Mathematical Modeling of Sheet Forming Limits with Special Attention to Low Nickel Austenitic Stainless Steels

A. Kanni Raj

Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science & Technology, 400 feet Outer Ring Road, Avadi, Chennai-600062, Tamil Nadu, India

Abstract* - Models based on plastic instability, geometric instability and vertex theory were used to predict forming limits of austentitic stainless steels, with special attention to low nickel grades. Geometric instability predicted well forming limits of AISI 204 Cu (2.5%Ni, 0.42mm thick) sheet due to finest grain size. Bulk shear band formation when added to geometric instability, predicted very well the forming limits in the case of AISI 204 Cu (1.25% Ni, 0.7mm thick) and AISI 204 Cu (1.25%Ni, 0.9mm thick) sheets. Geometric instability model treating β fitting parameter as variable, predicted well forming limits of AISI 204 Cu (2.5% Ni, 1.15mm thick) sheet. Geometric instability model using void growth parameters, correlated well with experimental values for AISI 204 Cu (1.25%Ni, 0.7mm thick) sheet. Geometric instability when combined with bulk shear band formation, β parameter as variable and void growth parameter, predicted well for AISI 304 (8%Ni, 0.5mm thick) sheet, compared to AISI 304 (8%Ni, 1.25mm thick) sheet. The difference is traced mainly to the large difference in n values. Predictions agreed with experiment for models using more inputs, and for some cases, fit was better with approximate versions of geometric instability, instead of the more complete one.

***Keywords:* Formability, Forming Limit Diagram, AISI 204 Cu Stainless Steel, AISI 304 Stainless Steel, Plastic Anisotropy.**

I. INTRODUCTION

Early attempts at theoretically predicting formability were due to diffuse and local plastic instability criteria[1-6]. Next attempt to predict forming limit or flow localization is based on geometric instability criterion. This type of geometric instability based methods proved better than plastic instability based models and provided better estimate of forming limit, and formed basis of most of finite element based forming limit calculations [1-5,7-10]. Vertex theory was good in estimating plain strain condition. This is based on vertex formation on the yield surface due to a velocity discontinuity under continued plastic flow leading finally to flow localization by bifurcation [1-3,8,10-12]. Out of these modeling theories, geometric instability criterion was modified and made more reliable by adding more extra features, such as formation of bulk shear bands during flow localization leading to bifurcation, treating fitting parameter β as a variable, and by using void growth parameters [2,3,7,10,13-15].

All these models were applicable to all types of metallic materials, such as, carbon steels, alloy steels, stainless steels, non-ferrous alloys, super-alloys, welded metals, etc [3]. In this research work, all these theories were applied to low nickel austenitic stainless steels. These steels are falling in AISI 200 series of austenitic stainless steels. These steels contain Cr, Mn, Ni, N, and Cu to stabilize austenitic structure. Ni content ranges from 0-4% and still in austenitic structure due to 5-15%Mn, 1000-1500ppm N and 1-4%Cu. In AISI 200 series stainless steels, AISI 204 Cu stainless steel is used extensively in India, and exported to various countries. Sales and export potentials for these stainless steels are staggering. AISI 204 like AISI 304 finds application in the manufacture of household utensils, bathroom tubs, sinks, modern building decors, sports stadium, train coaches, etc[16]. Its formability is less understood even today and hence experimental works such as room temperature tensile tests, high temperature tensile tests, strain rate sensitivity tests, plastic anisotropy tests, cupping index tests, forming limit diagrams, strain distribution profiles, etc were done to analyze the complete mechanical behavior [17]. Formability of sheets is well presented in forming limit curves generated by punch stretching experiments. Punch stretching experiments uses heavy machinery and involving laborious work. So, modeling sheet forming limit curves were done to assess formability of low nickel stainless steel. All aforesaid theories and models were applied [14].

II. MATERIALS & METHOD

All paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified. Plastic instability set in when the load reaches a maximum in plane strain condition (Case 1) [1-6]. Flow localisation based on geometric instability gave better estimate of forming limits. Their hypothesis is that the material contains initial thickness inhomogeneity which proceeds from the beginning of biaxial stretching of sheets. An adjustable inhomogeneity parameter takes care of more strain accumulation in surface roughness leading to failure. Magnitude of inhomogeneity parameter depends on the degree of correlation of the theoretically calculated limit strain values with the experimental values. During stretching, the inhomogeneity grows and leads to flow localisation (Case 2) [1-5,7-10]. Vertex theory reported the formation of a vertex on the yield surface due to a velocity discontinuity under continued plastic flow which leads to flow localisation by bifurcation. From this theory, bifurcation and the onset of localised necking are found to occur in power law hardening material (Case 3)[1-3,8,10-12]. All equations concerned to these three theories are in “TABLE I”.

Geometric instability model along with formation of bulk shear bands proposes that as deformation proceeds, geometric instability resulting from a loss in cross section (due to thickness strain, surface roughening and void growth) and the shear bands forming in the material subsequent to bifurcation, coexist. Therefore, the limit strain potential, as predicted by the geometric instability analysis, is considerably reduced by the existence and growth of shear bands which can be analysed using the bifurcation equation. With regard to an increase in surface roughening and void formation with strain, this model incorporates relevant features from an earlier analysis. (“TABLE II” lists all equations used in this theory). Numerical calculations can be based on two different methods [2,3,7,10,13-15].

Method A: The predicted limit strains for all strain paths are taken as the average of the limit strain potentials of the destabilising modes (obtained as equivalent geometric and bulk shear band formation strains). This is in view of the assumption that each of the two modes of instability contributes half its limit strain potential to the total strain.

Method B: For plane strain condition, shear instability strain determined using the bulk shear band formation equation is taken as the limit strain and Method A is followed for the positive and negative strain ratios.

The model recommends Method A for materials with ř>1 and Method B for those with ř<1.00. The input parameters involved in the calculations are average plastic strain ratio (ř), tensile properties-strain hardening exponent (n) and strain rate sensitivity index (m), roughness parameters-initial surface roughness (R_0) and rate of growth of roughness (k), initial grain size (d_0) and void growth parameters-initial void volume fraction (k_1) and rate of void growth (k_2). For predicting the forming limit strains under different strain states used many equations (Case 4) [2,3,7,10,13-15].

Some new possibilities are tried in this work vide equations found in “TABLE III”. In one new possible option, Method A is used along with β as variable. (The inherent assumption here is that the above relationship is valid for all materials (Case 5). In the another possibility, Method A is used along with the following modified Avrami equation for void growth to take into account the effect of strain /stress state (Case 6). The third possibility is an unified geometric instability approach inwhich Method A is used along β variable and the modified Avrami equation to take into account the effect of strain (stress) state in void growth. This approach pays equal weightage to all available approaches discussed so far in this paper and tries to bring appropriate solution (Case 7) [2,3,7,10,13-15]. The input parameters involved in the calculations were the average plastic strain ratio (ř), the tensile properties of: the strain-hardening exponent (n) and the strain-rate sensitivity index (m), the roughness parameters: initial surface roughness (Ro) and rate of growth of roughness (k), the initial grain size (do) and the void growth parameters: initial void volume fraction (k_1) and rate of void growth (k_2). The details of the measurement of the strain-hardening exponent (the tensile test), the strain-rate sensitivity index (the jump test), the normal anisotropy (the method of Liu and Johnson), the grain size (the linear intercept method), the roughness parameters (measured using a perthometer) and the void growth (density measurements) are given elsewhere [14].

III. Results & Discussion

Chemical compositions (wt%) of the stainless steel sheets considered are given in “TABLE IV”, whilst the material properties used in the calculations are given in “TABLE V”. The results obtained using the geometric instability theory and its refined versions were compared with the predictions of the plastic instability and the vertex theories, and is found in “TABLE VI”. In each plot, corresponding to the given grade, at least one model resulted in the closest fit to the experimental results. Plastic instability estimated the forming limits very conservatively and rather badly in the case of all of the six sheets. (This is because this theory considers only the effect of the strain hardening exponent). Still, this theory is used by some persons because of its simplicity and generality. Geometric instability theory predicts the FLD within the experimental error limits for the AISI 204 Cu (2.5%Ni, 0.42mm thick) sheet. The theory underestimates the FLDs of the other sheets. The finest grain size (d_0) associated with the sheet is responsible for the good prediction as the limit strain in this model varies as ($-d_0^{1/n}$). Also, the very poor prediction in the right hand side of the FLD for the AISI 204 Cu (2.5% Ni, 1.15mm thick) sheet is due to its very high surface roughness as in that region according to the model the limit strain varies as ($-R_0^{1/n}$). Vertex theory predicts all the six FLDs poorly because this theory does not consider plastic anisotropy, strain rate hardening, etc. Still, because of its intrinsic generality, the theory continues to be used by some researchers.

Bulk shear band formation theory along with geometric instability provided better estimate of forming limits. When an attempt is made to include the effect of some important experimental parameters, viz., surface roughness, void growth, sheet thickness, grain size, strain hardening exponent, strain rate sensitivity index and normal anisotropy (planar isotropy is assumed), the predictions of this model are close to the experimental values and are in facttly within the experimental error range in the cases of the AISI 204 Cu (1.25%Ni, 0.7mm thick) sheet and the AISI 204 Cu (1.25%Ni, 0.9mm thick) sheet. (The predicted forming limit deviates by 6% at a minor strain of 15% (biaxial stretching) in the case of the AISI 204 Cu (1.25%Ni, 0.9mm thick) sheet. Under plane strain and deep drawing conditions, the predicted limit strain values for this sheet thickness lay within the experimental error range. In the worst case, a 0.5% negative deviation from the error limit is observed in the deep drawing region.)

TABLE I
PLASTIC AND GEOMETRIC INSTABILITIES AND VERTEX THEORY

	Model	Equations used in calculation
Case1	Plastic Instability	$\varepsilon_1 = \frac{n}{1+\rho}$, $\rho = \frac{\varepsilon_2}{\varepsilon_1}$ (-0.5 <ρ<0), $\varepsilon_1 = \frac{2n(1+\rho+\rho^2)}{(\rho+1)(2\rho^2-\rho+2)}$, $\rho = \frac{\varepsilon_2}{\varepsilon_1}$ (0 <ρ<1)
Case 2	Geometric instability	$f = \frac{t_B}{t_A}$, $\sigma = K(\varepsilon_o + \varepsilon)^n \varepsilon^m$ $\varepsilon_2(-)$region, $\sigma = K\varepsilon^n \acute{\varepsilon}^m$, with ∞ loading, $\rho = \frac{d\varepsilon_2}{d\varepsilon_1} = \frac{\varepsilon_2}{\varepsilon_1}$, And so, $d\acute{\varepsilon}_A^m \varepsilon^n e^{-C\varepsilon_A} = f\varepsilon^n e^{-F\varepsilon_B} d\acute{\varepsilon}_B^m$ Where $C = \sqrt{\frac{3}{2}}\sqrt{\frac{(1+2\check{r})}{(\check{r}+2)(\check{r}+1)}}\left[1+\frac{2\rho_2^2}{(\check{r}+1)}\right]^{-\frac{1}{2}}$, $\rho_2 = \frac{(1-\rho)\sin\varphi\cos\varphi}{\cos^2\varphi+\rho\sin^2\varphi}$, $\varphi = \sigma_1$ and groove direction $F = \sqrt{\frac{3}{2}}\sqrt{\frac{(1+2\check{r})}{(\check{r}+2)(\check{r}+1)}}[1+2(\check{r}+1)\alpha^2]^{-\frac{1}{2}}$, $\rho_2 = \frac{(1-\alpha)\sin\varphi\cos\varphi}{\cos^2\varphi+\alpha\sin^2\varphi}$, $\alpha = \frac{\sigma_2}{\sigma_1}$ $\varepsilon_2(+)$region, $\sigma = K\varepsilon^n$, $\varepsilon = \frac{4n(1-\alpha+\alpha^2)^{\frac{3}{2}}}{(4-3\alpha-3\alpha^2+4\alpha^3)}\left[1-\frac{\beta\left(\frac{kd_o\varepsilon}{t_o}+\frac{R_o}{t_o}\right)}{e^{\left(1-\frac{(1+\alpha)}{2(1-\alpha+\alpha^2)^{\frac{1}{2}}}\varepsilon\right)}}\right]^{\frac{1}{n}}$, ε is related to ε_1 and ε_2 as $\frac{d\varepsilon_1}{(2-\alpha)} = \frac{d\varepsilon_2}{(2\alpha-1)} = -\frac{d\varepsilon_3}{(1+\alpha)} = \frac{d\varepsilon}{2(1-\alpha+\alpha^2)^{\frac{1}{2}}}$
Case 3	Vertex theory	$\varepsilon_1 = \frac{3\rho^2+n(2+\rho)^2}{(1+2\rho)\sqrt{(1+\rho+\rho^2)}}$, $\rho = \frac{\varepsilon_2}{\varepsilon_1}$ (-0.5 <ρ<1)

Thus, the forming limit diagram predicted by the model correlates very well with the experimental forming limit diagrams in the case of both the AISI 204 Cu (1.25% Ni, 0.7mm thick) sheet and AISI 204 Cu (1.25%Ni, 0.9mm thick) sheet. But the model estimates the FLD's relatively poorly in the case of the AISI 204 Cu (2.5%Ni) and the AISI 304 sheets. The main advantage of this model is that the high imperfection sensitivity of the original geometric instability criterion is reduced here since the effects of an alternative mode of failure, i.e., bulk shear band formation, that does not depend on the presence of imperfections has also been included.

Geometric instability model treating β parameter as variable predicts the FLD of the AISI 204 Cu (2.5%Ni, 1.15mm thick) sheet within the error range between minor strains of -2% and 8% and showed a maximum deviation of about 12% at a minor strain of 15%. Also, in other cases too, the predictions of this model are not poor. All in all, the FLDs predicted by this modified form of the geometric instability based model show a good correlation with the experimental FLDs. The better correlation between the experimental and the theoretical FLDs is mainly due to the use of a variable β parameter in whose value a change of one decade can be observed. Geometric instability model using void growth parameters correlated well with experimental values and are in fact within the experimental error range in the case of the AISI 204 Cu (1.25%Ni, 0.7mm thick) sheet. But in all the other cases the errors are more. The predictions differed only slightly from those of the original geometric instability model which reveals the very limited effect of the present level of the stress state on void growth. Geometric instability improved predictions are using bulk shear band formation, β parameter as variable and void growth parameter. It predicts the FLD of the AISI 304 (0.5mm thick) and the AISI 304 (1.25mm thick) sheets with small errors. The error is higher (12%) in the case of the AISI 304 (0.5mm thick) sheet, whilst the prediction is within the experimental error limits in the case of the AISI 304 (1.25mm thick) sheet. The difference is traced mainly to the large difference in the values of the strain hardening exponent. In an overall sense, the FLDs predicted by this analysis show a very good correlation with the experimental FLDs. Thus, in most cases either the this unified approach model or its approximate versions, viz., the original geometric instability model, the modified geometric theory or the one in which only the β parameter or cavitations is treated as a variable dependent on stress (strain) state, are able to predict the experimental FLDs of the six heats fairly accurately. In the worst cases, for the AISI 304 sheets, a maximum error of 12% is seen with the AISI 304 (0.50mm thick) sheets and a maximum error of 6% is encountered in the case of the AISI 304 (1.25mm thick) sheet.

The reason why in some cases the fit is better with approximate versions of the model instead of the more complete one is not clear at this stage.

TABLE II
GEOMETRIC INSTABILITY WITH BULK SHEAR BAND FORMATION (Case 4)

Limit strain for shear band formation is $\varepsilon_b^2 = n[2\varepsilon_b \coth(2\varepsilon_b) - n]$. It is used for determining the limit strain potential in plane strain, and is used along with geometric instability. More general geometric instability equation is accordingly given by $W(x,y,z) = F(\theta)B(\varphi) - G(x,y)H(x,y)Q(x,y,z) = 0$. It is solved using Runge-Kutta iterative procedure to obtain ε_{1A} and $\varepsilon_{2A.}$

$F(\theta) = \frac{\psi(1-\theta)^p + (1+\theta)^p}{[\psi(1-\theta)^N + (1+\theta)^N]^{\frac{1}{M}}}$, $N = \frac{M}{M-1}$, $\psi = \left[\frac{1}{2+2\check{r}}\right]^p$, $p = \frac{1}{1+M}$, $M = 0.88\check{r} + 1.12, \text{when } \check{r} < 1 \ \& \ M = 2, \text{when } \check{r} < 1$

$\theta = \frac{d\varepsilon_{2A}}{d\varepsilon_{1A}}$, $B(\varphi) = \frac{(u\varphi)^p}{\psi(1-\varphi)^p + (1+\varphi)^p}$, $\mu = \frac{1}{2[2(1+\check{r})]^{\frac{1}{M}}}$, $= \frac{\psi(1-\varphi)^N + (1+\varphi)^N}{\theta z}$, $z = \frac{d\varepsilon_A}{d\varepsilon_B}$, $\varphi = \frac{d\varepsilon_{2B}}{d\varepsilon_{1B}}$, $\frac{1}{z} = \frac{\acute{\varepsilon}_B}{\acute{\varepsilon}_A}$, $G(x,y) = \left[\frac{X+\varepsilon_i}{y+\varepsilon_i}\right] z^{-m}$, $x = \varepsilon_B - \varepsilon_i$ and $y = \varepsilon_A - \varepsilon_i$, where ε_i=instantaneous strain, ε_A=strain adjacent to groove, ε_B=strain in the groove.

$H(x,y) = \frac{1+k_1 e^{k_2(y+\varepsilon_i)}}{1+k_1 e^{k_2(x+\varepsilon_i)}}$, $Q(x,y,z) = f_i e^{\left\{(R-S)y - \int \frac{dx}{u[\psi(1-\varphi)^N + (1+\varphi)^N]^{\frac{1}{N}}}\right\}}$, $f_i = \frac{t_{Bi}}{t_{Ai}} = \frac{\beta}{t_o[R_o + kd_o\varepsilon_i]}$, $R = \frac{\left(\frac{1+\theta}{\mu}\right)}{[\psi(1-\varphi)^N + (1+\varphi)^N]^{\frac{1}{N}}}$,

$S = \frac{\left(\frac{\theta}{\mu}\right)}{[\psi(1-\varphi)^N + (1+\varphi)^N]^{\frac{1}{N}}}$, β=1-biaxial stretch. $QA(x,y,z) = \frac{f_i e^{\left\{-Sy - \int \frac{dx}{u[\psi(1-\varphi)^N + (1+\varphi)^N]^{\frac{1}{N}}} - \frac{\beta}{t_o[R_o + kd_o\varepsilon_i]}\right\}}}{e^{\left\{-Ry - \frac{\beta}{t_o[R_o + kd_o\varepsilon_i]}\right\}}}$, QA(x,y,z) is used in place of Q(x,y,z). W(x,y,z)=0 is solved using Runge-Kutta iterative procedure by differentiating with respect to x, y and z and equating to zero, i.e.,

$$F(\theta)\frac{\partial B(\varphi)}{\partial x} - QA(x,y,z)H(x,y)\frac{\partial G(x,y)}{\partial x} - G(x,y)QA(x,y,z)\frac{\partial H(x,y)}{\partial x} - H(x,y)G(x,y)\frac{\partial QA(x,y,z)}{\partial x} = dW = 0$$

Similarly, partial derivatives with respect to y and z are determined. Using these derivatives, and the condition that dW=0 we obtain the differential equation $\frac{dz}{dx} = \frac{-\left(\frac{\partial W}{\partial x} + \frac{\partial W}{\partial y}\right)}{\frac{\partial W}{\partial z}}$. 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. Or, Instability was defined as the point where $\varepsilon_A/\varepsilon_B$ became less than 0.01. The solution of the differential equation of geometric instability and equation for bulk shear band formation provides ε_{1B} and ε_{2B}. Case 4A : For ř>1, If ε_2=0, ε is ε_b & if ε_2=(-/+), ε=ε_{1B} or ε_{2B} & ε_b. Case 4B : For ř<1, All ε_2 regions, ε's is average of ε_{1B} or ε_{2B} and ε_b.

TABLE III
GEOMETRIC INSTABILITY MODELS WITHOUT INITIAL INHOMOGENEITY

	Model	Equations used in calculation
Case 5	Parameter β as variable	$\beta = p\varepsilon^q$, $p = 6912.4\check{r}n^{4.36}k^{3.91}\left(\frac{t_o}{d_o}\right)^{0.687}$, $q = 1.032\check{r}k\left(\frac{t_o}{d_o}\right)^{0.29}$, $\alpha = \frac{\sigma_2}{\sigma_1}$, β is a fitting parameter used in geometric instability model. Instead of constant value, this equation treats β as a variable.
Case 6	Avrami Equation	Void growth, $\frac{\Delta V}{V} = k_1\left(\frac{\varepsilon_2}{\varepsilon_1}\right) + k_2$, Effect of stress (strain) state is taken by this in geometric instability.
Case 7	Geometric instability applied to LNASS	All equations concerned for geometric instability based calculation are used in combination, ie Case 2 - Geometric instability based model, along with Case 4 - Limt strain due to the formation of bulk shear bands $\{\varepsilon_b^2 = n[2\varepsilon_b \coth(2\varepsilon_b) - n]\}$, Case 5 - Treating β parameter as variable ($\beta = p\varepsilon^q$), and Case 6 - Incorporating void growth parameters [$\frac{\Delta V}{V} = k_1\left(\frac{\varepsilon_2}{\varepsilon_1}\right) + k_2$]. Case 7A : For ř>1, FLD in plane strain is $\varepsilon_b(FLD_o)$ and FLD for negative and positive minor strain is given by $\varepsilon_{1(FLD)} = \frac{\varepsilon_{1B} + \varepsilon_b}{2}$, $\varepsilon_{2(FLD)} = \frac{\varepsilon_{2B} + \varepsilon_b}{2}$. Case 7B : For ř<1, FLD data for all minor strain regions is $\varepsilon_{1(FLD)} = \frac{\varepsilon_{1B} + \varepsilon_b}{2}$, $\varepsilon_{2(FLD)} = \frac{\varepsilon_{2B} + \varepsilon_b}{2}$

TABLE IV
CHEMICAL COMPOSITION (in wt.%) OF THE SIX HEATS

Type	Grade	Gauge	C	Cr	Mn	Ni	N	O	Cu	Fe
AISI 204 Cu	1.25%Ni	0.7mm	0.076	14.9	9.19	1.18	0.155	0.046	1.38	73.07
		0.9mm	0.094	14.1	7.21	1.2	0.163	0.045	1.35	75.84
	2.5%Ni	0.42mm	0.098	14.3	9.14	2.57	0.087	0.089	1.22	72.5
		1.15mm	0.069	15.3	8.64	2.5	0.07	0.085	1.23	72.11
AISI 304	8% Ni	0.5mm	0.061	17.8	1.57	8.47	0.015	0.129	0.045	71.91
		1.25mm	0.042	18.5	1.56	9,24	0.017	0.125	0.044	70.47

TABLE V
MATERIAL PROPERTIES (MODEL INPUTS) OF THE SIX HEATS

Type	Grade	Gauge	n	m	ř	k_1	k_2	Ro (mm)	k	do(mm)
AISI 204 Cu	1.25%Ni	0.7mm	0.45	0.015	1.07	0.004	1.5	0.0002	0.0739	0.023
		0.9mm	0.55	0.016	1.01	0.004	1.5	0.0002	0.077	0.025
	2.5% Ni	0.42mm	0.41	0.013	1.15	0.004	1.5	0.0001	0.2238	0.007
		1.15mm	0.5	0.013	0.97	0.004	1.5	0.0022	0.1493	0.02
AISI 304	8% Ni	0.5mm	0.47	0.012	1.09	0.005	2	0.0003	0.2239	0.013
		1.25mm	0.52	0.012	0.96	0.005	2	0.0001	0.1627	0.014

TABLE VI
DEVIATION OF THE PREDICTIONS FROM THE EXPERIMENTAL VALUES

e_1(y-axis) →	Type	Grade	Gauge	(x-axis) ↓e_2	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Percentage deviation of theoretical e_1 from experimental e_1 values for the six sheets under different strain states	AISI 204 Cu	1.25% Ni	0.7mm	e_2 = -10%	-9	+3	-13	-4	+2	-3	+3
				e_2 = 0%	-3	+2	-3	-3	0	-3	0
				e_2 = 10%	-6	-3	-2	-2	+3	-2	+4
			0.9mm	e_2 = -10%	-6	+2	-10	-3	+5	-3	+5
				e_2 = 0%	0	-3	0	0	+7	0	+7
				e_2 = 10%	-1	-3	+3	+4	+10	+4	+11
		2.5%Ni	0.42mm	e_2 = -10%	-28	-2	-30	-22	-17	-21	-17
				e_2 = 0%	-11	-3	-12	-12	-7	-12	-7
				e_2 = 10%	-11	-3	-7	-7	-2	-7	-1
			1.15mm	e_2 = -10%	-13	-6	-16	-10	-4	-9	-5
				e_2 = 0%	-5	-17	-5	-5	0	-5	0
				e_2 = 10%	-6	-17	-3	-2	+5	-1	+6
	AISI 304	1.25% Ni	0.5mm	e_2 = -10%	-21	-13	-24	-17	-10	-15	-8
				e_2 = 0%	-7	-6	-7	-7	-1	-7	-1
				e_2 = 10%	-12	-12	-9	-10	-4	-9	-3
			1.25mm	e_2 = -10%	-10	0	-14	-7	0	-6	0
				e_2 = 0%	-5	-5	-5	-5	+1	-5	+1
				e_2 = 10%	-7	-9	-6	-6	+1d	-6	+2

IV. CONCLUSION

From the present results, the following conclusions could be drawn.

(1) Plastic instability and vertex theories were rather inaccurate for all sheets. At least one model predicted well the forming limits for one sheet.
(2) Geometric instability theory predicted well forming limits of AISI 204 Cu (2.5%Ni, 0.42mm thick) sheet.

This is due to finest grain size (d_0), as the limit strain in this model varies as ($-d_0^{1/n}$).

(3) Bulk shear band formation added to geometric instability predicted very well with the forming limits in the case of AISI 204 Cu (1.2% Ni, 0.7mm thick) and AISI 204 Cu (1.2%Ni, 0.9mm thick) sheets. But the model estimates relatively poorly in the case of the AISI 204 Cu (2.5%Ni) and AISI 304 sheets.

(4) Geometric instability model treating β parameter as variable predicted well forming limits of AISI 204 Cu (2.5% Ni, 1.15mm thick) sheet.

(5) Geometric instability model using void growth parameters correlated well with experimental values for AISI 204 Cu (1.25%Ni, 0.7mm thick) sheet.

(6) Geometric instability using bulk shear band formation, β parameter as variable and void growth parameter predicted well for AISI 304 (0.5mm thick) sheet, compared to AISI 304 (1.25mm thick) sheet. The difference is traced mainly to the large difference in n values.

(7) Predictions agreed with experiment for models using more inputs. For some heats, fit was better with approximate versions of geometric instability instead of the more complete one.

REFERENCES

[1]. Lakshmi, A.A. (2018) : Forming Limit Diagram of AISI 304 Austenitic Stainless Steel at Elevated Temperature: Experimentation and Modelling. Int J Mech Eng Tech, 9, 403–407

[2]. Paul, S.K.; Manikandan, G,; and Verma, R. K. (2013) : Prediction of entire forming limitm diagram from simple tensile material properties. I Mech E : J Strain Anal, 48, 386–394

[3]. Paul, S.K.; and Mishra, S. (2013): Theoretical analysis of strain- and stress-based forming limit diagrams. I Mech E : J Strain Anal, 48, 177-188

[4]. Habibi, M.; Ghazanfari, A,; Assempour, A.; Naghdabadi, R,; and Hashemi, R. (2017) : Determination of Forming Limit Diagram Using Two Modified Finite Element Models AJSR Mech Eng, 48, 141-143

[5]. Slota J & Spisak E (2005) : Comparison of Forming Limit Diagram Models for Drawing Quality (DQ) Steel Sheets. Metallurgija, 44, 249-253

[6]. Domiaty, A.E.; Mourad, A.H.I.; and Bouzid, A.H. (2015) : Modeling of Forming Limit Bands for Strain-Based Failure-Analysis of Ultra-High-Strength Steels. ASME Proc Mater Fab, 6A, 9pages, doi:10.1115/PVP2015-45990

[7]. Gologanu, M.; Comsa, D.S.; and Banabic, D. (2013) : Theoretical Model for Forming Limit Diagram Predictions without Initial Inhomogeneity. AIP Conf Proc, 1532 (2013) 245-253

[8]. Habibi, M.; Hashemi, R.; and Ghazanfari, A. (2016): Forming limit diagrams by including the M–K model in finite element simulation considering the effect of bending. Proc I Mech E - J Mater : Des App, 10pages, https://doi.org/ 10.1177/ 1464420716642258

[9]. Bayat, H. R.; Sarkar, S.; Anantharamaiah, B.; Italiano, F.; Bach, A.; Tharani, S.; Wulfinghoff, S.; and Reese, S.; (2018): Modeling of Forming Limit Bands for Strain-Based Failure-Analysis of Ultra-High-Strength Steels. Metals, 8, ID-00631,1-25

[10]. Jeong, Y.; Pham, M.S.; Iadicola, M.; and Creuziger, A. (2015) : Forming Limit Diagram Predictions Using a Self-Consistent Crystal Plasticity Model: A Parametric Study. Key Eng Mater, 651-653, 193-198

[11]. Li, S.; He, J,; Xia, Z.C.; Zeng, D.; and Hou, B. (2014) : Bifurcation Analysis of Forming Limits for an Orthotropic Sheet Metal. J Manuf Sci Eng, 136, 051005, 1-10

[12]. Paraianu, L.; Comsa, D.S.; Gracio, J.J.; and Banabic, D. (2007) : Modelling of the Forming Limit Diagrams Using the Finite Element Method. Adv Meth Mater Form, 2007, 151-165

[13]. Kanni Raj, A. (2010) : Calculation of Lankford coefficient from orientation distribution function and modelling of forming limit diagram using Marcniak-Kuczynski hypothesis of geometric instability. Ind J Eng Mater Sci, 17, 256-264

[14]. Kanni Raj, A. (2011), Formability, OmniScriptum Publishing, Saarbrucken, Germany

[15]. Chalal, H,; and Meraim, F.A. (2017): Determination of forming limit diagrams based on ductile damage models and necking criteria. Lat Amer J Solid Struct, 2017, 1-17, doi:10.1590/1679-78253481

[16]. Kerr, J.; and Paton, R. (2004): Preliminary investigations of low-nickel stainless steels for structural applications. Proc 10th Int Ferroalloy Cong, 757-880

[17]. Pisano, C.P.C.; Alves, H.J.B.; Oliveira, T.R.; and Schon, C.G. (2017): Comparative investigation of deep drawing formability in austenitic (AISI 321) and in ferritic (DIN 1.4509) stainless steel sheets. Researchgate, https:// www.researchgate.net / publication/ 318311285, 9pages