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INVESTIGATION OF FORMABILITY OF LOW CARBON STEEL SHEETS BY FORMING LIMIT DIAGRAMS[*]

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Abstract– Low carbon steel sheets have many applications in industries, especially in automotive parts, therefore it is necessary to study formability of these steel sheets. Forming limit diagram (FLD) is one of the strong pieces of equipment used to study the formability of sheet metals. In this study, FLDs have been determined experimentally for three grades ST12, ST14, and Interstitial free (IF) by conducting punch-stretching experiments using suitably designed and fabricated tools. Formability observed from FLDs has been correlated with mechanical properties and formability parameters like punch type, punch diameter, friction between punch and sheet, work hardening exponent (n) and plane-anisotropy (r) of the sheets. Results have indicated that forming strains in IF and ST14 steel sheets are higher than ST12 and higher n×r values and thickness are desirable to raise the forming strains. The sheet orientation can be effective and in addition, depends on the strain path .For example, forming limit strains in 45° angles with respect to the rolling direction are less than that for 0° and 90° within the right band of FLDs.

Keywords– Forming limit diagram, formability, r, n values, low carbon steel

1. INTRODUCTION

Knowledge of the formability of sheet metals is critical to the success of sheet forming processes. The r value and the FLD are strong tools used to study the formability of sheet metals. They indicate the capacity of a sheet metal to endure stretching and drawing to its limiting strain values[1]. The *r* value defines the ratio between width and thickness strains in a simple tension test and this provides a comparative measure of sheet thinning ability, where *r* values greater than unity are preferable [1]. FLD provides the limiting in-plane surface strains (major and minor strains) a sheet metal can sustain whilst being formed or from another point of view, FLD is the maximum major principal strains that can be reached in sheet materials at given minor principal strains prior to the onset of localized necking [2]. Past engineering practices have shown the advantages of using FLDs in examining failure potential, which include a good representation of the materials stretchability and easiness when used for trouble shooting. The latter depends on the stress state existing at every point in the sheet and the initial condition of the material. Sheet stretching involves tensile biaxial strain, while for drawing and ironing processes the minor principal strain is compressive. Both modes may operate, each with different limiting strain values, when forming sheet under a punch in a die. In the deep drawing of a cup under a punch, for example, the base is stretched and the wall is drawn. Important to each deformation mode is the processing history of the material [1].

In the past 40 years, the concept of the forming limit diagram (FLD) introduced by Keeler and Backofen [3] and Goodwin [4] has created a significant impact in both academia and industry on how the maximum deformation that a material can withstand during a sheet metal stamping process can be determined. The experimental methods for determining FLDs are well established, from stretching over a

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hemispherical punch [5] or a circular punch with a flat bottom in a Marciniak cup test [6], to bi-axial stretching of Keeler and Backofen [3]. Experimental results of [8,9] showed that changes in strain path during the deformation raise or lower the forming limits which differ from those obtained from linear strain paths [7]. Defining the limits of all the possible strain path combinations in experiments is not only tedious, but also impossible. To address this issue, researchers have explored the possibility to predict the phenomenon numerically.

Parallel to the forming limit diagram, the forming limit stress diagram (FLSD) was proposed by Zhao *et al*. [10]. Their results showed that regardless of the shape of the FLD and the type of pre-strain (linear, bilinear and trilinear straining) imposed, all the FLSDs were almost identical. In contrast, when plotted in strain space the FLD was very sensitive to the type of straining path [7].

Laboratory testing has shown that the FLD is sensitive to lubrication, sheet curvature, thickness [11], previous strain history [12], orientation and finishing temperature of hot rolling [13]. These shift the characteristic V-shaped diagram and so one seeks to benefit from increasing limiting strains by raising the diagram. Material properties also influence the position of the FLD. The intercept made with the major strain axis and the gradients of their sloping sides depend on the n- and r values of a material [2]. Moreover, the previous strain history [11] and sheet thickness [12] appear to have a translatory effect on the FLD. Such influences have either been predicted or are based on extensive testing within the two quadrants of strain. To find the limiting strains experimentally, test pieces are gridded prior to tension tests, strip and disc indentation with a spherical punch, Erichsen tests and bulge forming through circular and elliptical apertures. The user is most interested in the lower line in the scatter band from these tests if splits and weaknesses are not to appear in production panels. The testing process is long and prone to experimental variability and so it is not surprising that there has been much interest in theoretical predictions to the FLD [14]. By admitting sheet orientation, prestrain, thickness and the material r- and n-values, it is shown how these alter the position of the predicted FLDs. This shows, for example, that as a means of controlling formability, n should be high, tensile prestrain should be avoided and 45 sheet orientations may not be preferable [2].

2. EXPERIMENTAL

a) Materials

The materials used in the present investigation are listed in Table 1 along with their compositions. The quality of low carbon steel sheets is divided into four categories[15]:

- Commercial Quality (CQ)
- Drawing Quality (DQ)
- Deep Drawing Quality (DDQ)
- Extra Deep Drawing Quality EDDQ)

ST12, ST14 are Al killed steel sheets with DQ and DDQ and the IF is interstitial free steel sheet with EDDQ.

Table 1. Chemical composition of the materials studied (%Wt)

	%C	%Si	%Mn	%P	%S	%Cu	%Al	%Ti	N(ppm)
ST12	0.039	0.011	0.229	0.006	0.007	0.020	0.054	_	28
ST14	0.035	0.004	0.223	0.006	0.004	0.027	0.057	_	41
IF	0.011	0.009	0.143	0.010	0.011	0.01	0.043	0.048	16

b) Mechanical properties

Tensile tests were carried out using DIN 50114 standard specifications. The specimens were tested along the three directions, with the tensile axis being parallel (0°), diagonal(45°), and perpendicular (90°) to the rolling direction of the sheet, on a 5000 kgf capacity Instron testing machine. The standard tensile properties namely, 0.2% yield stress (YS), ultimate tensile stress (UTS), total elongation and strain hardening exponent (n) were determined from the load–elongation data obtained from these tests. A constant cross head speed of 0.5 mm.min^{-1} was employed in all cases. Three samples were tested in each of the three directions and average values were reported to account for the scatter.

c) Determining n and r value

The n value, or strain hardening exponent, is determined by the slope of the graph of the logarithm of the true stress versus the logarithm of the true strain in the region of the uniform elongation [16]

$$n = \frac{d \ln \sigma_T}{d \ln \varepsilon}$$

The width and length are measured at 5, 7, 9, 11, 13, 15, and 17% elongation. Then, the r value or anisotropy factor is calculated by the average of these values and the assumption of volume constancy ($lwt = l_0 w_0 t_0$) as:

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln({}^{w}\!/_{w_0})}{\ln({}^{t}\!/_{t_0})} = \frac{\ln({}^{w}\!/_{w_0})}{\ln({}^{l_0 w_0}\!/_{lw})}$$

The normal anisotropy (r_m), and the planar anisotropy, or Δr value, can be calculated from the values of r in different directions

$$r_m = \frac{r_0 + 2r_{45^\circ} + r_{90^\circ}}{4} \qquad \Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2}$$

d) Forming limit curves

The FLD was evaluated following Hecker's simplified technique [17]. In this method, the experimental procedure mainly involves three stages—grid marking the sheet specimens, punch-stretching the grid-marked samples to failure or onset of localized necking and measurement of strains.

1. Applying circle grids to the blanks. Many types of circle grid patterns have been used such as; square arrays of contacting or closely spaced noncontacting circle and arrays of overlapping circles. Circles with 5 mm diameters have been found to have a good size and are used in this study. The circle grids can be applied to the blanks by printing, a photographic technique or by electrochemical etching. Figure 1 shows circle grids with 5 mm diameters applied to the blanks by the printing technique in this study.

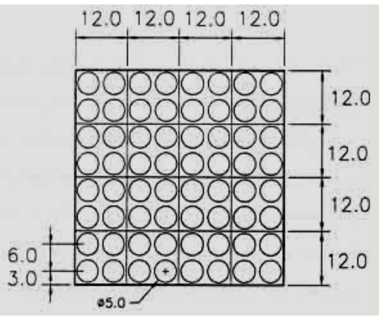

Fig. 1. Circle grids with 5 mm diameters

2. Punch-stretching the grid-marked samples. For determining FLDs, circle-gridded specimens ranging in width from 20 mm to 110 mm with an 80 mm notch diameter, shown in Fig. 2, are used. The specimens clamped in a die ring and stretched to an incipient fracture by a 120 mm diameter steel punch .The narrowest specimen fractures at a minor-to-major strain ratio of about –0.5, is comparable to that obtained in a tensile test. With increasing specimens' width, all states of strains from uniaxial tension to biaxial stretching are achieved [18].

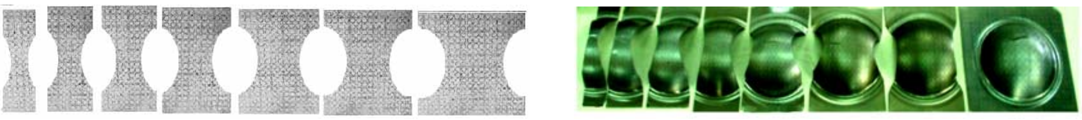
(a) (b)

Fig. 2. Grided specimens, a) before and b) after deformation

3. Measuring strains from deformed circles. Deformed circles were measured by transparent Miller tape[16]. The tapes have a pair of diverging lines graduated to give a direct reading of the strain, as shown in Fig. 3.

When the metal is strained, the original circle with the finite diameter becomes ellipses with two principal strain directions. These directions can be classified by the major and minor axes of strains (Fig. 4). The major axes of resulting ellipses show both the directions and magnitudes of the major strains in the deformed sheet metal surface. The minor axis, which is always perpendicular to the major axis, indicates the magnitude of the minor strain in the sheet metal surface [16].

The strains are measured in and around regions of visible necking and fracture. The forming limit diagram is drawn above the strains measured outside the necked regions and below those measured in the necked and fractured regions, as shown in Fig. 5.

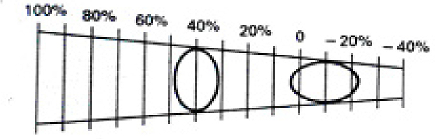

Fig. 3. Transparent tape for measurement of deformed circles

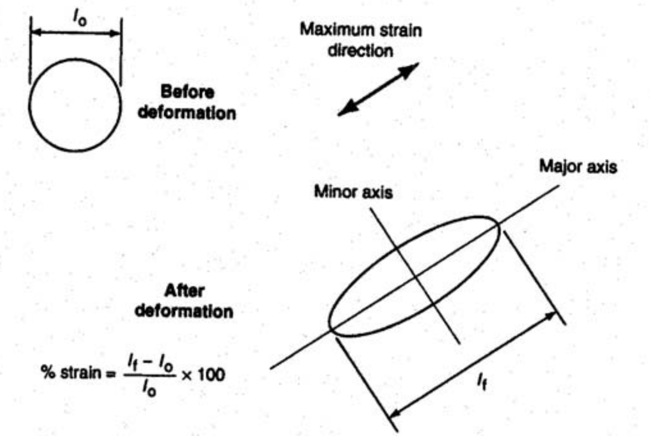

Fig. 4. Major and minor axes of the ellipse that provide the major and minor strain

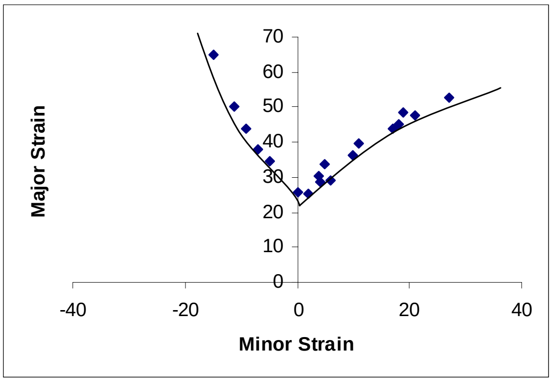

Fig. 5. Forming limit diagram drawn below the necking strain

3. RESULTS

a) Mechanical properties

The room temperature mechanical properties of the three grades, determined by tensile testing, with the specimen axis oriented at 0°, 45°, and 90° to the rolling direction, are reported in Table 2. In most cases, the UTS value was higher at 45° (D) to the rolling direction than in the direction parallel (L) or perpendicular (T) to the rolling direction. While the elongation to fracture was greater along the rolling direction than along directions perpendicular or diagonal to the rolling.

Table 2. Mechanical properties of the materials studied

Specimens	Orientation w.r.t R.D°	UTS (MPa)	YS (MPa)	Total Elongation (%)
	L	312	182	38
ST12	T	319	185	37
	D	318	190	37
	L	300	145	42
ST14	T	297	154	40
	D	307	158	36
	L	292	148	43
IF	T	287	153	41
	D	296	156	38

b) Formability parameters

The conventional parameters of formability such as: the strain hardening exponent n, average plastic strain ratio or normal anisotropy r, the product n×r value and planar anisotropy Δr, for all the grades are summarized in Table 3. The strain hardening exponent n is high (in the range of 0.23–0.24) for St14 and IF grades, indicating their excellent stretchability. Among the three grades, ST12 is expected to possess low formability as is evident from its low n and r values. As given in Table 3, the product n×r which is indicative of overall press performance factor, is high for IF and ST14 steel. As expected, ST12 has the lowest value. However, this factor has no physical significance and it is only a numerical index used as a rough measure of formability. The planar anisotropy value, which gives an idea about the type of earing that occurs during the drawing of sheet metals, is highest in the IF grade, making it the most susceptible to the earing problem among the three grades studied. It is consistent with the fact that a sheet with a high r_m value generally possesses a high Δr value also. It is to be noted that the ideal situation of a high r_m and a low Δr is difficult to achieve under normal processing conditions [19].

Table 3. Formability parameters of the materials studied

	Direction w.r.t R.D	n	r	n×r	$\mathbf{r}_m$	Δr
	L	0.217	1.73	0.375		
ST12	T	0.209	1.88	0.392	1.67	-0.245
	D	0.201	1.54	0.309		
	L	0.233	1.87	0.435		
ST14	T	0.232	2.14	0.496	1.82	-0.515
	D	0.221	1.65	0.3640		
	L	0.24	2.1	0.504		
IF	T	0.246	2.3	0.568	2.03	-0.423
	D	0.231	1.86	0.433		

c) Forming limit curves

A comparison between the experimental forming limit curves for ST12, ST14 and IF steel sheets are shown in Fig. 6. The limit strains in the plane-strain state and the nearby regions for ST12 steel sheet are much lower than those for IF steel, which may be associated with its much higher strength. In general, a higher FLD level means a better formability. Although a rigorous relationship between the FLD level and basic mechanical properties of materials has not yet been set up, it is clear that it depends on the yield and tensile strengths, strain-hardening rate and strain-rate sensitivity.

Conditions of a lower strength level, higher strain-hardening rate and positive strain-rate sensitivity will lead to higher FLD levels. The ST12 steel sheet used in this investigation shows the highest strength level combined with very low total elongation, as well as poor *r*-and n values.

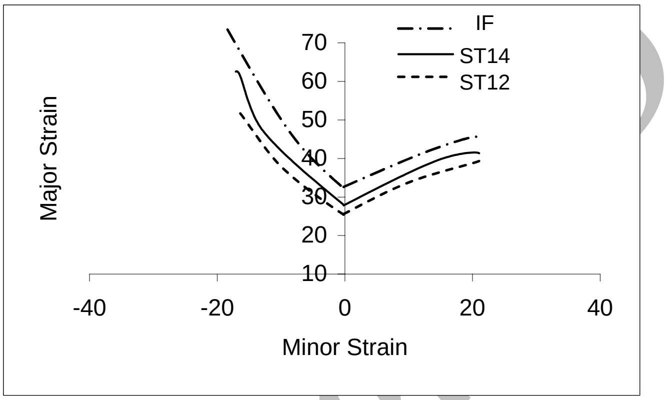

Fig. 6. The experimental forming limit curves of ST12, ST14 and IF steel sheets with thickness of 0.9 mm

1. Influence of sheet thickness. It is commonly believed that the thickness of sheet metal has a strong influence on its formability. Triantafyllidis and Samanta [20], based on experimental and numerical calculations, concluded that if the onset of strain localization is used as the failure criterion, material thickness has little influence. For thin sheets, they predicted that there is no significant difference between the strain corresponding to the onset of localization and the fracture strain. For thick sheets, however, they predicted that strain localization does not proceed rapidly after the onset of localization. Therefore they demonstrated that increase in forming limits with sheet thickness has a higher nearby failure rather than the onset of localization. Figure 7 shows the forming limit curve for low carbon ST14 grade with two thicknesses. With increasing the thickness of the sheets, the forming limit strain is increased.

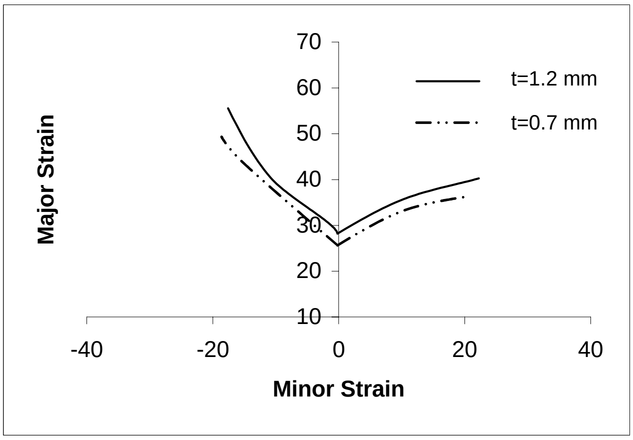

Fig 7. Effect of thickness on the FLD of ST14 steel sheet

2. Influence of lubricant. Some of the steel specimens in the Erichson testing were lubricated with mineral oil and then deformed by an Erichson punch. The effects of lubrication on the FLD of a ST14 steel sheet are shown in Fig. 8. Results show that the cup height is higher because lubrication improves the strain distribution and causes failure at a higher limit strain. Also, lubricant can affect minor strain by changing metal flow from one area of the stamping to another, or by causing the failure location to shift to an area having a different prevailing minor strain. During deformation by means of a rigid punch, the rate of straining near the pole has been shown to decrease on account of restrictions imposed by a combination of geometrical and frictional conditions, causing the deformation region to move toward the edge. As a result, the strain-peak (thinned region) that is developed is moved from a location of positive biaxial strain state (the pole) toward one of plane strain (the edge). By use of lubricant, the deformation region is moved from the location of plane strain stretching toward biaxial stretching [21]. Hecker showed that the slope of cup height –vs- n plot (in the Erichson test) was considerably less for the lubricated tests than that for the dry test. It shows that the dry test is much more sensitive to small variations in material properties [22].

3. Influence of r and n value. Plastic anisotropy rises due to the preferred orientation of grains in a polycrystalline material and is usually characterized by the r value. It is generally recognized that the high r value is useful for improved drawability, but in stretch forming operations, the role of plastic anisotropy is less clear. Theoretical predictions of the effect of the r value on stretch forming limits are conflicting.

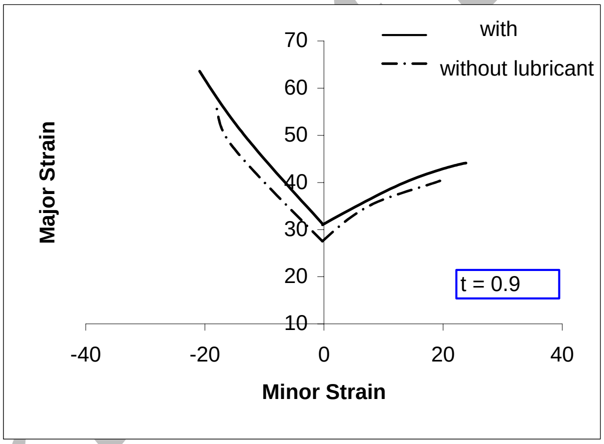

Fig. 8. Influence of lubricant on the FLD of ST14 steel sheet

Using the classical Hill yield criterion, the Marciniak- Kuczynski [23] analysis predicts a significant decrease in stretch forming limits with increasing r value, whereas no influence of r value on stretching limits is predicted when using the Hosford yield criterion [24].

The theory shows that, in the range of (r < 1), a high *r* value would be beneficial to stretching in the right hand side and a low r value beneficial to draw in the left hand side when a working FLD is taken to be constructed from appropriate diffuse and local branch limits [1].

Material properties such as r and n value affect the FLDs. It is impossible to vary one parameter while the other parameters are constant. Therefore, the effect of orientation and n×r value on the FLDs must be considered together.

Figure 9 defines the forming limit diagram (FLD) based upon the onset of diffuse instability. The FLD shows how the limiting strains depend upon the sheet orientation in a manner dictated by the material's *r* and *n* values. A 90˚ orientation provides the greatest limiting strains for stretching (in the right side of the FLD) and the 45˚ orientation gives the least strains. Although in the left side of the diagram, the FLD is bounded by the 90˚ and 45˚ orientations showing improved and worsened formability respectively over a 0˚ orientation, their limiting strains are close together. It follows that a 90˚ orientation is beneficial to stretching operations. In contrast, no benefit is derived from 45° orientation under pure stretching operations. The latter is largely dependent upon the *r* and *n* values of a material. ST14 cold rolled sheets have minimum n×r value at the 45° orientation and maximum n×r value at 90° orientation. The limiting strains increase with increasing the n×r value for this steel sheet (Table 4)

Table 4. Sample orientation versis n×r value

Orientation	r×n
L	0.555
T	0.596
D	0.389

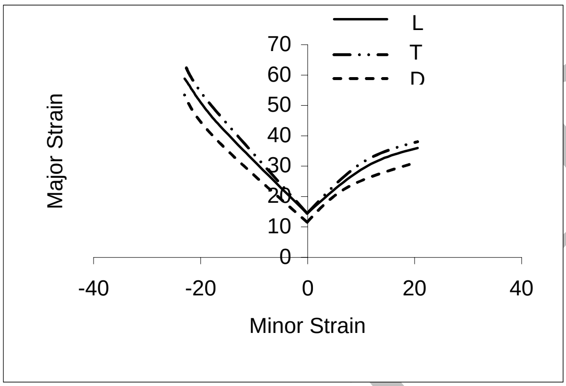

Fig. 9. Influence of orientation and n×r value on the FLD of ST14 steel sheet

4. CONCLUSIONS

Based on the results and discussions presented in the foregoing sections, the following conclusions can be drawn:

1. In most cases, YS and UTS values are somewhat higher at 45° to the rolling direction and elongation to fracture is maximum in the direction of rolling.
2. The r value is maximum at 90° and is minimum at 45° to the rolling direction. ST14 and IF steel sheets have an r value >1.6, which is generally expected in the case of DDQ and EDDQ grade steels.
3. Variation in *r* in the plane of the sheet is a pointer to the dependence of the limiting strains upon orientation of the sheet. A 90° orientation provides the greatest limiting strains for stretching and the 45° orientation gives the least strains. In the left side of the diagram, although the FLD is bounded by the 90° and 45° orientations, their limiting strains are close together. The limiting strains increase with increasing the n×r value for this steel sheet. A 90° orientation has a maximum n×r value and a 45° orientation has a minimum n×r value.
4. Lubrication improves the strain distribution and causes failure at a higher limit strain. Also, lubricant can affect minor strain by changing metal flow from one area of the stamping to another. Therefore, lubrication shift the FLD to the right side and causes the failure location to shift to an area having a different prevailing minor strain
5. With increasing the thickness of the sheets, the forming limit strain increases.

REFERENCES

1. Rees, D. W. A. (2001). Influences of rolling reduction on sheet metal formability. *Proceedings of the I MECH E Part B Journal of Engineering Manufacture, 215*(6), 887-895, Publisher: Professional Engineering Publishing.

2. Ress, D. W. (2001). Factors influencing the forming limit diagram of automotive sheet. *A Journal of Materials Processing Technology, 118*, 1.
3. Keeler, S. P. & Backofen, W. A. (1964). Plastic instability and fracture in sheets stretched over rigid punches. *ASM Trans. Quart. 56*, 25.
4. Goodwin, G. M. (1968). Application of strain analysis to sheet metal forming problems in the press shop. SAE paper No. 680093.
5. Hecker, S. S. (1972). A simple forming limit curve technique and results on aluminum alloys, sheet metal forming and formability. *Proceedings of the 7th Biennial Congress of the International Deep Drawing Research Group*, Amsterdam, 5.1–5.8.
6. Marciniak, Z. & Kuczynski, K. (1967). Limit strains in the processes of stretch-forming sheet metal. *Int. J. Mech. Sci. 9*, 609.
7. Yao, H. & Cao, J. (2002). Prediction of forming limit curves using an anisotropic yield function with prestrain induced backstress. *International Journal of Plasticity, 18*, 1013.
8. Graf, A. & Hosford, W. F. (1993). Calculations of forming limit diagrams for changing strain paths. *Metall. Trans. A 24*, 2497.
9. Graf, A. & Hosford, W. F. (1994). The influence of strain path changes on forming limit diagrams of Al 6111-T4. *Int. J. Mech. Sci. 36*, 897.
10. Zhao, L., Sowerby, R. & Sklad, M. P. (1996). A theoretical and experimental investigation of limit strains in sheet metal forming. *Int. J. Mech. Sci. 38*, 1307–1317.
11. Laukonis, J. A. & Ghosh, K. (1978). Effects of strain path changes on the formability of sheet metals. *Metallurgical Transactions-A, 9*, 1849.
12. Hiam, J. & Lee, A. (1978). Factors influencing the forming-limit curves of sheet steel. *Sheet Metal Ind, 55*, 631.
13. Agababa, J., Ashrafizadeh, F. & Azari, H. N. (2002). Effect of manufacturing parameters on the formability of low –C sheet steel. *Iranian Journal of Science and Technology, Transaction B, 26*(B1), 14.
14. Power, R K. (1997). Orientation and formability of orthotropic sheet metals. Department of Manufacturing and Engineering Systems, Brunel University.
15. Martinez, V. J. & Romano, G. (2001). Optimization of hot-rolled textures through cold rolling and annealing. *materials characterization, 47*, 119.
16. Davis, J. R. (1996). *Carbon and alloy steels*. ASM, Specialty Handbook.
17. Hecker, S. S. (1975). Simple technique for determining forming limit curves. *Sheet Met. Ind., 52*, 671.
18. Hecker, S. S. (1973). Formability of HSLA steel sheets. *Metals Engineering Quarterly, 13*(3), 42-48.
19. Ravi Kumar, D. (2002). Formability analysis of extra-deep drawing steel. *Journal of Materials Processing Technology, 130*, 31.
20. Triantafyllidis, N. & Samanta, S. K. (1986). Bending effects on flow Localization in metallic sheets. *Proc. R. Soc., London, 406*, 205-226.
21. Ghosh, A. K. & Hecker, S. S. (1974). Stretching limits in sheet metals, In-plane versus Out-of plane deformation. *Metallurgical Transactions, 5*, 2162
22. Hecker, S. S. (1974). A cup test for assessing stretchability. *Metals Engineering Quarterly, 14*, 30-36.
23. Marciniak, Z. & Kuczynski, K. (1967). Limit strains in the processes of stretch forming sheet metal. *International Journal of Mechanic Science, 9*, 609.
24. Friedman, P. A. & Pan, J. (2000). Effects of plastic anisotropy and yield criterion on prediction of forming limit curves. *International Journal of Mechanic Science, 42*, 29.