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DETERMINATION OF THE FORMING LIMIT DIAGRAM OF ZINC ELECTRO-GALVANIZED STEEL SHEETS

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Forming limit curves (FLC) of deep drawing steel sheets have been determined experimentally and calculated on the base of the material tensile properties following the Hill, Swift, Marciniak-Kuczyński and Sing-Rao methods. Only the FLC modeled from a singly linear forming limit stress curve exhibits good consistence with experimental curve. It was established that a linearized limit stress locus describes adequately the actual localized neck conditions for the material chosen in this study. The quantitative X-ray microanalysis of the Fe contents in the sheet surface layer composition was used to determine cracking limit curve (CLC) of electro-galvanized steel sheet. The change in zinc layer (and base sheet metal) thickness was used as a criteria in calculation of the CLC.

Key words: FLC; CLC; strain hardening; plastic anisotropy; electro-galvanizing

Određivanje dijagrama granične deformacije elektrogalvansko pocinčanih čeličnih limova. Krivulje graničnih deformacija (KGD) pri dubokom izvlačenju čeličnih limova su ustrojene eksperimentalno a također su proračunate na temelju svojstava čvrstoće materijala po metodama Hill, Swift, Marciniak-Kuczyński i Sing-Rao. Dobra podudarnost s eksperimentalnom KGD daje jedino KGD dobivena na temelju modela krivulje graničnih deformacija. Utvrđeno je da linearizirano granično naprezanje dovoljno točno opisuje uvjete lokalnog progiba za materijale rabljene u ovom radu. Za određivanje krivulje graničnog prijeloma (KGP) na površini elektrogalvaniziranih cinkom čeličnih limova rabljena je kvantitativna X-zrakama mikroanaliza sadržaja Fe. Izmjene debljine sloja cinka (i osnovnog metala lima) je rabljena kao krivulja za proračun KGP.

Ključne riječi: KGD, KGP, deformacijsko otvrdnjavanje, anizotropija, elektrogalvansko pocinčavanje

INTRODUCTION

Sheet metal forming under multiaxial states of stress, as in sheet metal operations, usually fails by localized necking. The current interest in understanding sheet metal formability has led to several theoretical analyses of localized necking based on different criteria. The localized necking criteria include; a localized shear zone along a direction of zero-extension, materials imperfection, the presence of a vertex on the yield surface and void growth. Localized necking along a direction of zero-extension was originally proposed by Hill, 1952. Hill's theory predicts that the maximum principal strain ε_{1l} prior to localized necking has a magnitude of $\varepsilon_{1L} = n$ at plain strain and increase to $\varepsilon_{1L} = (1+R)n$ for the uniaxial tension deformation of sheet exhibiting normal anisotropy with a plastic anisotropy parameter R, which is defined as a ratio of the width strain to thickness strain of sheet specimen deformed under uniaxial promotes formability in drawing. Strain localization plastic tension. It is well known that the high degree of anisotropy as represented by a large R-value development by local weakness of material was first proposed by Marciniak and Kuczyński [1], as a means of describing localized necking in biaxial stretching. The M-K analysis assumes the presence of material imperfection in the form of a groove. M-K has shown that deformation within groove occurs at a faster rate than the rest of the sheet. The concentration of strain within the groove eventually leads to the plane strain condition within the groove and localized necking. The M-K model is thus able to explain localized necking in biaxial stretching.

Experimental studies of formability of various materials have, however revealed basic differences in behaviour, such as the "brass-type" and the "steel-type", exhibiting respectively, zero and positive dependencies of forming limit on the strain ratio. Calculations of the forming limit diagram (FLD) according to different methods lead to the general conclusion that in the case of steel sheets the value of calculated limit strains were visibly smaller than the experimental results.

For several materials like copper, low carbon steel, and aluminium some authors have proposed assessing the formability of sheet metals based on states of stress rather than state of strain. They constructed the forming limit stress curve (FLSC) by plotting the state of stress at the onset of localized necking in stress space (Figure 1). They found that the FLSC is almost path-independent and can be established, either experimentally or analytically, and

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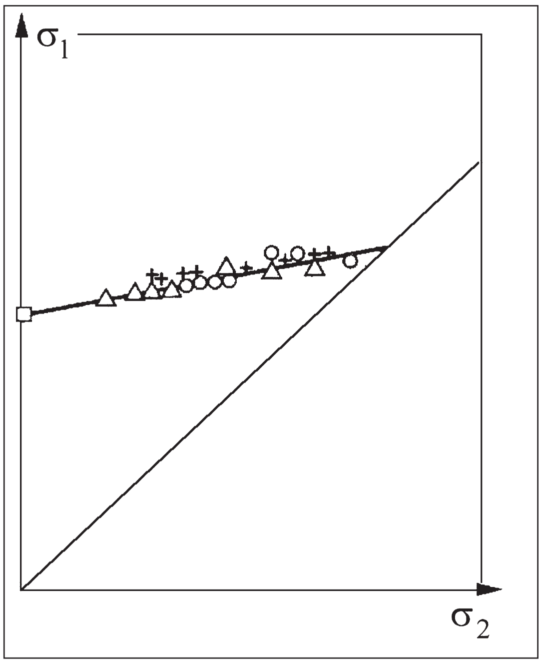

Figure 1 Forming limit stress curve (FLSC)

then the limits to formability will be predicted accurately, not only for proportional loading but also in cases where a sheet element has a complex strain history.

Sing and Rao [2] has proposed a novel approach for the prediction of the FLSC, which is based entirely on material properties readily measured from only tensile test. Starting from the knowledge of a single limit yield stress, a continuous yield locus based on Hill's anisotropic yield criterion could be developed, and, subsequently, a linear limit yield stress state locus could be obtained using the linear regression technique. From this FLSC, the corresponding FLC can, in turn, be deducted using the appropriate strain-hardening law, associated flow rule, and Hill's general criterion.

If the stresses or the stress ratio $\chi = \sigma_2/\sigma_1$ are known, the corresponding strains can be found using the associated flow rule from the following relationship:

$$d\varepsilon_{ij} = \frac{\partial f(\sigma)}{\partial \sigma_{ij}} d\lambda \; ; \; d\lambda = \frac{d\varepsilon_e}{\frac{df(\sigma)}{d\sigma_e}} \qquad (1)$$

where: λ - proportionality factor,

ε_e, σ_e - effective strain and effective stress respectively.

The stress-strain behavior of various materials is commonly represented using the simple Hollomon equation $\sigma = K\varepsilon^n$. For anisotropic materials, the critical strain for localized neck is obtained as

$$\varepsilon_{eL} = \varepsilon_{1L} = (1 + R)\, n \qquad (2)$$

where: ε_{eL}, ε_{1L} - limit effective and major strain respectively,

R - plastic anisotropy factor,

n - strain hardening exponent.

Hence, the resultant localized neck stress for uniaxial tension can be obtained as

$$\sigma_{eL} = K\,(\varepsilon_{1L})^n \qquad (3)$$

where: σ_{eL} - limit effective stress.

According to Hill's yield criterion

$$\sigma_{eL} = \left[\sigma_{1L}^2 + \sigma_{2L}^2 - \left(\frac{2R}{1+R}\right)\sigma_{1L}\sigma_{2L}\right]^{0,5} \qquad (4)$$

where: σ_{1L}, σ_{2L} - limit major and minor stress respectively.

From equation (3)

$$\varepsilon_{eL} = exp\left(\frac{ln\sigma_{eL} - ln K}{n}\right) \qquad (5)$$

where: K - strain hardening coefficient.

For anisotropic sheet the surface strain ratio ρ could be expressed as

$$\rho = \frac{(1+R)\chi - R}{1 + R - R\chi} \qquad (6)$$

and

$$\lambda = \frac{\varepsilon_{eL}}{2(1+R)\sigma_{eL}} \qquad (7)$$

On the base of flow rule and eqs. (4÷7) the surface limit strains for different stress (or strain) ratio could be calculated as

$$\varepsilon_{1L} = [(1 + 2R)\,(\sigma_{1L} - \sigma_{2L}) + (\sigma_{1L} + \sigma_{2L})]\,\lambda$$
$$\varepsilon_{2L} = [-\,(1 + 2R)\,(\sigma_{1L} - \sigma_{2L}) + (\sigma_{1L} + \sigma_{2L})]\,\lambda \qquad (8)$$

The use of coated steel in sheet metal forming is becoming a quite common practice. Coated steel sheets are manufactured according to three processes: electro-galvanized, hot dip galvanized and roller coatings. The application of coated steel sheets in press forming raises three main questions: the formability of the coated sheets, adherence of coating during forming, and the effect of the forming process on the behavior of the coating [3-7].

The two phenomena, cracking and flaking, are successive stages in the damaging of the coating during press forming. They will also have an effect on corrosion resistance. Thus the practical use of pre-coated steel sheets makes it necessary to determine the strain fields within which these phenomena occur.

Cracking and flaking resistance to deformation of pre-coated steel were studied by Arrigoni and Sarracino [8]. The cracking limit curve and flaking limit curve for electro-galvanized (EG) and hot dip galvanized (HDG), were compared by using the FLC of base steel. As far as cracking is concerned, the best performance was that of EG, HDG sheet gave a lower-level curve. The explanation for this lower cracking limit is that hot dipping leaves a brittle iron-zinc alloy layer between zinc coating and steel. Comparing the flaking curves, it became that HDG and EG materials did not flake at all, and their curves were coincident with the FLC.

This paper presents the results of experimental determination and analytical calculation of both the forming limit diagram (FLD) and cracking limit curve (CLC) of electro-galvanized steel sheet by using of a new testing method.

MATERIALS AND MECHANICAL TESTING

The test material for both mechanical testing and FLD determination was 0,8 mm thick electro-galvanized deep drawing quality steel sheet with 7,5 μm thickness of zinc coating. Where the mechanical testing is concerned, tensile specimens of 240 mm gauge length and 20 mm width were prepared from strips cut at 0°, 45° and 90° to the rolling direction of the sheet. The experiments were carried out using a special device which recorded simultaneously the tensile load, the current length and the current width of the specimens. The effective stress - effective strain relationship was described using the Hollomon model. The plastic anisotropy factor *R* has been determined on the base of the relationship between the width strain and thickness strain in the whole range of specimen elongation. The value of the tensile parameters (Table 1) has been averaged according to: $x_{mean} = (x_0 + 2x_{45} + x_{90})/4$: where the subscripts refer to specimen orientation.

Table 1 **Mechanical properties of materials tested**

Spec. orient.	*n*	*K* / MPa	*R*	$R_{p0,2}$ / MPa	R_m / MPa
0°	0,215	580	1,95	190	336
45°	0,212	584	1,44	194	341
90°	0,212	536	2,04	176	308
Mean	0,213	571	1,72	187	329

In the present investigation, the FLD was determined using in-plane stretching test over rigid punch, according to the method proposed by Marciniak et al. [9]. This method is characterised by (i) the elimination of the friction between the specimen and tool surface, which enables realisation of homogeneous straining in the wide region of the sheet tested: and (ii) the retention of the flat surface of the specimen during the straining process, which enables more convenient and more precise measurements of the strain value to be made.

The surface roughness of the materials tested has been measured during step by step deformation by means of a mechanical stylus type profilometer with a tip radius of 5 μm, at the interval of about $\Delta\varepsilon = 0,05$ of applied strain. As it should be expected, the value of the surface roughness parameter R_a increased linearly with strain increasing according to the relation

$$R_a = 0,89 + 3,8\,\varepsilon_e \tag{9}$$

Sheet blanks 250 mm in length and successively narrower width afforded a range of different strain ratios. A circular grid was marked on the sheet surface in the central part of the specimens. The driving blanks were prepared from the same material as the specimens, the central hole in the driving blank is 52 mm in diameter. The test was continued until a crack or necking was visible on the specimen surface, at that moment the test being interrupted. The presence of a few small crack or visible grooves on the gauge area of the deformed specimen's surface confirmed the homogeneous straining of the sheet. The true major strain ε_1 and minor strain ε_2 were measured on the circle adjacent to the crack or visible groove, but not crossing it: this means that the measured circle includes the relatively homogeneously strained area, away from the crack. On the base of these results the FLD was obtained.

A new method of cracking limit curve determination was used in this investigation, basing on the results of X-ray microanalysis of the sheet surface layer composition. It was assumed that deformation of the sheet and especially cracking of the coating should result in the change of the Fe contents in the surface layer composition. The SEM equipped with LINK ISIS system was used to carry-up the experiment.

RESULTS AND DISCUSSION

According to the original Sing-Rao proposition the FLSC could be obtained using the linear regression technique based on the results of calculation using above mentioned scheme taking into account mean plastic anisotropy ratio. However in our calculation we have made some modification taking into account different specimen orientation according to rolling direction and we suggest that this modification (Figure 2) should result in better determination of the FLSC.

On the base of the material tensile testing results the FLC was calculated taking into account four different methods: by Hill, Swift, Marciniak-Kuczyński and Sing-Rao. In the case of M-K method the value of material imperfection coefficient increase with strain increasing and was defined as

$$f = 1 - \frac{R_a}{t} \tag{10}$$

where: R_a - is surface roughness parameter determined according to equation (9),

t - sheet thickness.

The results of experimentally determined and calculated FLCs are summarized in Figure 3. From this presentation it is visible that:

- FLC calculated according to the method proposed by Sing and Rao seemed to be in good correlation with experimental results,

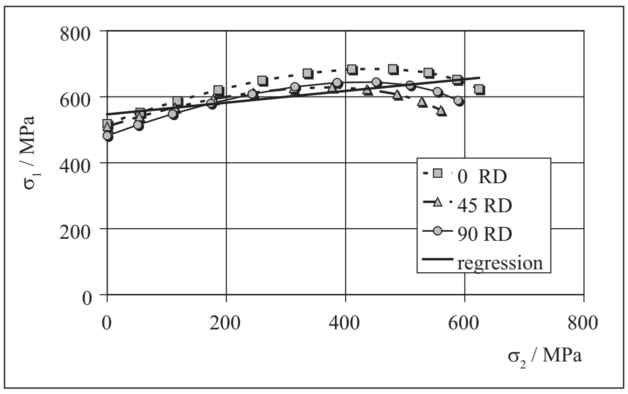

Figure 2 FLSC of deep drawing quality steel sheet obtained on the base of tensile testing results for different specimen orientation according to the rolling direction

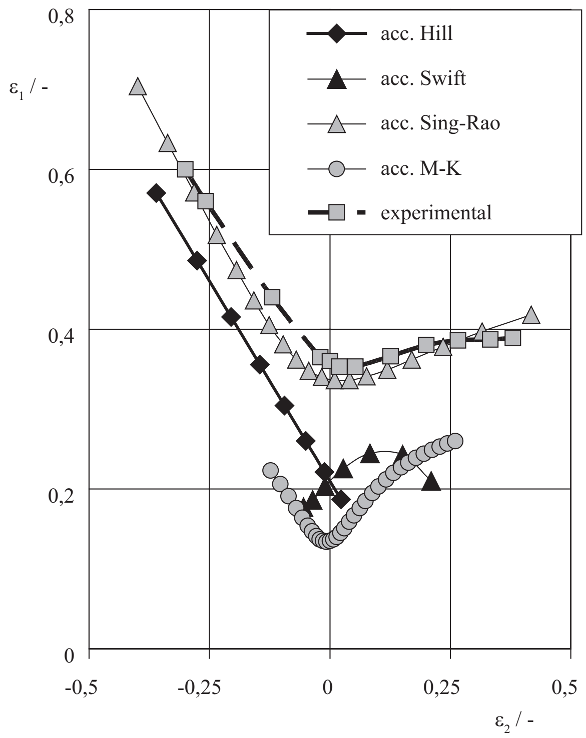

Figure 3 FLCs determined experimentally and calculated according to Sing-Rao, M-K, Hill and Swift methods

- calculation of limit strains according to Hill and Swift methods underestimate the results determined experimentally,
- the worst correlation between calculated and experimental results was obtained in the case of calculation according to M-K method.

Table 2 **Surface and thickness strains at the moment of localized necking of base material and at the moment of zinc-coating cracking**

Strain state	Limit strains of base material		Limit strains of Zn-coated material		*Difference / %*
	ε_{1L}	ε_{3L}	ε_{1L}	ε_{3L}	
Uniaxial tension	0,61	-0,24	0,47	-0,18	25,8
Plane strain	0,35	-0,35	0,26	-0,26	25,7
Equibiaxial stretching	0,40	-0,80	0,31	-0,60	25,0

In the case of all types of specimens (Figure 4) the Fe contents in surface layer increases slowly with the sheet deformation. It may be explained as a result of coating thickening. The X-rays penetrate through the coating to the base material. At some stage of deformation the Fe contents in surface layer composition started to accelerate - this may be explained as a result of the coating cracking.

The strain value corresponding to cracking of the coating is strain state dependent. The cracking appeared at the smallest deformation in the case of plane strain (Figure 4 lower) and in the latest stage of deformation in the case of uniaxial tensile (Figure 4 upper). Strain state dependence of appeared cracking is more evident when plotting The Fe content in surface layer as a function of effective strain (Figure 5).

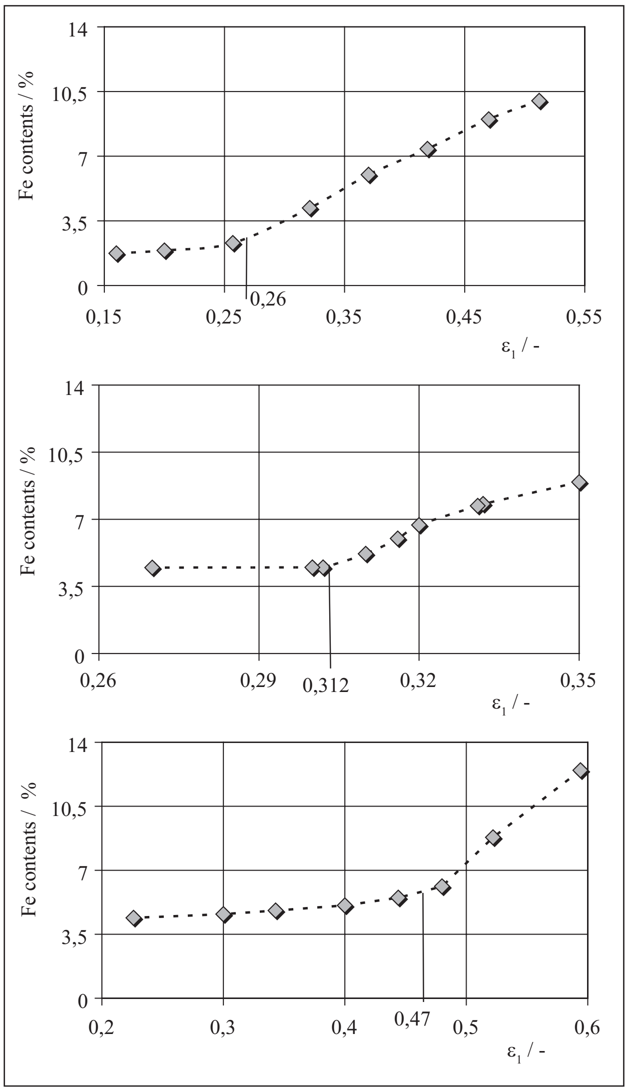

Figure 4 Increase in the Fe contents in surface layer composition with uniaxial (upper), plane strain (middle) and equibiaxial (lower) deformation of zinc coated steel sheet specimen

The results of X-ray analysis of sheet surface layer composition were used in calculation of CLC. It was assumed that the visible decreasing in anti-corrosion abilities of zinc-coatings take place when coating thickness is reduced to a certain, critical value.

Taking into account limit surface strain ε_{1L} and volume constancy of deformed material, the thickness limit strain ε_{3L} for the characteristic strain states could be determined as:

$\varepsilon_{3L} = - \varepsilon_{1L} /(1 + R)$ - for uniaxial tensile,
$\varepsilon_{3L} = - \varepsilon_{1L}$ - for plane strain,
$\varepsilon_{3L} = - 2\varepsilon_{1L}$ - for equibiaxial stretching.

Under assumption that at the beginning of zinc-coating cracking the thickness strain of base material and thickness strain coatings are at the same level, the limit thickness strain at the moment of coating cracking was calculated.

The results of these calculations (Table 2) have shown that the zinc-coatings started to crack when the thickness strains are 25 % smaller than that at the moment of base material localized necking - and this ob-

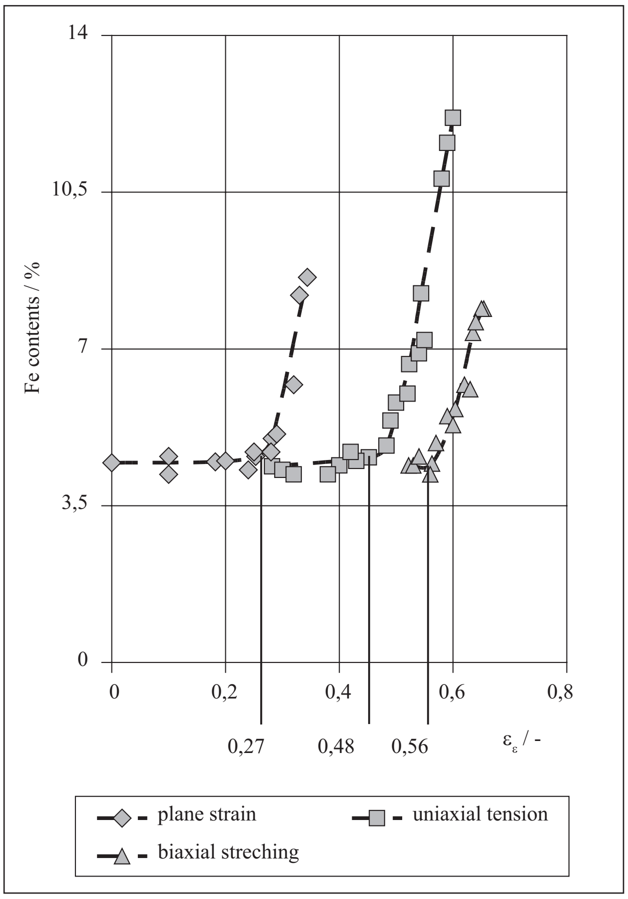

Figure 5 Fe contents in surface layer composition as a function of effective strain

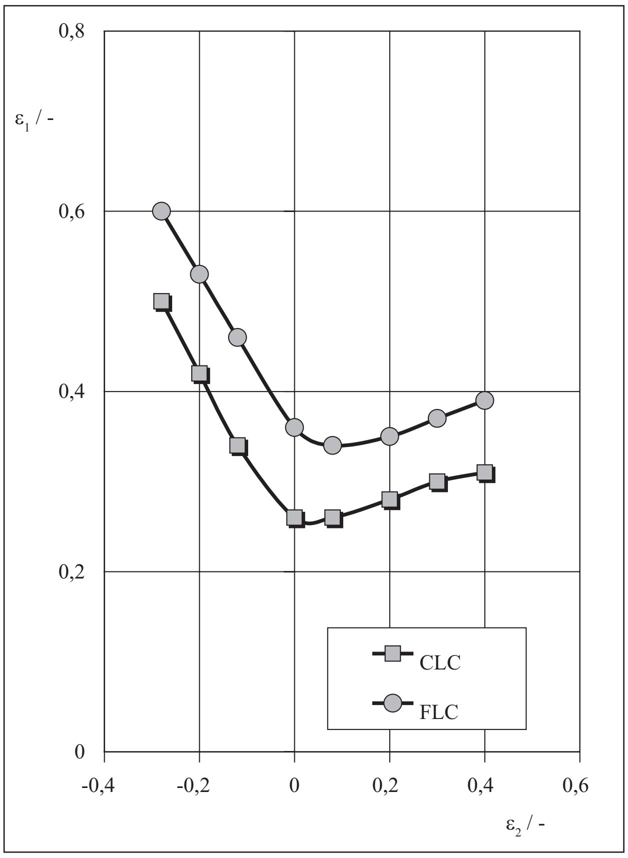

Figure 6 FLC of base material and CLC of coatings of zinc-coated deep drawing quality steel sheet

servation was the base for calculation of the CLC using Sing-Rao method (Figure 6).

CONCLUSIONS

The stress state of localized instability of sheet metal can be represented by a rectilinear FLSC. Such an FLSC can be computed from tensile properties in conjunction with the Hill's yield criterion, Hollomon strain hardening law and associated flow rule. Therefore sheet metal formability can be adequately assessed directly from the tensile properties on the base of a method proposed by Sing and Rao. The FLC of deep drawing quality steel sheet obtained using FLSC matches closely with the experimental curve. The moment when the zinc coating of steel sheet started to crack, i.e. cracking limit curve, may be determined by quantitative microanalysis of the sheet surface layer composition. The CLC differs from FLC of the base material, especially under biaxial stretching. The CLC of zinc-coated deep drawing quality steel sheet could be calculated using Sing-Rao method taking into account the limit thickness strain in the range of 25 %.

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Note: The responsible translator English language is the Lecturer from Rzeszów University of Technology, Rzeszów, Poland.