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FORMABILITY EVALUATION OF LOW-CARBON STEEL STRIP

VYHODNOCENÍ TVÁŘITELNOSTI NÍZKOUHLÍKOVÉ PÁSOVÉ OCELI

Abstract

Contribution concerns formability evaluation of low-carbon steel strip St 4, which is used for production of intricate deep stampings. The properties of sheet-metal which have the principal influence upon the success of deep drawing or strech-forming are described, i. e. directional and mean values of mechanical properties, the values of coefficients of planar anisotropy of mechanical properties, directional and mean values of coefficients of normal plastic anisotropy ratio, directional and mean values of strain-hardening exponents.

From values, evaluated by tensile tests, the forming limit diagram, which comes out from criterion of plastic deformation stability loss at the tensile strength, can be constructed. These diagrams are advantageous for comparison of sheet-metal plastic properties at various stress states or in range of stresses according to the working up technology.

Abstrakt

Příspěvek se týká vyhodnocení tvářitelnosti nízkouhlíkové pásové oceli St 4, která se používá pro výrobu hlubokých výtažků složitých tvarů. Jsou rozebrány vlastnosti plechů, které mají hlavní vliv na úspěšnost hlubokého tažení nebo vypínání, tj. směrové a střední hodnoty mechanických vlastností, hodnoty koeficientů plošné anizotropie mechanických vlastností, směrové a střední hodnoty součinitelů normálové anizotropie, směrové a střední hodnoty exponentů deformačního zpevnění.

Z hodnot zjištěných zkouškami tahem může být sestrojen diagram mezních deformací zkoušeného plechu, a to pro kritérium ztráty stability plastické deformace na mezi pevnosti. Ty-to diagramy jsou výhodné pro porovnání plastických vlastností plechů při různých stavech napjatosti nebo v rozsahu napjatostí daných zvolenou technologií zpracování.

INTRODUCTION

Thin sheets from steel afford a wide scope for shaping and utilisation because of their high rigidity and cold-forming properties. They are therefore widely used in industry for manufacturing the most varied components and products. However, for economic production reliable conditions and limiting values are required.

Formability of sheet metal is dependent on the mechanical properties of the material. Some materials form better than others. A material that has the best formability for one stamping may behave poorly in a stamping of another configuration.

Complex stamping require varying amounts of stretching and drawing, to which bending, unbending, buckling and other complications are added. Most forming operations can be qualitatively, though not quantitatively, categorized as primarily stretching, primarily drawing, or varying ratios of each.

The important material characteristics which determine the forming capacity of sheet metal are strength and ductility. Strength determines the size of the machinery needed for the forming process, while ductility determines the deformation a material can withstand without failure. In forming,

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ductility generally depends on the plastic properties rather than the fracture behaviour of materials, for ductile fracture occurs as a consequence of prior localization of the deformation to form a neck. The plastic properties characterizing ductility are usually obtained from uniaxial tension tests. It is recognized that the tension test does not duplicate sheet forming, but it is believed that the same factors are involved and that a correlation between them exists.

Recent research work in laboratories and press shops has shown that the forming capacity of sheet metal depends primarily on plastic anisotropy ratio *r*, which is the ratio of the strain in the width direction to that in the thickness direction and the strain-hardening exponent *n*. In drawing operations, *r* is of prime importance, while *n* is of lesser importance. In stretch-forming, however, the opposite is true. These two properties can be evaluated using a standard tension testing machine and normal tensile specimens.

The tensile test offers considerable advantages as compared with tests of the simulating type. The latter are always very slow to carry out, and are influenced by numerous technological parameters such as lubrication, surface condition of the sheets and tools, speed of testing, test-piece thickness, etc. Most of these parameters are outside the scope of a production laboratory check.

The strips from steel DC04, which are produced in joint-stock company VSŽ Oceľ, Košice, Slovak Republic, are currently used for deep drawing of intricate stampings in Czech Republic. With respect to changeable properties of separate deliveries of this steel strips, which disgracely influence on the production of stampings, it has been decided to test the suitability of steel strip St 4 from Germany for production of intricate deep stampings. The detailed evaluation of mentioned steel properties was accomplished at Department of Mechanical Technology, Faculty of Mechanical Engineering, VŠB – Technical University of Ostrava.

Suitable choice of sheet-metal during production of stampings must secure as reliable production course as required properties of finished stamping. That is why it is important to know the formability of sheet-metal.

1 SHEETS FROM STEEL St 4 BY DIN 1624

Steel St 4 by DIN 1624 represents especially deep-drawing grade of steel. By cold rolling thin sheets in strips with thickness to 3 mm are produced from it. Steel strips are recrystallizationly annealed with additional light cold re-rolling (version LG by DIN 1624) or with additional finish rolling with the use of greater reductions (versions K32 to K70 by DIN 1624). The technical delivery conditions are determined by DIN 17 010. The strip can be deliveried with four grades and stages of surface, which are marked by DIN 1624 GD (darkly annealed), GBK (glossy annealed), RP (without fissures and pores) and RPG (glossy overglazed). Steel St 4 has guaranteed weldability.

The strips are currently deliveried with guarantee of standardized properties by DIN 1624 (see Tab. 1 and Tab. 2). At killed steels, which the steel St 4 is one of, the mechanical properties are guaranteed for the time of six months from the date of sheets sending from producer.

Tab. 1 Chemical composition of the steel St 4, specified in DIN 1624.

C (wt %)	Si (wt %)	Mn (wt %)	P (wt %)	S (wt %)
max. 0.10	0.03 ÷ 0.10	0.20 ÷ 0.45	max. 0.030	max. 0.035

Tab. 2 Demands on mechanical properties of steel St 4 by DIN 1624.

Tensile strength R_m across the strip (MPa)	Ductility A_{80} across the strip (%)	Deepening by Erichsen *IE* (mm) for thickness 0.80 mm
294 ÷ 392	min. 36	min. 10.45

2 EVALUATION OF PROPERTIES OF STRIP FROM STEEL St 4

For detailed evaluation of properties the coil of sheet-metal from steel St 4 with dimensions 0.80 × 250 mm was chosen, which was deliveried by German firm C. D. Wälzholz with dimensions and limit deviations of strip dimensions by DIN 1541. The steel strip was deliveried in version LG by DIN 1624, i. e. light cold re-rolled, with grade of surface RP by DIN 1624, i. e. without fissures and pores, with edges GK, i. e. with cut off edges.

2.1 The metallography judgment

In order to judge the microstructure of sheet the metallographic samples from thickness of sheet-metal etched by 3 % Nital solution, i. e. 3 % solution of nitric acid HNO_3 (density 1.4 g/cm^3) in ethyl alcohol C_2H_5OH, were carried out. Felt polishing and etching were generally three times repeated. The photographs of etched metallographic samples with magnifications 200 x and 500 x were carried out on microscope Neophot 2 (Carl Zeiss Jena). On photographs the ferrite grain with lamellar pearlite on grain lines is visible (see Figures 1, 2, 3 and 4).

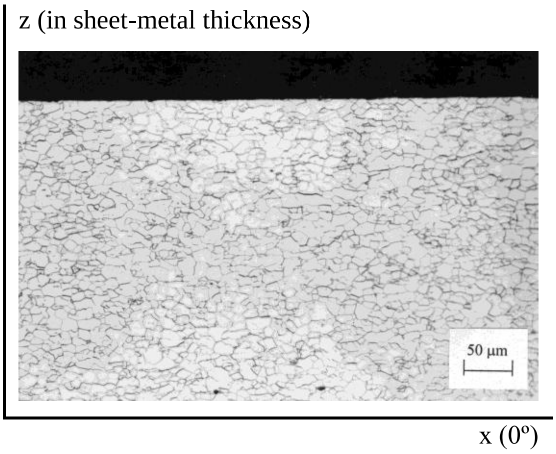

Fig. 1 Metallographic sample from thickness of sheet-metal from steel St 4 in direction of 0º according to direction of rolling (etched by 3 % Nital solution).

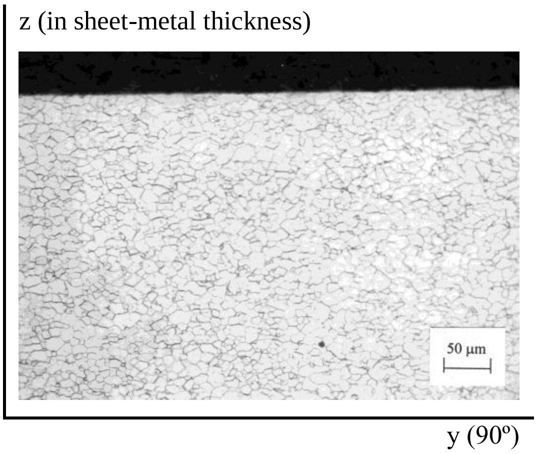

Fig. 2 Metallographic sample from thickness of sheet-metal from steel St 4 in direction of 90º according to direction of rolling (etched by 3 % Nital solution).

At steel St 4 the ferrite grain size of 10.5 according to the Czech State Standard (ČSN) 42 0462 was found out. The currently used steel DC04 has usually the ferrite grain size of 7 [1, 3, 5]. The ferrite grains shape at tested steel St 4 was flattened, lens-shaped, the longer axes were in sheet-metal plane. The ferrite grains were extended in direction of rolling with dimensions heterogeneity less than 2 numbers according to scale of ČSN 42 0462.

The medium degree of contamination of steel St 4 by non-metallic inclusions was less than 1 according to ČSN 42 0471, which gives evidence about great fineness of their microstructure and from that following good formability. The highest degree of cementite presence has been found out 2/1A according to ČSN 42 0469, i. e. equally situated formatios with dimensions approximately

10 μm at grain lines with sign of creation of network on the range approximately to 1/6 of their circumferences.

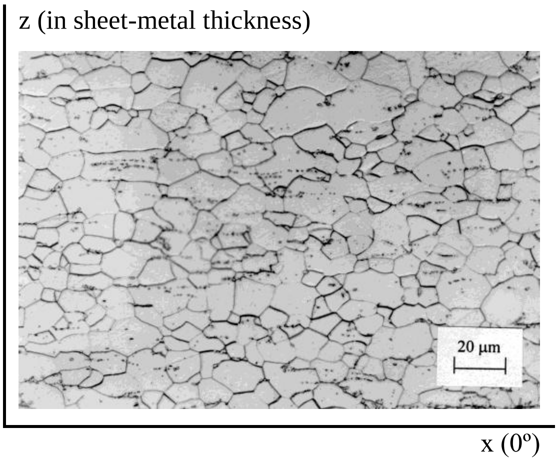

Fig. 3 Metallographic sample from thickness of sheet-metal from steel St 4 in direction of 0º according to direction of rolling (etched by 3 % Nital solution).

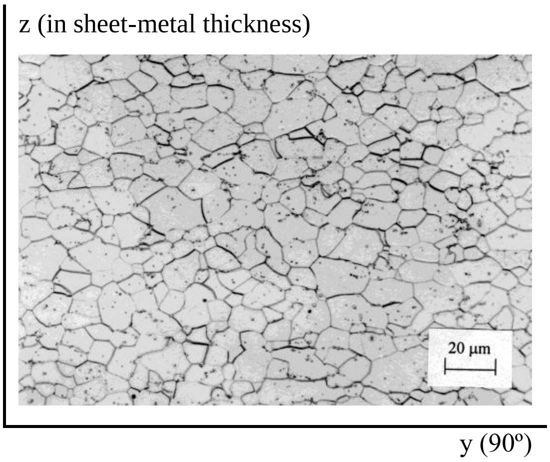

Fig. 4 Metallographic sample from thickness of sheet-metal from steel St 4 in direction of 90º according to direction of rolling (etched by 3 % Nital solution).

2.2 Evaluation of mechanical properties

The evaluation has been carried out by tensile tests according to ČSN EN 10002-1. These tests were carried out on tensile testing machine (Fig. 5), which is in accordance with ČSN 25 0251. The tensile specimens had their dimensions according to standards ČSN EN 10002-1, ČSN ISO 10113 and ČSN ISO 10275. Taking of tensile specimens from sheet-metal tables or strips was carried out in accordance with standard ČSN EN ISO 377, which determines the principles of taking and processing of tensile specimens from steels for mechanical testing.

Fig. 5 Tensile testing machine with tensile specimen after test.

The yield points in tension $R_{p\,0,2}$ were found out from tensile diagrams by graphical method. The directional values of mechanical properties were calculated like arithmetic means from values measured at three test specimens (see Tab. 3).

According to the fact, that the sheets are unidirectionally rolled, the planar anisotropy of their mechanical properties exists. That is why it was important to evaluate the mechanical properties of sheet-metal in orientations 0°, 45° and 90° in relation to the direction of rolling.

Tab. 3 Mechanical properties of steel strip St 4.

Mechanical properties	Direction in relation to direction of rolling			Medium value
	0°	45°	90°	
$R_{p\,0,2}$ (MPa)	204.0	205.6	204.7	205.0
R_m (MPa)	346.7	355.8	349.0	351.8
$R_{p\,0,2}/R_m$ (MPa)	0.588	0.578	0.587	0.583
A_{80} (%)	36.6	39.3	36.9	38.0
Z (%)	55.2	58.0	60.1	57.9
ε_r (–)	0.267	0.283	0.268	0.275
C (MPa)	528.9	543.5	529.2	536.3

Nevertheless the solitary mechanical properties are not sufficient for correct choice of sheet-metal according to its formability, so it is necessary farther to evaluate the planar anisotropy of mechanical properties, to calculate the directional and mean values of normal plastic anisotropy ratio and the strain-hardening exponents. Acording to these criteria it is possible to determine the formability of sheet metal for concrete shapes of stampings even to choose better the sheet-metal according to its formability.

2.3 Evaluation of planar anisotropy of steel strip mechanical properties

At deep drawing of symmetrical shape stampings the planar anisotropy causes arising of peaks either on their external edge or on flange. The height of peaks depends on sheet-metal initial anisotropy grade and on drawing rate. The planar anisotropy also increases the dimension deviations of deep stampings according to its required shape [1]. The influence of planar anisotropy of mechanical properties from this point of view is thinked as negative [2].

From evaluated directional and medium values of mechanical properties the values of coefficients of planar anisotropy were calculated according to ČSN 42 0437 with the use of formula:

$$PR_{m(x)} = \frac{R_{m(x)} - R_{m(0)}}{R_{m(0)}} \cdot 100 \ \ (\%) \qquad (1)$$

where P is the coefficient of planar anisotropy of separate mechanical property, x (º) is angle between tensile axis and rolling direction, 0º is angle of rolling direction.

Tab. 4 Planar anisotropy coefficients of tested steel strip St 4

Planar anisotropy coefficient	Direction in relation to direction of rolling	
	45°	90°
$P_{Rp\,0,2}$ (%)	0.78	0.34
P_{Rm} (%)	2.62	0.66
$P_{Rp\,0,2/Rm}$ (%)	-1.70	-0.17
P_{A80} (%)	7.38	0.82

At drawing of intricate shape stampings thanks to planar anisotropy of mechanical properties the orientation of initial blanks at blanking from sheet-metal table or strip and the blanks orientation at placing in the drawing tool are very important. The directions at initial blank, in which the plastic properties of sheet-metal are the best, need to be in directions or places of the biggest deformations at the stamping.

2.4 Evaluation of normal plastic anisotropy ratio

Normal anisotropy describes variations in properties between directions in the plane of the sheet and normal to it, i. e. in the direction of thickness. Its practical importance turns on the fact that the resistance of sheet metal to thinning, which is advantageous for deep pressing operations, is a function of its normal anisotropic plasticity. The lower the value of normal plastic anisotropy ratio, the poorer is the formability (deep-drawability) of tested sheet-metal.

The value of normal plastic anisotropy ratio can be used as criterion of sheet-metal formability in cases of deep drawing, where pressure-tension mechanical schemes of deformation predominate [3].

The values of normal plastic anisotropy ratio r were determined from measurements according to ČSN ISO 10113 using the relationship:

$$r = \frac{\ln \dfrac{b_0}{b_k}}{\ln \dfrac{L_k \cdot b_k}{L_0 \cdot b_0}} \tag{2}$$

where ln indicates natural logarithm, L_0 and b_0 are the initial length and width of the gauge section and L_k and b_k their values after deformation.

The mean normal plastic anisotropy ratio $\bar{r}$ was calculated from formula:

$$\bar{r} = \frac{1}{4} \cdot \left(r_0 + 2r_{45} + r_{90} \right) \tag{3}$$

where r_0, r_{45} and r_{90} are the values of normal plastic anisotropy ratio in orientations 0°, 45°, 90° in relation to the direction of rolling.

Planar anisotropy of normal plastic anisotropy ratio is in direct relation to the traditionally ascertained value of the peak height. The values of mean planar anisotropy of normal plastic anisotropy ratio were calculated from formula:

$$\Delta r = \frac{1}{2} \cdot \left(r_0 - 2r_{45} + r_{90} \right) \tag{4}$$

With $+\Delta r$ the peaks show up at 0° and 90°; with $-\Delta r$ they show up at 45° in relation to the direction of rolling; with $\Delta r = 0$ there is no peak.

The values of coefficients of normal plastic anisotropy ratio and the grade of planar anisotropy of coefficient of normal plastic anisotropy ratio Δr were calculated according to ČSN ISO 10113 (see Tab. 5).

Tab. 5 The coefficients of normal plastic anisotropy ratio and the grade of planar anisotropy of this coefficient of steel strip St 4.

r_0 (–)	r_{45} (–)	r_{90} (–)	$\bar{r}$ (–)	Δr (–)
1.32	1.49	1.86	1.54	0.10

2.4 Evaluation of strain-hardening exponent

The strain-hardening exponent characterizes the intensity of sheet-metal strain hardening during uniaxial tension plastic deformaton. The value of strain-hardening exponent can be used as criterion of sheet-metal formability in cases of deep drawing, where tension mechanical schemes of deformation predominate. The high value of mean strain-hardening exponent, i. e. high speed of strain hardening of sheet-metal, causes more uniform distribution of deformations at biaxial state of tension stress and by it helps to reach higher value of general deformation. The higher the value of strain-hardening exponent, the better the formability (deep-drawability) of tested sheet-metal.

The mean strain-hardening exponent n_m can be calculated from formula:

$$n_m = \frac{1}{4} \cdot (n_0 + 2n_{45} + n_{90}) \quad (5)$$

where n_0, n_{45} and n_{90} are the values of strain-hardening exponent in orientations 0°, 45°, 90° in relation to the direction of rolling.

The values of mean planar anisotropy of strain-hardening exponent can be calculated from formula:

$$\Delta n = \frac{1}{2} \cdot (n_0 - 2n_{45} + n_{90}) \quad (6)$$

The values of mean planar anisotropy of strain-hardening exponent can be also calculated from maximal uniform elongation with the use of formula:

$$n_m = \ln (1 + \varepsilon_u) \quad (7)$$

The values of strain-hardening exponent and the grade of planar anisotropy of strain-hardening exponent Δn were calculated according to ČSN ISO 10275 (see Tab. 6).

Tab. 6 The values of strain-hardening exponent and the grade of planar anisotropy of strain-hardening exponent of steel strip St 4 calculated with the use of equations (5) and (6)

Used equation	n_0 (–)	n_{45} (–)	n_{90} (–)	n_m (–)	Δn (–)
5	0.157	0.159	0.157	0.158	-0.003
7	0.219	0.234	0.221	0.227	-0.028

2.5 Calculation of formability index

For reciprocal comparison of formability of tested materials the formability index I was calculated [1]:

$$I = r_{\alpha min} \cdot n_m \cdot 1{,}000 \quad (8)$$

where $r_{\alpha min}$ is the minimal normal plastic anisotropy ratio from values of it in orientations 0°, 45°, 90° in relation to the direction of rolling, n_m is the mean strain-hardening exponent.

2.6 Cuping tests

By cupping tests according to ČSN 42 0406 (see Fig. 6) at steel strip St 4 the medium value of deepening IE = 10.56 mm was found out. The zone of localization of plastic deformation had shape of circle or circular arc (Fig. 7), which gives evidence about homogeneous material.

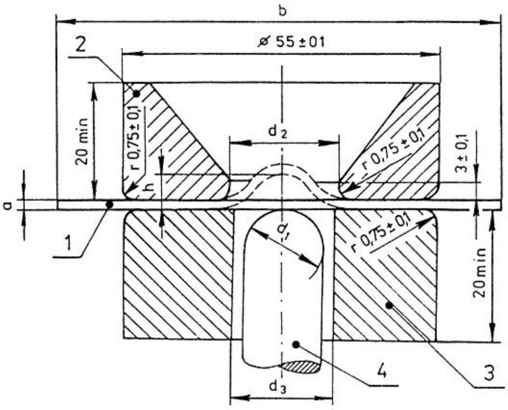

Fig. 6 Scheme of operating area of testing device (1 – test specimen, 2 – die, 3 – blankholder, 4 – punch, d_1 – punch spherical end diameter, d_2 – die internal diameter, d_3 – holding ring internal diameter, b – test specimen width, h – cavity depth).

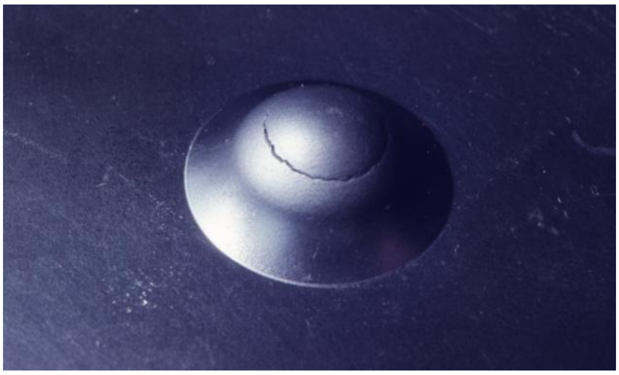

Fig. 7 Specimen after cupping test with the zone of localization of plastic deformation.

2.7 Forming limit diagram

For judgment of formability of steel strip St 4 the forming limit diagram (Fig. 8) was constructed, which comes out from criterion of plastic deformation stability loss at the tensile strength.

Autobody stampings can generally be classified as rejects if any form of necking is visible, and it can therefore be argued that instability strains should be the limiting criteria of sheet-metal formability.

3 CONCLUSIONS

The steel strip St 4 did not present in any direction of 0°, 45° and 90° compared with direction of rolling outstanding yield point in tension R_e, which gives evidence about right carried out light re-rolling of this steel at their production. The great medium values of $R_{p\,0,2}$ and R_m are connected with found out very fine grain (see 2.1). Owing to high value of $R_{p\,0,2}$ and sufficiently high value of R_m the low value of relation $R_{p\,0,2}/R_m = 0.583$ (see Tab. 3) was calculated at this steel. It gives evidence about very good formability [1, 3] and about great plasticity supply of this material for cold forming.

At steel strip the very low planar anisotropy of mechanical properties was found out, which makes possible to achieve smaler dimensions deviations of deep stampings with respect to required shape. As well the value of Δr (see Tab. 4), which is expressive of prone to creation of tips at drawing, was low, at deep drawing of rotary symmetrical stampings from this steel the tips of small dimensions would be arising. The tips would be in directions 0° and 90° compared with direction of rolling, because the value of Δr was positive.

The steel strip St 4 presented low value of $\bar{r} = 1.54$ (see Tab. 5), which corresponds to good formability [1, 3]. This value gives evidence about sufficient thin resistance of sheet-metal at deep drawing and about suitability of this steel strip for cases of deep drawing, where pressure-tension mechanical schemes of deformations predominate.

Found out value of $n_m = 0.227$ (Tab. 6), which corresponds to good formability [1, 3], gives evidence about relatively good suitability of this steel for cases of deep drawing, where the tension stress predominate. The value of n_m also influence forming limit diagram of this steel.

The calculated value of formability index $r_{\alpha\min} \cdot n_m \cdot 1{,}000 = 299.6$ corresponds to good formability [1, 3, 5]. Mentioned fact, which is first of all caused by low value of n_m, gives evidence about smaller suitability of this steel for cases of deep drawing, where as pressure-tension as tension mechanical schemes of deformations at the same time occur.

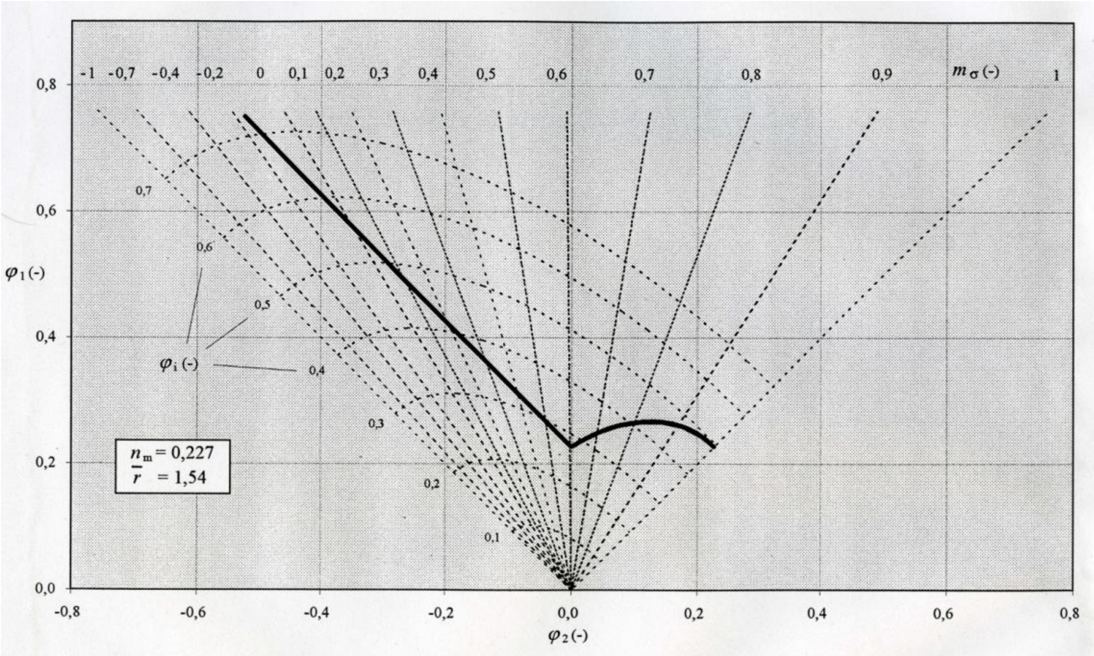

Fig. 8 Forming limit diagram of tested steel St 4 which comes out from criterion of plastic deformation stability loss at the tensile strength.

Generally it is possible to assert, that favourable mechanical properties and very low planar anisotropy of mechanical properties, which raises accuracy of stampings, compensed the negative influence of very fine grain (spring mounting), so the positive influence predominate, i. e. reaching of very smooth surface of stamping. The principal wants of this steel strip from standpoint of formability are sufficiently low value of $\bar{r}$ and relatively low value of n_m, which are principal for suitability of sheet-metal for deep drawing. This steel strip is suitable for cases of deep drawing, where pressure-tension mechanical schemes occur, steel is less suitable for combine and least suitable for tension mechanical schemes of deformations.

At tested steel strip St 4 the lower value of medium strain-hardening exponent has been found out ($n_m = 0.227$) that it is current at steel strip DC04 ($n_m = 0.230$ and more). This reality is caused by great content of impurity elements at steel strip St 4 and finess of ferrite grain ($G = 10.5$). According to lower n_m value at steel strip St 4 the speed of strain-hardening at drawing is lower, the transposition of plastic deformations from places with great initial stress (biaxial tension zone) to places with lower initial stress is slow and that is why less uniform situation of deformations on stamping arises. So at drawing from steel strip St 4 there is greater danger of arising of secondary waviness or integrity failure than at drawing from steel DC04.

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