research[10–14] has yielded quantitative descriptions of texture, in the form of crystallite orientation distribution functions, which can be used to predict elastic and plastic anisotropy with some accuracy. The object of the present paper is to show how the crystallite orientation distribution function can be used to study earing in sheet steels of deep-drawing quality. The procedures described are of more general applicability.

ANALYTICAL BASIS

Pursey and Cox[15] in their analysis of elastic anisotropy in cubic crystals showed that only four independent coefficients of the crystallite orientation distribution function enter into the expression for the polycrystalline elastic constants. The usual expression for the distribution function,[10] is

$$w(\psi, \xi, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \sum_{n=-}^{l} W_{lmn} Z_{lmn}(\xi) \exp(-im\psi) \exp(-in\phi)$$

where ψ, θ ($= \cos^{-1}\xi$) and ϕ are the Euler angles describing the crystallite orientation, W_{lmn} are the coefficients of the generalised spherical harmonic series and $Z_{lmn}(\xi)$ is a generalisation of the associated Legendre function (the so-called augmented Jacobi polynominals[12]). In this function it is the independent coefficients, W_{000}, W_{400}, W_{420} and W_{440} (W_{4m4} being linearly dependent on W_{4m0}) which determine elastic anisotropy.

Similarly, it has been shown[16] that these fourth order coefficients largely determine the plastic anisotropy of cubic metals. This is a consequence of the observation that when the anisotropy of plasticity of a cubic single crystal deforming by polyslip according to the Bishop and Hill theory[17,18] is expressed as a series of generalised spherical harmonics the coefficients, $G_{lmn}(q)$ of higher than fourth order are an order of magnitude smaller than those for the zeroth† or fourth order (see Table I).

TABLE I

Mean absolute values of the coefficients $G_{lmn}(r)$ for various orders of the expansion of the function describing flow stress anisotropy according to the Bishop and Hill theory, with contraction ratio r

Order	Mean absolute value of $G_{lmn}(r)$
0	4.470
2	0
4	0.191
6	0.012
8	0.022
10	0.003
12	0.005
14	0.003

In making the analysis of plastic anisotropy[16] the series coefficients, $G_{lmn}(q)$ are evaluated for successively different values of an assumed contraction ratio, q, given by

$$q = \frac{d\epsilon_{yy}}{d\epsilon_{yy}+d\epsilon_{zz}} = \frac{r}{1+r}$$

where $d\epsilon_{yy}$ and $d\epsilon_{zz}$ are strains in the width and thickness directions, respectively, and r is the conventional strain ratio (width strain/thickness strain).

In deriving Table I the values of $G_{lmn}(q)$ have been calculated for contraction ratios $q = 0$, 0.1, 0.2 . . . 1.0 for different orders of l up to and including the fourteenth. In predicting the plastic anisotropy of polycrystals[14,16] this information is combined with the crystallite orientation distribution data. If the lower-order texture coefficients, W_{lmn}, are of the same order of magnitude (this is normally the case), the contribution of product terms of order greater than four can be neglected. Cross terms are not present because of the orthogonal properties of generalised spherical harmonic functions.

The analysis of drawability can be undertaken in a parallel way. Hosford and Backofen[2] showed that good drawability in sheets of cubic metals is obtained when the parameter, β, given by the ratio of the yield strengths under the plane-strain conditions existing in the cup wall and flange respectively, is large.‡ This parameter can easily be related to the crystallographic texture.[2] Kallend[19] showed that for the coefficients of the crystallite orientation distribution function a large negative W_{400} gives a large β value and thus good drawability. Furthermore, a positive W_{420} controls the tendency to form two ears at 90° and 270° from the rolling direction and a positive W_{440} leads to four ears at 0°, 90°, 180° and 270° to the rolling direction. Correspondingly, a negative W_{420} gives two ears at 0° and 180° and a negative W_{440} gives four ears at 45°, 135°, 225° and 315° to the rolling direction. The earing tendency is decreased as the values of W_{420} and W_{440} tend to zero.

The present work involves firstly the manipulation of the fourth-order coefficients of the crystallite orientation distribution function obtained experimentally for a commercial rimming steel and the correlation of changes in the drawability and earing tendency with changes in the textural components of the distribution. Subsequently the results are applied to a commercial killed steel. The initial texture analysis was made using rimming steel because the orientation distribution function for this steel was such as to allow the ready identification of the different texture components. The crystallite orientation distribution function for the killed steel obscured small changes in intensity due to its higher overall severity.

EXPERIMENTAL

The steels considered were commercial deep-drawing quality rimming steel and killed steel whose compositions are given in Table II. Samples of the steels were cold rolled to different reductions using an oil lubricant. Rolling was followed by a simulated commercial annealing treatment, viz.: slow heat (25°C per hour) to 700°C, hold for 20 hours, slow cool to room temperature (25°C per hour), in an atmosphere of argon at reduced pressure. Texture measurements were made on samples prepared by the composite specimen method of Elias and Heckler[20] using a Siemens texture goniometer with filtered MoKα radiation. {110}, {200}

†The zeroth order coefficients give rise to orientation independent properties.

‡It should be noted that the β-parameter is difficult to measure experimentally. For this reason the plastic strain ratio, r, is more frequently used as a measure of drawability.

TABLE II

Composition and hot process treatment of rimming and killed steels

Element	Rimming steel wt. %	Killed steel wt. %
C	0.020	0.035
S	0.022	0.022
P	0.006	0.008
Mn	0.27	0.24
Cu	0.090	0.030
Ni	0.060	0.025
Sn	0.020	0.010
Si	0.01	—
Cr	0.070	—
N	0.0028	0.0074
Total Al	0.030	0.047
Sol Al	0.01	0.040
Finishing Temperature	898–937°C (mean 920°C)	882–904°C (mean 893°C)
Coiling Temperature	653–620°C	598–549°C

The section used for experimentation was from the centre of the coil.

TABLE III

Euler angles for given ideal orientations

Ideal orientation *hkl*	*uvw*	θ	ϕ	ψ
100	011	90	45	0
		90	45	90
		0	$(\phi+\psi)=45$	
110	001	45	0	90
		45	90	90
		90	45	0
320	001	56.3	0	90
		90	33.7	0
		33.7	0	90
		90	56.3	0
100	001	0	$\phi+\psi=0, 90$	
		90	0	0
		90	0	90
		90	90	0
		90	90	90
111	*uvw*	54.7	45	any
110	*uvw*	45	0	any
		45	90	any
		90	45	any
100	*uvw*	0	$(\phi+\psi)=$any	
		90	0	any
		90	90	any

and {211} pole figures were used to determine the coefficients of the crystallite orientation distribution functions for each pre-annealing reduction.

Constant ϕ sections of the crystallite orientation distribution function were plotted automatically using a curve plotter controlled by a contouring program. Specific orientations were indexed by reference to the charts published previously.[21] Table III lists orientations of interest in terms of the corresponding Euler angles θ, ϕ and ψ.

Using the experimental distribution function for a sample of rimming steel given a treatment close to that adopted commercially (viz. 60% cold reduction prior to annealing) the effect of setting W_{420} and W_{440} to zero both separately and together was evaluated. In each case constant-ϕ sections were reconstituted and comparison made with the original plots. In this way those textural components influencing earing could be identified.

The crystallite orientation distribution function data were also used to predict the planar anisotropy of the yield stress and of the plastic strain ratio using the method of Bunge and Roberts[11] and Kallend and Davies.[14,22]

RESULTS AND DISCUSSION

Fourth Order Texture Coefficients

Figure 1 shows the variation in the W_{4m0} coefficient with increasing true strain from cold rolling prior to annealing for the rimming steel. As mentioned above, a large negative W_{400} gives rise to a large β-value and good drawability. This is achieved by increasing the rolling reduction prior to annealing although the rate of change decreases significantly above reductions of about 60%.

W_{420} is always negative and nearly independent of reduction. Thus a pair of ears at 0° and 180° are expected after all reductions. W_{440}, however, is negative below 30% reduction and above 88% reduction. The positive values reach a maximum at 60% reduction. Thus this coefficient should give rise to ears at 45°, 135°, 225° and 315° outside the range 30–88% reduction and at 0°, 90°, 180° and 270° within this range. Experimental observations[4] confirm these predictions. This is also confirmed by results presented in Figure 2† which shows the variation in ear height with rolling reduction for a

†Data supplied by R. C. Hudd, British Steel Corporation, Strip Mills Division.

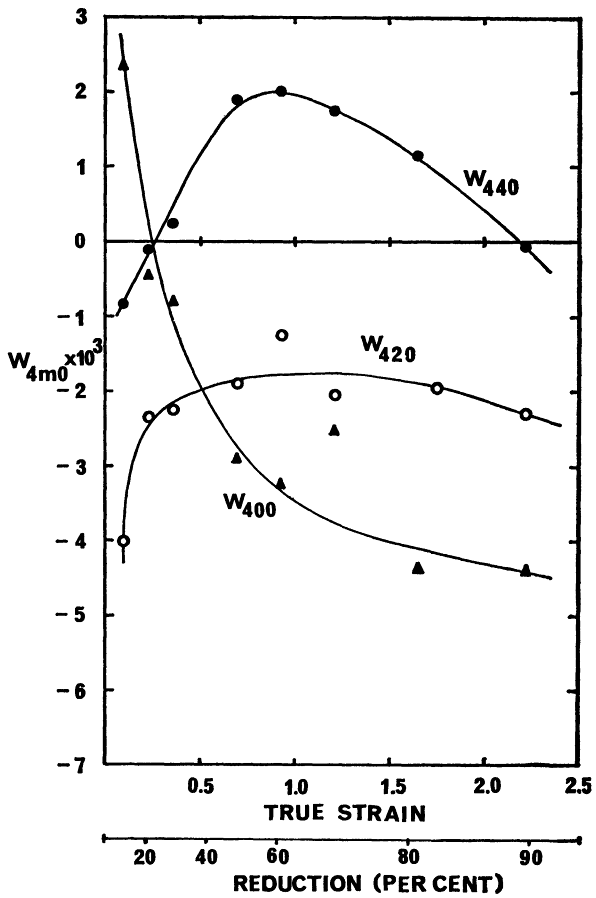

FIGURE 1 The variation of the W_{4m0} texture coefficients with rolling reduction prior to annealing for the rimmed steel.

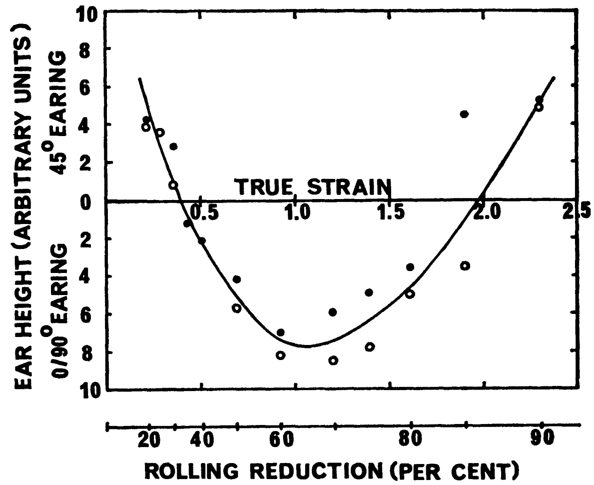

FIGURE 2 The variation in ear height with rolling reduction for a rimming steel similar to the one used to derive Fig. 1.

● Sample 1 from the front end of the coil.
○ Sample 2 from the back of the coil.

rimming steel similar to the one used to derive Figure 1.

The best earing behaviour is obtained by minimising the deviation of the top of the cup from being flat. In some cases this can be achieved by using balanced textures. The procedures developed empirically[7,24] for cubic metals to minimise earing by combining 0°/90° and 45° earing, effectively minimise W_{440}. In the present case since W_{420} is independent of reduction optimisation would involve minimising W_{440} to as large a degree as possible consistent with increasing drawability. Notwithstanding this, it should be noted that the W_{420} and W_{440} coefficients are not crystallographically independent since textural components contributing to W_{420} can also contribute to W_{440}.

In commercial practice the cold reduction adopted depends on the final thickness and properties required of the sheet. Figure 1 shows that W_{400} does not change much beyond 60% reduction. For good drawability and in applications where earing is not disadvantageous, reductions of about 60% are commonly employed. Where non-earing properties are particularly desirable, the cold reduction will be closer to either 30 or 88% and this may result in some loss of drawability.[24]

In Figures 3, 4 and 5 only the series coefficients W_{000} and W_{400}, W_{000} and W_{420}, and W_{000} and W_{440} together with the linearly dependent coefficients have been used, respectively. W_{000}, the texture independent coefficient, effectively sets the contours for random texture to be everywhere unity. Examination of these figures with reference to Table III and the indexing charts[21] shows that W_{400} is controlled mainly by the amount of orientations with {111}-planes parallel to the plane of the sheet. This was expected, since it is well known that a large proportion of {111}-oriented planes in a textured material gives good drawing properties,[1] and, as stated above, the overall level of any parameter used to quantify drawability is dependent on W_{400}.

From Figure 4 it can be seen that the orientations which most affect W_{420} are those close to {110}

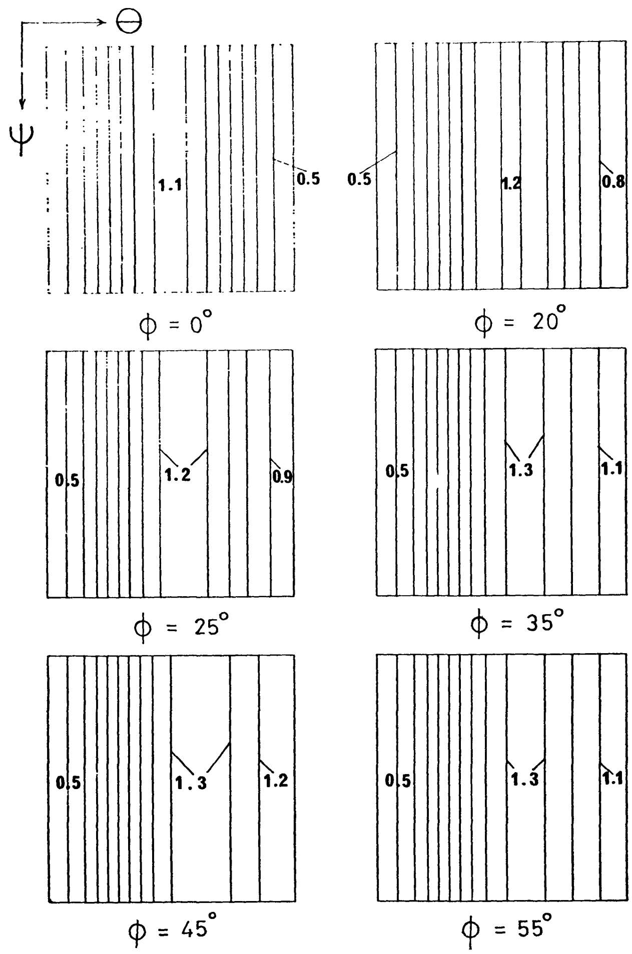

FIGURE 3 The crystallite orientation distribution function for the W_{000} and W_{400} coefficients alone, for rimmed steel rolled 60% and annealed.

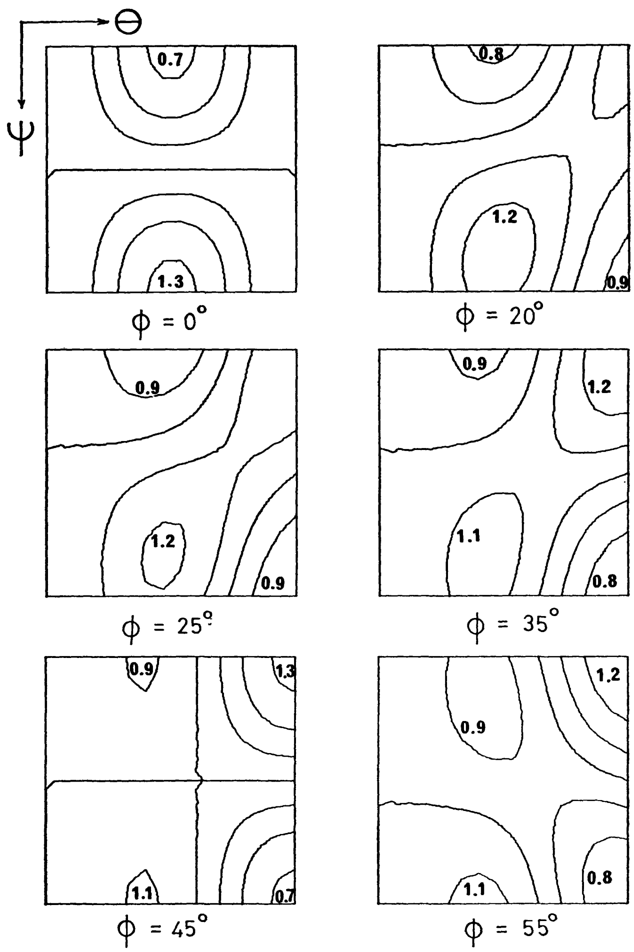

FIGURE 4 The crystallite orientation distribution function for the W_{000} and W_{420} coefficients alone, for rimmed steel rolled 60% and annealed.

⟨001⟩. These orientations, if present, will cause the "two ear" phenomenon. Figure 5 shows that the major orientations contributing to the "four ear" phenomenon are those with ⟨001⟩ parallel to the rolling direction, in particular the cube texture, {100} ⟨010⟩. Since these include {110} ⟨001⟩, and cube texture is not present to any great extent in the steel, it is clear that the amount of orientations close to {110} ⟨001⟩ is going to control the extent to which earing occurs on deep drawing in rimming steel.

The levels of contours for the peak orientations in Figure 3 should be made as large as possible for W_{400} to be large and if good drawability is to be achieved. This will be a result of *normal anisotropy* and hence will involve the preferred alignment of plane normals. {111}-planes are most conducive to favourable drawability. {110}-planes give good drawability while {100}-planes will give the minimum drawing performance. From Figures 4 and 5 it can be seen that W_{420} and W_{440} should be minimised as far as possible to avoid earing. This involves *planar anisotropy* the extent of which will be determined by the degree of alignment of crystallographic directions. Orientations with ⟨100⟩ in the rolling direction should be eliminated as far as possible. In addition the amount of the {100} ⟨011⟩ component should be increased in order to reduce W_{440} and get a reduction in ear height, but this would decrease the value of W_{400}.

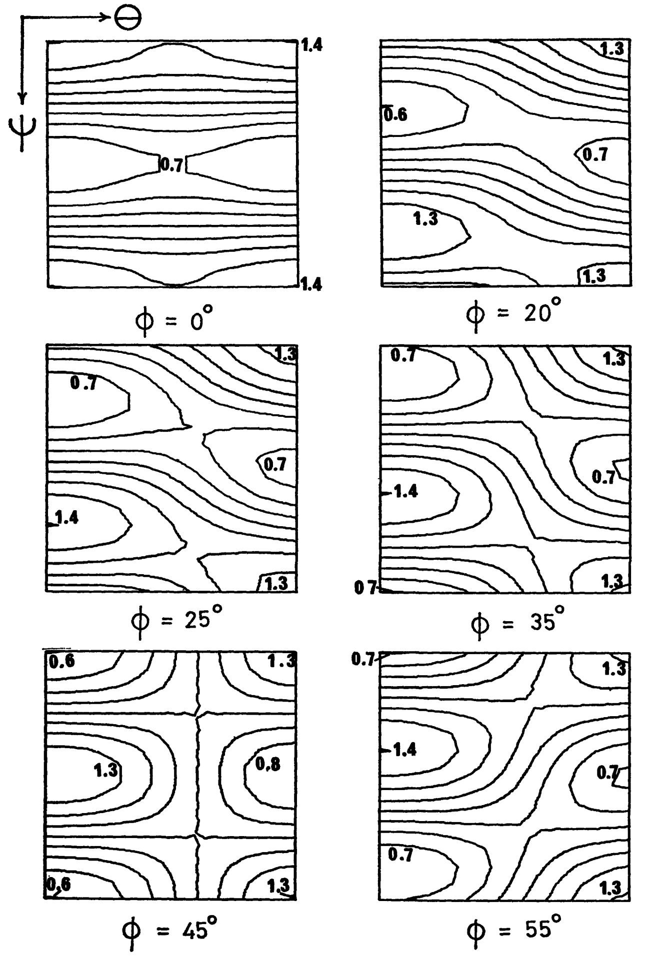

FIGURE 5 The crystallite orientation distribution function for the W_{000} and W_{440} coefficients alone, for rimmed steel rolled 60% and annealed.

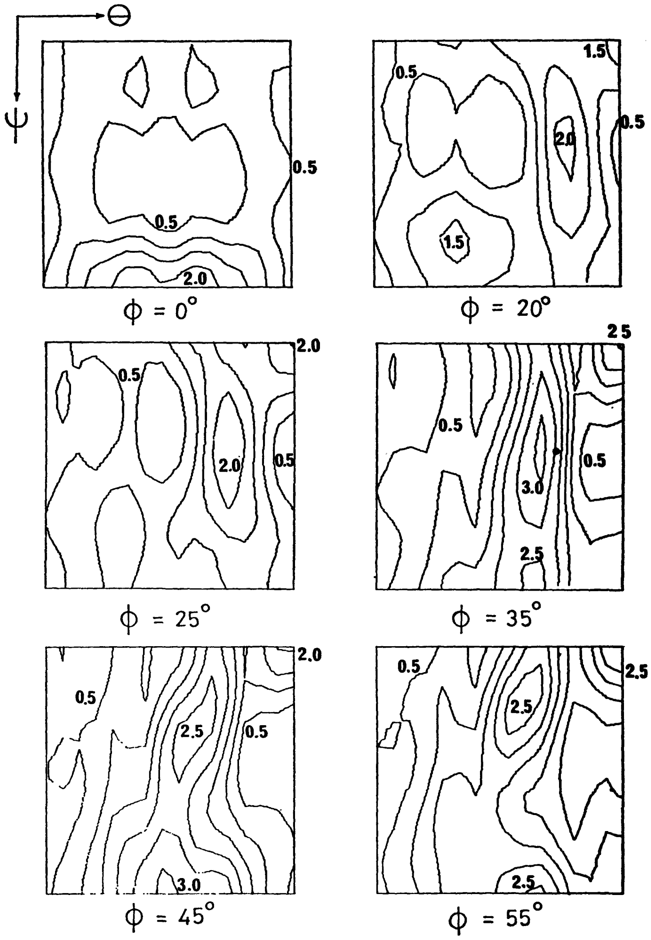

FIGURE 6 The crystallite orientation distribution function for rimmed steel cold rolled 60% and annealed.

Variations in the Cold-Rolled Texture of Rimming Steel Produced by Manipulation of the Texture Coefficients

Constant-ϕ sections of the crystallite orientation distribution function for the sample of rimmed steel cold rolled 60% and annealed involving all coefficients up to twentieth order are presented in Figure 6. Setting W_{420} to zero produces the new set of constant ϕ-sections given in Figure 7. Likewise, W_{440} is set to zero in Figure 8, and both W_{420} and W_{440} are zero in Figure 9.

Removing W_{420} measurably affects orientations close to {110} ⟨001⟩ (including {320} ⟨001⟩), as does the removal of W_{440}. This latter coefficient affects all orientations of the form $\{hkl\}$ ⟨001⟩.

Setting both W_{420} and W_{440} to zero has an even more marked effect. Figure 9 represents the hypothetical texture of the rimmed steel which would produce the same level of deep drawability as the experimental sample (same average plastic strain ratio) but without a significant earing tendency. It is worth noting that an improvement effected by making W_{440} zero by slightly increasing the proportion of {100} ⟨011⟩ would lower the overall level of performance by reducing *r*. Some compromise would therefore seem to be inevitable in practice.

Variations in Plastic Anisotropy of Rimming Steel Produced by Manipulation of the Texture Coefficients

Figure 10 shows the predicted variation of the plastic strain ratio, *r*, with angle from the rolling direction using coefficients up to the fourteenth order,

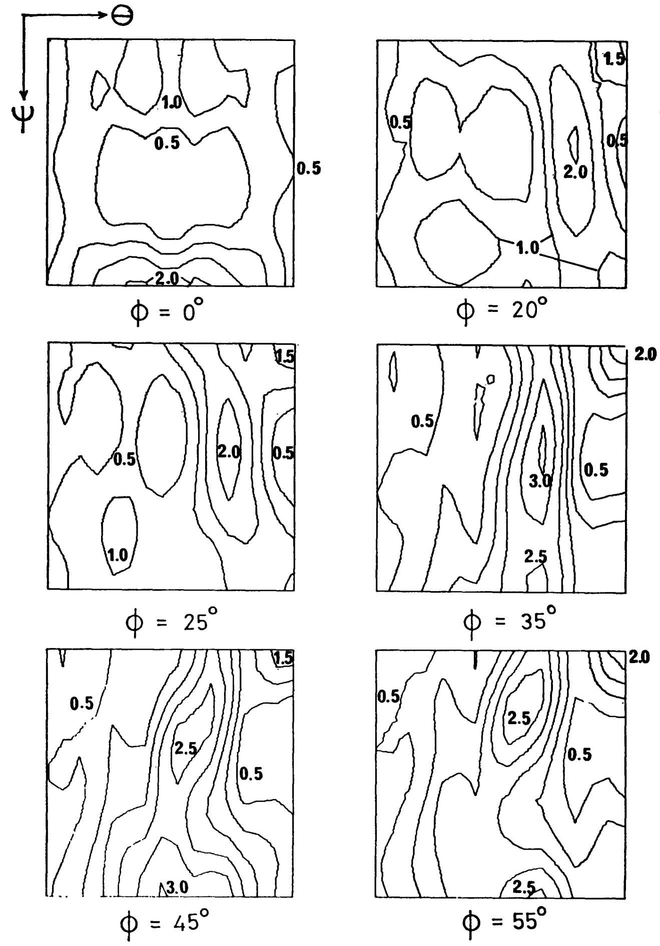

FIGURE 7 The crystallite orientation distribution function for rimmed steel cold rolled 60% and annealed with the W_{420} coefficient set to zero.

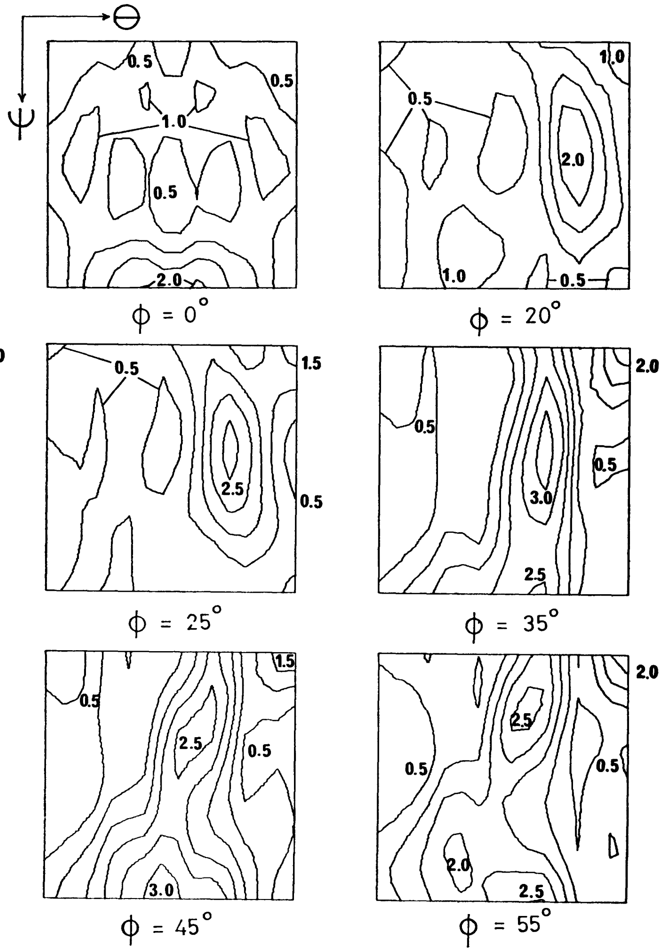

FIGURE 8 The crystallite orientation distribution function for rimmed steel cold rolled 60% and annealed with the W_{440} coefficient set to zero.

for the various cases considered above. The unmodified curve exhibits considerable planar anisotropy, the r-value in the transverse direction being greater than that in the rolling direction. The results agree fairly well with the expected behaviour from similar steels.[24] Removing W_{420} means that W_{440} alone controls the earing behaviour. This correlated well with the observed form of the predicted planar anisotropy. W_{440} is seen to have the greatest influence on r. When both W_{420} and W_{440} are set to zero almost no planar anisotropy is predicted. This latter observation is further confirmation of the predominance of the fourth order coefficients in determining the plastic anisotropy.

The data of this and of the preceding section can readily be combined to define the developments to be aimed for to produce steels of high drawability with low earing tendency.

Applications to Killed Steel

Figure 11 shows the variation in the W_{400}, W_{420} and W_{440} coefficients for the killed steel reduced by varying amounts and annealed. Comparison with Figure 1 shows that the overall variations are quite similar in rimmed and killed steels. The much larger W_{400} values, however, reflect the superior drawability of killed steel. The variation of W_{400} with cold reduction agreed well with the variation of average strain ratio obtained by Held[25] for a killed steel given a series of reductions prior to annealing under similar rolling conditions, viz.:

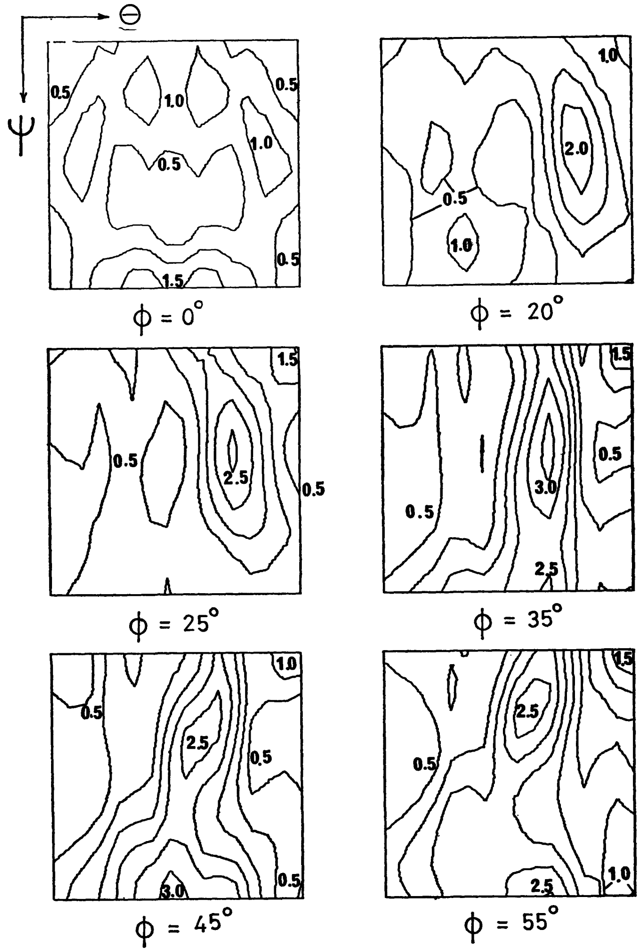

FIGURE 9 The crystallite orientation distribution function for rimmed steel cold rolled 60% and annealed with both the W_{420} and W_{440} coefficients set to zero.

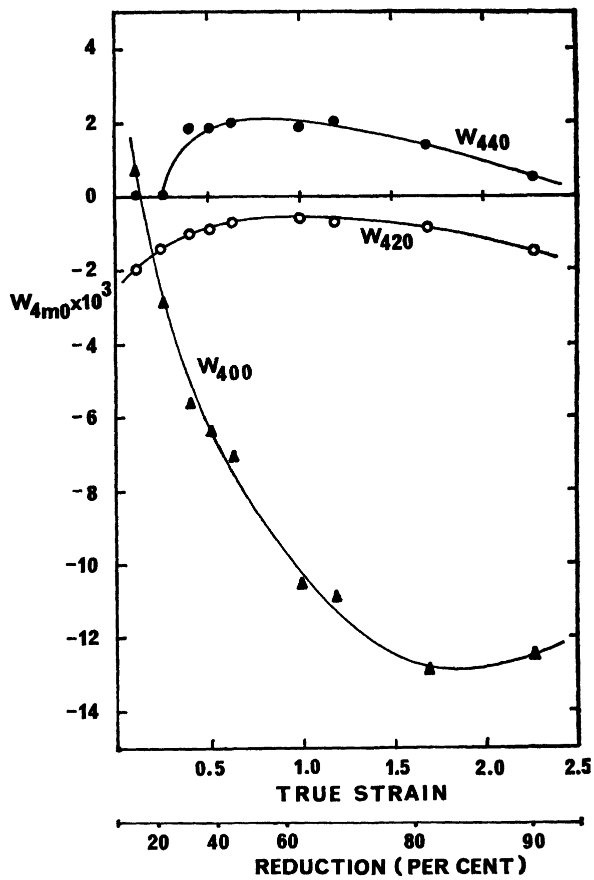

FIGURE 11 The variation of the W_{4m0} texture coefficients with rolling reduction prior to annealing for the killed steel.

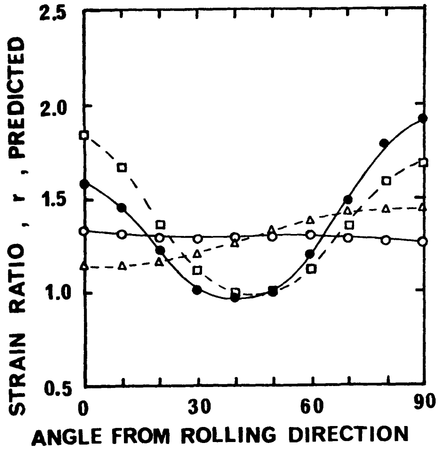

FIGURE 10 The predicted angular variation of the plastic strain ratio for the texture data of Figures 6, 7, 8, and 9.

● predicted from experimental texture data.
□ as● with $W_{420} = 0$.
△ as● with $W_{440} = 0$.
○ as● with W_{420} and $W_{440} = 0$.

good lubrication and heavy reductions on each pass.

Figure 12† shows the variation in ear height with rolling reduction for an aluminium stabilised steel similar to the one used to derive Figure 11. This is similar to Figure 2 for the rimmed steel. In general aluminium stabilised steel shows a greater degree of earing than rimming steel but this effect is not shown between the curves presented in Figures 2 and 12.[24] Usually the lower critical cold reduction for zero earing is less for the killed steel than the rimmed, and the upper critical reduction higher.

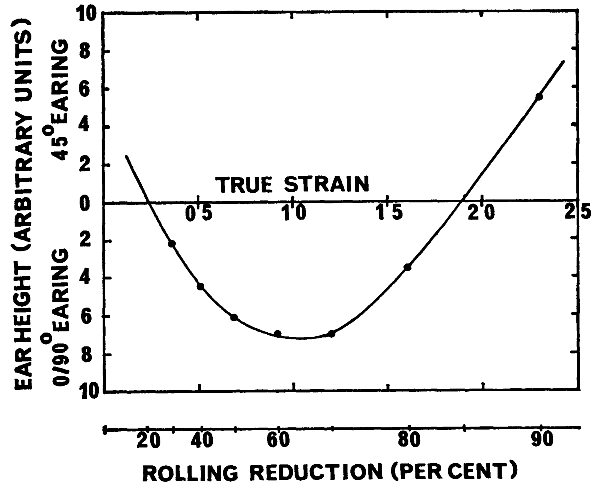

FIGURE 12 The variation in ear height with rolling reduction for an aluminium stabilised steel similar to the one used to derive Fig. 11.

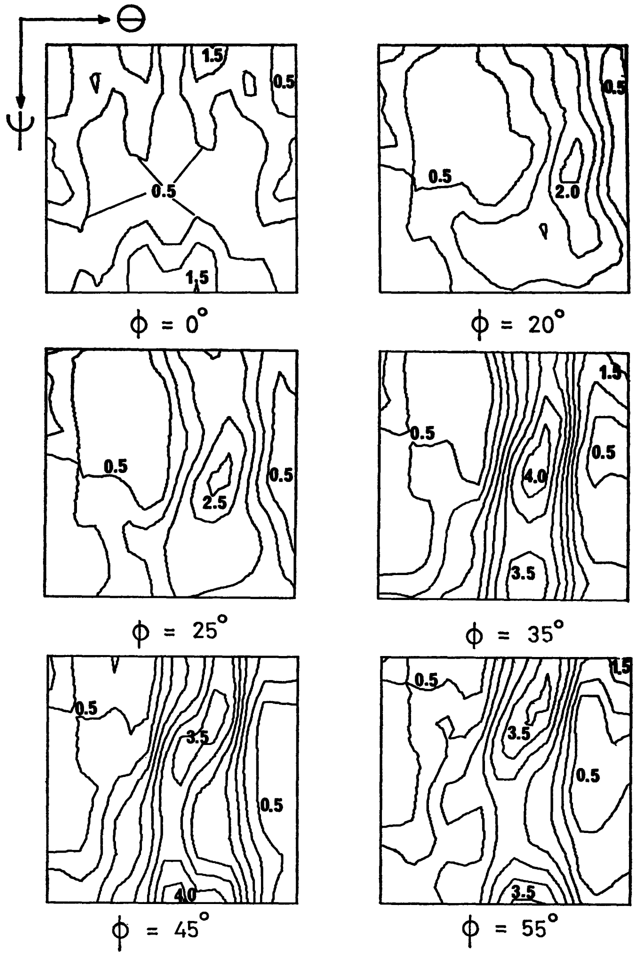

FIGURE 13 The crystallite orientation distribution function for killed steel cold-rolled 40% and annealed.

Examination of the crystallite orientation distribution function for killed steel reduced by 40% and annealed (Figure 13) shows that the components described above which contribute to W_{420} and W_{440} are present. A specimen of killed steel cold rolled 40% prior to annealing was chosen since this treatment produced a similar overall level of texture severity as that of the rimmed steel cold rolled 60% and annealed (Figure 6). It can thus be deduced that the steps necessary to reduce the earing tendency in this steel are the same as those for the rimming steel.

CONCLUSIONS

1) W_{400} is the single texture coefficient obtained from spherical harmonic analysis of texture data for commercial steels which most affects the overall normal anisotropy and drawing performance. W_{420} and W_{440} control the planar anisotropy and earing behaviour.

2) Components with {111}-planes in the plane of the sheet will produce the optimum normal anisotropy and associated maximum drawability. {110} ⟨*uvw*⟩ will have a deleterious effect.

3) The magnitudes of W_{420} and W_{440} are decided largely by the proportion of {*hkl*} ⟨001⟩ components present.

4) To improve the earing behaviour some compromise with the overall drawability is necessary. Increasing the proportion of {100} ⟨011⟩ will improve earing behaviour but reduce the drawability. However, reducing components near {110}

†Data supplied by R. C. Hudd, British Steel Corporation, Strip Mills Division.

⟨001⟩ in steels should not significantly affect the drawability but is expected to reduce earing considerably.

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