Calculation of Lankford coefficient from orientation distribution function and modelling of forming limit diagram using Marcniak-Kuczynski hypothesis of geometric instability

A Kanni Raj*
Department of Mechanical Engineering, The Indian Engineering College, Raja Nagar, Vadakangulam 627 116, India

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Complex stampings are developed with the aid of data obtained from laboratory tensile test and average plastic strain ratio that enables the press formability of sheet metals to be reliably predicted. Formability is best assessed by Hecker’s method of punch stretching and drawing the forming limit diagrams. Analytically, the forming limit diagrams are modeled by geometric instability analyses based on Marciniak & Kuczynski with a high degree of accuracy. Also, texture analysis is used to get average plastic anisotropic ratio input parameter to the above model. This analysis provided orientation distribution function which is in turn used to calculate average plastic anisotropic ratio. The data from texture and others experiments, such as tensile test, roughness measurement and density measurement are used in the analytical model to get forming limit diagrams. The theoretical forming limit diagrams obtained show significant departure from the experimentally evaluated ones only in plain strain condition.

Keywords: Orientation distribution function (ODF), Aluminium killed extra deep drawing (AK-EDD) steel sheet, Forming limit diagram (FLD), Texture, Formability, Instability, Anisotropy

The development of a single parameter which can comprehensively describe the forming characteristics of a material under various conditions in actual press working is made difficult because of complex interactions of large number of variables which affect the formability of sheet metals. Although the quest for such a parameter has proved to be elusive, efforts in that direction remain unremitting. So, the complex stampings required for today’s automotive and other industries are now developed with the aid of forming limit diagrams. Its construction is laborious because of the interaction all variables. In forming a sheet into a specific shape, the design variables, e.g., punch diameter, die radius, draw bead geometry, etc are fixed. The process variables, e.g., mode of stretching, the strain path, pre-stain, lubrication, etc are assessed during tryout in shop floor manufacture and are optimized to yield maximum production rates at minimum cost. The full exploitation of material ductility is dependent on the material properties. Most sheet forming operations can be qualitatively categorized as drawing, stretching or a combination of the two operations in varying degrees.

Testing of fundamental mechanical properties and testing of forming properties by simulating forming operations under laboratory controlled condition have been the two conventional, complementary methods of evaluating the overall forming characteristics of sheet metals. Properties such as hardness and tensile properties fall into the first category while forming tests such as Swift flat bottom cup test and Erichsen cup test come under the second group. To overcome the lack of a high degree of reproducibility and amenability of the tests for a reliable and direct correlation with press performance, new innovative tests have been periodically proposed. However, none of these simulative tests independently give a reliable and comprehensive formability index for a stamping in which several types of forming operations are involved. In Hecker’s greatly simplified formability testing, rectangular specimens of various widths were stretched to failure using a single punch-die assembly provided with a draw bead. This helps to obtain various combinations of strain ratios corresponding to a spectrum of stress states. The forming limit diagrams thus obtained were found to be independent of interface friction and specimen orientation. This method has since gained wide acceptance in

*E-mail: akanniraj@gmail.com
sheet metal research and industry for assessing formability.$^4,^7$

The forming limit diagram can be generated using tension test data and tool design data. The models so far available to predict forming limit includes plastic, shear or geometric instabilities based analysis.$^8,^24$ It is usually modeled by Marciniak-Kuczynski geometric instability based analyses with a high degree of accuracy. Texture analysis can be used to incorporate plastic anisotropy input parameter to the above model. The texture analysis was used to get average plastic anisotropic ratio.$^{25,27}$ The data from texture and others used in Date-Padmanabhan model proposed by modifying Marciniak-Kuczynski analysis to get forming limit diagrams.$^{28-32}$ Orientation distribution function can also be incorporated directly into the model to predict forming limit in future (only it makes the differential equation and its numerical solution tough). Presently, various rigorous numerical models available make research on these area delayed.

**Experimental and Analytical Methods**

**Preliminary tests to assess formability qualitatively**

The relationship between the mechanical properties and forming performance has been studied extensively in many investigations. It is generally agreed that the performance of sheet metal in drawing-type operation is related to normal anisotropy ($\tilde{r}$ value), while the performance in stretch type operation is related to the strain hardening exponent ($n$). The $n^{th}$ product reflects the plane strain forming operation. So, detailed experiments were conducted on the sheet steel to evaluate the above parameters. The selected heat of the steel sheet was first analyzed to get the chemical composition exactly using and advanced spectrometer called Spectrovac Metals Analyser ARL 3460. The optical metallography to get grain size ($d_o$) using the optical micrographs taken in a Leitz Metallovert Microscope and Heyn intercept method. The tensile tests were done on ASTM E8M subsize specimens at a constant crosshead speed of 0.5 mm/min using a 250 kN Schenck Trebel Electro Mechanical Testing Machine. Strain rate jump tensile tests were done on ASTM A370 specimens using the same machine. Lower crosshead speed of 0.1 mm/min was increased by 11 times, i.e., the crosshead speed after jump was 1.1 mm/min. Procedure of Liu and Johnson was adopted in ASTM E517 specimens in a 400 kN Schenck Servo Hydraulic Testing Machine at a crosshead speed of 1.0 mm/min. The specimens were prepared with their tensile axis at 0°, 45° and 90° to the sheet rolling direction. A traveling microscope with a least count of ±0.01 mm was used to measure strain.

**Mathematical basics of orientation distribution function**

As crystallographic texture is a major fundamental property, which affects formability, the texture profiles of the sheets have been analysed using the orientation distribution function techniques. Finally theoretical forming limit diagrams of these heats have been obtained using a model recently developed by Date and Padmanabhan$^{31}$ based on Marciniak-Kuczynski hypothesis for predicting forming limit diagrams and the results have been compared with the experimental ones.

Steel sheets often exhibit pronounced crystallographic textures which influence product quality by causing plastic anisotropy which may be desired or undesired. The control of different textures in steel sheets in general and aluminium-killed drawing quality sheets in particular is an important task during commercial processing particularly hot strip rolling, cold rolling and annealing stages. Good formability behaviour is favoured by the formation of a texture in such a way that during deep drawing, material flow occurs easily in the plane of the sheet but is resisted in the thickness direction of the sheet, i.e., by materials with high $\tilde{r}$ value and low $\Delta r$ value. Both properties can be achieved by a texture that after re-crystallization consists of a homogeneous strong fibre texture with {111} plane parallel to the sheet plane. On the other hand, a high $n$ value (strain hardening exponent) and a high $m$ value (strain rate sensitivity index) are required for stretching applications and this is obtained by controlling the grain size (fine grain size) and the uniform distribution of precipitates.

In the present work, a comprehensive analysis of texture in steel sheets of 0.8 mm thickness by ODF technique was performed and also the $\tilde{r}$ value calculated from ODF coefficients. The $\tilde{r}$ value was used to predict forming limit diagram using a model by Date and Padmanabhan$^{31}$. The resulting theoretical FLD was compared with experimental FLD.

The generalization of orientation distribution function is provided in the following paragraph. According to Bunge, an orientation distribution function (ODF) of a polycrystalline materials may be expressed as a series of generalized spherical harmonics in the form of Eq. (1).
where $g$ is an orientation described by 3 Euler angles $(\Phi_1, \Phi, \Phi_2)$, $C_{\mu\nu}^{l}$ are the series of coefficients and $T_{l}^{\mu\nu}(g)$ are symmetrical spherical harmonic functions. The plastic anisotropy parameter ($\tilde{\sigma}$) was calculated from the experimentally determined coefficients ($C_{\mu\nu}^{l}$) on the basis of Taylor theory using the Bunge, Schulze and Grzerik formulation (Eq. 2).

\[
M(q, \alpha) = \sum_{p=1}^{r} \sum_{l=0}^{L} \sum_{\mu=1}^{N(l)} \sum_{\nu=1}^{N(l)} \frac{1}{2l+1} m_{p}^{\mu\nu} C_{\mu\nu}^{l} \cos(n\alpha) pq^{p+1}
\]

where $M(q, \alpha)$ is a geometrical parameter, $m_{p}^{\mu\nu}$ are the Taylor coefficients, $q$ is contraction ratio and $\alpha$ is the angle of the tensile axis with respect to rolling direction. The above equation yields $q = q_{\min}(\alpha)$ which is related to the $\tilde{\sigma}$ value as follows.

\[
\tilde{\sigma} = \frac{q_{\min}(\alpha)}{1 - q_{\min}(\alpha)}
\]

Goniometric measurement of orientation distribution function

A X-ray texture measurements were performed for steel sheets of 0.8 mm thickness at the mid sections parallel to the rolling plane on an automatic texture goniometer fitted with a Siemens D500 diffractometer, using Mo-K$_\alpha$ radiation. For each ground and etched specimen 20 mm × 14 mm, the texture was determined by measuring four incomplete pole figures of the planes $\{110\}$, $\{200\}$, $\{112\}$ and $\{103\}$ using Schulze back reflection technique. For each measurement, the diffracted intensity was recorded continuously every $5^\circ$ along concentric circles in the angular range for $0^\circ$ to $75^\circ$ in steps of $5^\circ$ and subjected to background, geometrical and defocusing corrections using a random specimen of the pressed and sintered iron carbonyl powders. The three dimensional ODF were calculated from the data of four incomplete pole figures following the series expansion method and using the pseudo-normalisation technique. The series was extended up to $l=22$ using even terms only. The texture index, $J$ which determines the mean squares deviation of the ODF from random distribution was also determined in each case. The plastic anisotropy parameter ($\tilde{\sigma}$) was determined in each case, using Bunge’s formulation and the glide modes $\{110\}<111>$, $\{112\}<111>$ and $\{hkl\}<111>$ pencil glides.

Description of a modified Marciniak-Kuczynski model

In this analysis, it is proposed that geometric instability resulting from a loss in cross-section (due to both thickness strain and void growth) and shear bands forming in the material subsequent to bifurcation coexist as the deformation proceeds. Then, apart from geometric instability, shear bands also grow further (in the regions between the growing voids, for example) with deformation. Therefore, the limit strain potential, as predicted by the Marciniak-Kuczynski analysis, would be considerably reduced by the formation and growth of the shear bands. The portions of the groove were shear bands are formed would experience a plan strain condition. This condition would then be present in this region until localisation due to void sheet formation and failure take place. On the other hand, the remaining portion of the groove will experience a stress (and strain) state governed by geometric softening. The predicted limit strain for a combined mode would then comprise strain in the presence of both geometric instability and shear localization. The damage caused by both the modes is assumed to be additive and equal. Figures 1a and 1b show pictorially the presence of surface

![Fig. 1](https://via.placeholder.com/150)

Fig. 1—(a) A pictorial representation of the presence of surface groove as per Marciniak & Kuczynski analysis (no internal voids considered here) and (b) A pictorial representation of cross-sectional inhomogeneity assumed in Date & Padmanaban model (surface roughness as well as internal voids are considered here). SSa and SSb are respectively cross-sectional area in region adjacent to groove and in the groove. 
groove/roughness as per Marciniak-Kucynski analysis and as assumed by Date and Padmanabhan respectively. The later idea was selected for our analysis. (Various equations used in the calculation are listed below, however, rigorous derivations of the equations are omitted.) For predicting the forming limit strains under different strain states the following equations were used.

\[ W(x, y, z) = F(\theta)B(\phi) - G(x, y)H(x, y)Q(x, y, z) = 0 \]

Where

\[ F(\theta) = \frac{\psi(1-\theta)^p + (1+\theta)^p}{\psi(1-\theta)^N + (1+\theta)^N} \]

\[ N = \frac{M}{M-1} \]

\[ \psi = \left( \frac{1}{2 + 2r} \right)^p \]

\[ M = 0.88 + 1.14 \text{ when } r < 1 \]

\[ p = \frac{1}{1+M} \quad M = 2 \text{ when } r > 1 \]

\[ \theta = \frac{d\varepsilon_{2A}}{d\varepsilon_{1A}} \]

\[ B(\phi) = \frac{(1+\phi)^p}{\psi(1-\phi)^p + (1+\phi)^p} \]

\[ \mu = \frac{1}{2[1+\psi]} \]

\[ u = \frac{\psi(1-\theta)^N + (1+\theta)^N}{\theta \zeta} \]

\[ z = \frac{d\varepsilon_A}{d\varepsilon_B} \]

\[ \phi = \frac{d\varepsilon_{2B}}{d\varepsilon_{1B}} = \frac{1}{z} \]

\[ G(x, y) = \left[ \frac{x + \varepsilon_i}{y + \varepsilon_i} \right]^{-m} \]

\[ x = \varepsilon_B - \varepsilon_i \]

\[ \varepsilon_i = \text{instantaneous strain} \]

\[ \varepsilon_A = \text{strain adjacent to groove} \]

\[ \varepsilon_B = \text{strain in the groove} \]

\[ y = \varepsilon_A - \varepsilon_i \]

\[ \beta = 1 \text{ for biaxial stretching} \]

\[ H(x, y) = \frac{1 + k_i e^{k_2(y + \varepsilon_i)}}{1 + k_i e^{k_2(x + \varepsilon_i)}} \]

\[ f_i = \frac{t_{hi}}{t_{Ai}} = \frac{\beta}{t_0[R_o + kd_i \varepsilon_i]} \]

\[ R = \frac{1 + \theta}{\mu} \]

\[ S = \frac{\theta}{\mu} \]

\[ QA(x, y, z) = f_{iA} e^{-Ry} - \frac{\beta}{\psi(1-\phi)^N + (1+\phi)^N} \]

\[ QA(x, y, z) = \frac{f_{iA} e^{-Ry} - \beta}{\psi(1-\phi)^N + (1+\phi)^N} \]

\[ Q(x, y, z) = \frac{f_{iA} e^{-Ry} - \beta}{\psi(1-\phi)^N + (1+\phi)^N} \]

\[ dx = \left( \frac{\partial W}{\partial x} + \frac{\partial W}{\partial y} \right) \]

\[ dz = \left( \frac{\partial W}{\partial x} + \frac{\partial W}{\partial y} \right) \]

This differential equation is also solved using Ruge-Kutta iterative procedure. The step length is determined by the program to maintain the sensitivity of the method. The iterations are stopped and limit strains are said to have been reached when the ratio of the increment of strain outside the groove to the strain increment inside the groove (z) falls below, say, 0.01 indicating the unloading of region A and the concentration of strain in the groove. This is also the
limit strain potential for failure by localized necking alone. For determining the limit strain potential in bulk shear bands, the Hutchinson-Tvergaard equation in plain strain is used, i.e.,

\[ \varepsilon_b = n \left[ 2 \varepsilon_b \coth(\varepsilon_b) - n \right] \quad \ldots \quad (7) \]

where \( \varepsilon_b \) is the bulk instability strain in plain strain condition. Differential equation (5) and (7) on solving provides \( \varepsilon_{1B} \) and \( \varepsilon_{2B} \).

\[ \varepsilon_{1\text{-lim}tr} = \frac{\varepsilon_{1B} + \varepsilon_{2B}}{2} \]
\[ \varepsilon_{2\text{-lim}tr} = \frac{\varepsilon_{2B} + \varepsilon_{b}}{2} \quad \ldots \quad (8) \]

**Parametric inputs to compute forming limits**

The input parameters for the above model are initial void volume fraction \( (k_1) \), void growth rate \( (k_2) \), initial surface roughness \( (R_o) \) and rate of roughening of the sheet \( (k) \), sheet thickness \( (t) \) and grain size \( (d_o) \) in addition to the strain hardening exponent, \( n \); strain rate sensitivity index, \( m \) and average plastic strain ratio, \( \tilde{\dot{\varepsilon}} \). The experiments were conducted to evaluate them. Densities of the specimens before punch stretching deformation and after punch stretching were evaluated using Archmede's principle. Void growth parameters \( (k_1 \text{ and } k_2) \) were calculated. Pertheometer was used to measure the surface roughness of specimens before stretching deformation and after stretching for the determination of parameters \( (R_o \text{ and } k) \). Micrometer was used to get sheet thickness \( (t) \) exactly. Table 1 enumerate the input parameters and their method of evaluation.

**Results and Discussion**

**Chemical composition of aluminium killed extra deep drawing steel sheet**

The chemical composition of the sheet steel used in the present study is provided in Table 2. In addition, the usual ranges for various elements in AK-EDD low carbon steel is also provided so that any discrepancy can be accounted later. In the first look, the carbon content in the heat selected for investigation higher than the usual range and so expected to show poor drawability. Higher \( \tilde{\dot{\varepsilon}} \) value \((\geq 1.6)\) is connected to higher Al and N, lower levels of O, higher C and Mn levels, and effect of processing conditions. Comparing these levels between selected heat and usual EDD steel, it is expected that the present selected heat will be poor in forming performance.

**Orientation distribution function of a extra deep drawing steel sheet**

The contour line representation of ODF of crystallites at the center of the steel sheets of thickness 0.8 mm in constant \( \Phi_1 \) sections is shown in Fig. 2. The most concise, though not complete, representation of the components of these sheets is \( \Phi_2=45^\circ \) sections are presented in Fig. 3. It is evident from Figs 2 and 3 that there are limited tubes of preferred orientations in an orientation space. One of the orientation tubes has its \(<110>\) fibre axis parallel to rolling direction \(<110>||RD\) and stretches from an orientation \{001\}<110> to approximately \{111\}<110>. The second orientation tube has its \(<111>\) fibre axis parallel to normal direction \(<111>||ND\) and runs from \{111\}<110> to \{111\}<112>. The third orientation tube stretches for \{001\}<110> to \{110\}<001> and has its \(<110>\) fibre axis parallel to transverse direction. The orientation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \tilde{\dot{\varepsilon}} ) (ODF data)</th>
<th>( n )</th>
<th>( M )</th>
<th>( d_o(\mu m) )</th>
<th>( t(\mu m) )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( R_o(\mu m) )</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of Measurement</td>
<td>Calculated from ( q )</td>
<td>Tensile Test (Strain Rate Jump)</td>
<td>Optical Metallography</td>
<td>Micrometer (Screw Gauge)</td>
<td>Void growth experiment by density measurement</td>
<td>Void growth experiment by density measurement</td>
<td>Pertheometer</td>
<td>Pertheometer</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2—Chemical composition of AK - EDD low carbon steel sheet**

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Al</th>
<th>N</th>
<th>O</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usual ranges in EDD steel</td>
<td>0.06-0.08%</td>
<td>0.04-0.07%</td>
<td>0.0065-0.0095%</td>
<td>&lt;300ppm</td>
<td>0.3-0.4%</td>
<td>Balance</td>
</tr>
<tr>
<td>*Heat studied</td>
<td>0.082%</td>
<td>0.072%</td>
<td>0.0096%</td>
<td>289ppm</td>
<td>0.42%</td>
<td>Balance</td>
</tr>
</tbody>
</table>

*Composition was evaluated using spectrometer
Fig. 2—The contour line representation of orientation distribution function of crystallites at the center of the aluminium-killed extra deep drawing steel sheets of thickness 0.8 mm in constant $\Phi_1$ sections. The polycrystalline texture shows no trend and is random.
densities along the skeleton of the above mentioned 3 tubes were also plotted. It becomes evident from Fig. 2 that the textures in the 0.8 mm thick steel are nearly random. The \( J \) values calculated for 0.8 mm thick sheets were 1.26. The coefficients \( \gamma_{i,j}^{\mu \nu} \) calculated for the steel sheet were used to determine the \( q_{\text{min}}(\alpha) \) curve according to Eq. (2) and \( r(\alpha) \) curve according to Eq. (3) for 3 glide modes \{110\}<111>, \{112\}<111> and \{hkl\}<111> pencil glide. The curve is shown in Fig. 4. The experimentally determined \( r(0^\circ) \), \( r(45^\circ) \) and \( r(90^\circ) \) value for each sheet are also given in Fig. 4 which indicates very good agreement between the theoretically calculated and experimentally determined \( r \) value. It is interesting to observe that the pencil glide \{hkl\}<111> and \{112\}<111> are the favoured modes of deformation in random sheets. It has been shown in literature that increasing contents of carbon and manganese decrease the development of the desired \{111\} texture.

Since the C and Mn levels are greater than the desired ranges in the heat studied, it is expected to result in lower \( r \) value. This is consistent with experimental findings that the heat showed an \( r \) value lower than 1.6 (which is generally expected in the case of EDD steels) and the intensities of \{111\} texture component found in the ODF analysis were low. The ratio of Al/N which is in the optimum range could have been a factor in obtaining high intensity of \{111\} texture development. It was shown that the optimum contents for soluble Al and N should be in the range 0.025-0.040\% and 0.005-0.010\% respectively. Higher \( r \) value is connected to higher Al and N, lower levels of O, higher C and Mn levels, and effect of processing conditions like coiling temperature, degree of cold reduction, annealing temperature and heating rate and degree of austenitisation which have been found to affect the \( r \) value significantly. The chemical compositions for usual EDD steel and heat studied are provided in Table 2.

Material properties for aluminium killed extra deep drawing steel sheet

The input values are given in Table 3. The \( r \) evaluated from texture data and that calculated using experiment is same. So, forming limit curve is same irrespective of \( r \) evaluation methods.

Forming limit diagram for the extra deep drawing steel sheet

A computer programme written in BASIC programming language was used to get the limit...
Table 4—The percent deviation of experimental curve from theoretical curve

<table>
<thead>
<tr>
<th>Minor Strain</th>
<th>-30%</th>
<th>-20%</th>
<th>-10%</th>
<th>0</th>
<th>+10%</th>
<th>+20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per cent shift of the experimental curve above theoretical curve</td>
<td>10%</td>
<td>12%</td>
<td>-13%</td>
<td>19%</td>
<td>17%</td>
<td>15%</td>
</tr>
</tbody>
</table>

strains ($\varepsilon_{1B}$ and $\varepsilon_{2B}$). Forming limit diagram was plotted as per usual procedure and is shown in Fig. 5. The forming limit diagram obtained from the experimental technique is superimposed in this figure for a ready comparison. From the figure, it is observed that the limit strain predicted by the model are considerably lower than those predicted experimentally. Table 4 gives the percent deviation of experimental curve from theoretical curve. The experimental curve is always above in all the three modes (deep drawing, plane strain, and stretching). In case of 0.8 mm thick extra deep drawing aluminium-killed low carbon steel heat, a reasonably good correlation was obtained, especially in the stretching and drawing modes of deformation. However, at plane strain condition, the predicted limit strains differ more than 20% from the experimental data.

In an over all sense, the FLD’s predicted by this analysis for different heats of EDD steels are in the literature and displayed very good correlation with experimental one. Also, it is evident from the literature survey that no single model predicted the FLD’s for all materials within the experimental error limits. But at least one model was suitable for predicting each FLD’s accurately (either within experimental error limits or within limited error). The effects of composition and processing conditions/mode need careful study. When the number of input parameters increased the predictions were in better agreement with experimental results. Experimental parameters are more in recent models and hence the better correlation.

Table 3—Material properties for 0.8 mm thick EDD AK low carbon steel sheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\dot{\varepsilon}$</th>
<th>$n$</th>
<th>$m$</th>
<th>$d_o$, $\mu$m</th>
<th>$T$, mm</th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>$R_o$, $\mu$m</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.19</td>
<td>0.247</td>
<td>0.012</td>
<td>11</td>
<td>0.80</td>
<td>0.002843</td>
<td>4.5832</td>
<td>0.6419</td>
<td>0.0896</td>
</tr>
</tbody>
</table>

$\dot{\varepsilon}$ = 1.19 based on the experiments conducted as per Liu & Johnson’s Procedure

Comment on sheet formability using preliminary formability tests

To achieve higher $\dot{\varepsilon}$ value (i.e., $\geq 1.6$), carbon should be removed from solid solution before coiling (to facilitate recrystallisation during final annealing), but aluminium and nitrogen should be in solution until final cold rolling. It is to meet these requirements when the carbon content is $<0.07\%$. The carbon content in our case is 0.082%. Moreover, in annealing texture the $\{111\}$ component should be very strong but the $\{100\}$ should be very weak or absent. Towards this end and also for eliminating strain ageing and obtaining a pancake (grain) microstructure, the ratio of aluminium to nitrogen should be maintained at about 10. This criterion is also not satisfied in our case (Al/N=7.5%). The average plastic strain ratio ($\dot{\varepsilon}$ = 1.19). So, the $\dot{\varepsilon}$ value is not attractive as concluded above. Plenty of literature available on the significance of strain hardening exponent of formability. It was shown that under biaxial stretching, plastic instability appears in diffuse necking rather than localised necking which is controlled by strain hardening exponent. It was reported that reduction in grain size decreases $n$ value. So, the average strain hardening exponent ($n=0.247$) is higher as expected and shows better stretchability.

Conclusions

The textures in the 0.8 mm thick extra deep drawing steel sheets were nearly random and the orientation elements of $\{110\}$$\parallel$RD, $\{111\}$$\parallel$ND and $\{110\}$$\parallel$ITD fibres were approximately equal in complex strain hardening laws, the use of one or more fitting parameters and direct insertion of ODF into differential equation are employed. Also, the discrepancy can be decreased by considering planar anisotropy ($\Delta\sigma$), dynamic strain hardening, Bauschinger effect and metallurgical inhomogeneities like uneven distribution of inclusions/precipitates/second phase particles, especially strain induced phase changes. Strain induced phase transformation is a major problem as for as metastable autentitic stainless steels analysis.
strength. A very good agreement was observed between the theoretically calculated and experimentally determined average plastic anisotropic ratio values. The pencil glide \{hkl\}<111> and \{112\}<111> are the favoured modes of deformation in random and textured sheets respectively. The 0.8 mm thick extra deep drawing steel sheets had low intensity levels of \{111\} texture components indicating their lower drawing. High intensity of \{111\} is desirable for average plastic anisotropic ratio value. The theoretical forming limit diagrams are obtained using a model designed by Date and Padmanabhan modifying the basic model proposed by Marciniak and Kuczynski. The input parameter for the model includes the average plastic strain ratio values obtained from orientation distribution function. The theoretical forming limit diagrams show significant departure from the experimentally evaluated ones only in the plain strain condition.

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