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DETERMINATION OF MEASUREMENT UNCERTAINTIES OF MECHANICAL PROPERTIES AND PLASTIC ANISOTROPY RATIOS OF MATERIAL AT TENSILE TESTS

STANOVENÍ NEJISTOT MĚŘENÍ MECHANICKÝCH VLASTNOSTÍ A SOUČINITELŮ PLASTICKÉ ANIZOTROPIE MATERIÁLU U ZKOUŠEK TAHEM

Abstract

Paper deals with determination of measurement uncertainties of mechanical properties and plastic anisotropy ratios of material at the tensile tests at usage of either three or five test specimens in orientations 0º, 45º and 90º towards sheet-metal rolling direction. Standard for tensile tests ČSN EN ISO 6892-1 contains determining of uncertainties partly for input dimensions of test specimens, partly for testing device, no for values of measured mechanical properties. The standard for determination of plastic anisotropy ratios ČSN ISO 10113 does not include the determination of measurent uncertainties, hence the standard does not solve achieve results accuracy. In this contribution the selective averages, selective standard deviations and combined measurement uncertainties of directional and medium values of mechanical properties and plastic anisotropy ratios of steel strip DD11 (11 320) are calculated using statistical methods. For calculations the software MS Excel was used. Based on the values of weighted average of plastic strain ratio of tested steel strip and with the use of sheet-metal classification concept according to Shawki, the suitability of tested steel for drawing operations at which predominate pressure-pull mechanical diagrams of stress was evaluated.

Abstrakt

Příspěvek se týká stanovení nejistot měření mechanických vlastností a součinitelů plastické anizotropie materiálu u zkoušek tahem při použití jednak tří, jednak pěti zkušebních tyčí ve směrech 0º, 45º a 90º vůči směru válcování plechu. Norma pro zkoušky tahem ČSN EN ISO 6892-1 obsahuje stanovení nejistot měření jednak vstupních hodnot rozměrů zkušebních těles, jednak měřicího zařízení, nikoli hodnot měřených mechanických vlastností. Norma pro stanovení součinitele plastické anizotropie ČSN ISO 10113 neobsahuje stanovení nejistot měření, neřeší tedy přesnost dosažených výsledků. V příspěvku jsou pomocí statistických metod vypočteny výběrové průměry, výběrové směrodatné odchylky a kombinované nejistoty měření směrových a středních hodnot mechanických vlastností a součinitelů plastické anizotropie pásové oceli DD11 (11 320.0).

K výpočtům byl použit program MS Excel. Na základě vypočtených hodnot váženého průměru součinitele plastické anizotropie zkoušené pásové oceli a s využitím návrhu zatřídění plechů dle Shawkiho byla zhodnocena vhodnost zkoušené oceli pro tažné operace, u kterých převládají tlakově-tahová mechanická schémata napjatosti.

INTRODUCTION

From point of view of practice it is very important before drawing process starts to estimate a formability of sheet-metal in order to prevent defective work in production. For judgment of sheet-metal formability unconventional criteria can be used including plastic anisotropy ratio and strain

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hardening exponent. These criteria allow better classification of sheet-metal than mechanical properties evaluated by tensile test.

For finding plastic anisotropy in individual directions *x* towards rolling direcion of sheet-metal n_x the results of tensile tests according to ČSN EN ISO 6892-1 of test specimens taken from sheet-metal in directions 0°, 45° and 90° towards rolling direcion are used. The values of plastic strain rations in single directions *x* towards rolling direction of sheet-metal are calculated as arithmetical means from values measured minimally at three test specimens, that is exactly the way that standard prescribes. Values obtained in such a way already include measurement uncertainties.

The standard for tensile tests ČSN EN ISO 6892-1 solves measurement uncertainties only informative with meaning of determination of input values, test specimens shape and determination of uncertainties of measured mechanical properties values. The standard for determination of plastic anisotropy ratio ČSN ISO 10113 does not include the estimation of measurement uncertainty.

Method of evaluation of measurement uncertainties is described in preliminary standards ČSN P ISO/TS 21748:2005, ČSN P ISO/TS 21749:2007, ČSN P ENV 13005:2005 and informative in ČSN EN ISO 6892-1. Processing data using statistical methods adapts standards ČSN ISO 3534-1:1994, ČSN ISO 3534-2:1994 and ČSN 3534-3:2001.

This contribution describes determination of measurement uncertainties of mechanical properties and plastic strain ratio of steel strip DD11 (11 320.0) that was selected as an example of steel for drawing, using either three or five test specimens in orientations 0º, 45º and 90º towards the direction of rolling at tensile tests. Selective averages, selective standard deviations and combined measurement uncertainties of directional and medium values of mechanical properties and plastic anisotropy ratios of tested material were calculated using statistical methods. Based on the values of weighted average of plastic strain ratio of tested steel strip and with the use of sheet-metal classification concept according to Shawki, the suitability of tested steel for drawing operations at which predominate pressure-pull mechanical diagrams of stress was evaluated.

1 CHARACTERISTIC OF TESTED MATERIAL

For tests the strip from steel DD11 (11 320) with dimensions according to ČSN 42 5355: thickness of strip (2,6 ± 0,1) mm, strip width with natural edges (171 ± 1,35) mm was chosen. Due to ČSN 41 1320 this steel corresponds to steel St 22 according to DIN 1614 ÷ 74 and St 12 according to DIN 1623 ÷ 72. The steel is hot rolled, recrystillizationally annealed, not re-rolled with mill surface. According to ČSN 41 1320 the steel is suitable for drawing and cold forming operations and has a certain welding characteristic according to ČSN 05 1310. The demands on chemical composition of steel DD11 (11 320.0) according to ČSN 41 1320 are in Tab. 1, desirable values of mechanical properties are in Tab. 2.

Tab. 1 Demands on chemical composition of steel DD11 (11 320.0) according to ČSN 41 1320

C (wt %)	P (wt %)	S (wt %)
max. 0,11	max. 0,045	max. 0,045

Tab. 2 Demands on mechanical properties of steel DD11 (11 320.0) according to ČSN 41 1320

Yield strength R_e crosswise (MPa)	Tensile strengh R_m crosswise (MPa)	Ductility A_{10} along (%)	Test brittleness for $D = 0$ mm
max. 0,8 R_m	270 ÷ 370	min. 30	$\alpha = 180°$

2 ESTIMATION OF MEASUREMENT UNCERTAINTY

The degree of measurement uncertainty is standard deviation value (estimation of a real value). The value denoted in this way represents standard uncertainty u and determines value interval $-u$ and $+u$ round measured (rated) value that implies the probability interval to where the real value could fall into.

The uncertainty of measurement is an interval of measured values with 95 % probability, in which the measurement magnitude could be found.

It is possible to carry out the estimation of measurement uncertainty at tensile tests according to informative annexe J of standard ČSN EN ISO 6892-1. At tensile tests it is impossible to estimate a value of uncertainty absolutely because formulation of uncertainty is influenced by both materials depended and material independent contributions.

Standard uncertainty u of value parameter can be estimated by two methods:

a) by repeated measurement – by this way statistical standard uncertainty of A type is determined, which is given by equation:

$$u(x_1) = \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^{n} (\bar{x} - x_i)^2} \ , \tag{1}$$

where are $\bar{x}$ – standard deviation of measurement, x_i – measured value, n – number of observations that under standard circumstances is made as average for description result of measurement.

b) from others resources, e. g. from limit deviations – by this way determines standard uncertainty of B type is determined, which is given by equation:

$$u(x_2) = \frac{a}{\sqrt{3}} , \tag{2}$$

where is a – half of interval width in which occurrence of given quantily is assumed.

Combined uncertainty y which takes into consideration contributions of measurement uncertainty of all included quantities, is expressed by equation:

$$u(y) = \sqrt{(u(x_1)^2 + u(x_2)^2 + ... + u(x_n)^2} , \tag{3}$$

where is $u(x_1)$ – uncertainty in parameter x_1 etc.

2.1 Influence of device parameters, material and testing process upon results uncertainties at tensile tests

Uncertainty of results determined by tensile test includes compounds related to used device. Different testing results have different contributions of uncertainty which depend on method of their determination – e. g. yield strength R_e is dependent on measurement uncertainties of load strength and sectional surface, at contraction Z the measurement uncertainties of sectional surface both before and after fracture must be taken into account.

The values of uncertainties contributions given by device which are recommended to take for consideration at measurement of material properties are in Tab. 3. The values of uncertainties contributions that are no filled in are according to greatness irrelevant for measurement.

Tab. 3 Examples of uncertainties contributions induced by measured devices at various test results

Parameter	Contribution of uncertainty by measurement device (%)			
	R_e	R_m	A	Z
Force	1,4	1,4	-	-
Ductility	-	-	1,4	-
L_e, L_o	-	-	1	-
S_o	1	1	-	1
S_u	-	-	-	2

Standard uncertainty of load parameter has verified uncertainty 1.4 % (see Tab. 3). If uncertainty of load or uncertainty of measurement of elongation is taken into consideration, then combined uncertainty of test results R_e, R_m, R_e/R_m, and A is using equation (3) following:

$$u(y) = \sqrt{\left(\frac{1,4}{2}\right)^2 + \left(\frac{1}{\sqrt{3}}\right)^2} = 0,91\,\% \tag{4}$$

Combined uncertainty for contraction Z can be calculated:

$$u_Z = \sqrt{\left(\frac{a_{S_0}}{\sqrt{3}}\right)^2 + \left(\frac{a_{S_u}}{\sqrt{3}}\right)^2} = \sqrt{\left(\frac{1}{\sqrt{3}}\right)^2 + \left(\frac{2}{\sqrt{3}}\right)^2} = 1,29\,\% \tag{5}$$

In accordance with ISO/IEC Guide 98-3 the total expanded uncertainty is obtained by multiplication of combined standard uncertainties by expansion coefficient k. For 95 % confidence level $k = 2$. Calculated values of total expanded uncertainties are in Tab. 4.

Tab. 4 Total expanded uncertainties of device expressed in percentages for 95 % confidence level k = 2 for measured values by one test specimen

R_e	R_m	ε_r	A	Z
1,82	1,82	1,82	0,91	2,58

Results of tensile tests are dependent on factors related with tested material, testing device, testing process and on used methods for calculating of material properties. It is neccessary to take into account below mentioned factors:

a) testing temperature and speed of testing,

b) geometry of test body, method of body fixing, alignment of applied force,

c) characteristics of testing machine (consistency, drive and operation method).

Influence of these factors is dependent on specific material behaviour and could not be treated as defined value. If influence is known, it is recommended to take it into consideration within calculation of uncertainty.

3 EXPERIMENTAL EVALUATION OF SHEET-METAL MECHANICAL PROPERTIES AND DETERMINATION OF MEASUREMENT UNCERTAINTIES

Evaluation of mechanical properties, i. e. proof strength $R_{p\,0,2}$ or yield strength R_e, tensile strength R_m, ductility A_{80}, contraction Z, maximum uniform strain ε_r and strength coefficient C was carried out by tensile test according to ČSN EN ISO 6892-1. At tested steel strip DD11 (11 320.0) significant yield strenth R_e has occcured.

At evaluation of sheet-metal formability the values evaluated by tensile test cannot be judged separately. It is important the ability of deformation hardening of material, characterized by difference of yield strength and tensile strength. The ability is usually expressed as a ratio R_e/R_m and as suitable is considered when $0,6 < R_e/R_m < 0,8$.

Directional values of mechanical properties of steel strip DD11 (11 320.0) evaluated by five test specimens in directions 0°, 45° and 90° towards rolling direction of sheet-metal are in Tab. 5, Tab. 7 and Tab. 9.

With application of statistical methods and with the use of software MS Excel the selective averages, selective standard deviations and combined uncertainties of measurement directional values of mechanical properties of steel strip DD11 (11 320.0) were calcultated. Standard deviation of selective average was determined according to equation (1), combined measurement uncertainties were calculated according to equation (3). The results for three and five test specimens are in Tab. 6, Tab. 8 and Tab. 10.

Selective averages, selective standard deviations and combined measurement uncertaities of medium values of mechanical properties of steel strip DD11 (11 320.0) at application of three and five test specimens are in Tab. 11.

Tab. 5 Values of mechanical properties of steel strip DD11 (11 320) in direction 0° towards rolling direction

Mechanical properties	Test bar No. 1	Test bar No. 2	Test bar No. 3	Test bar No. 4	Test bar No. 5
R_e (MPa)	246,4	249,9	275,4	250,8	255,4
R_m (MPa)	338,5	335,38	356,86	332,8	340,3
R_e/R_m (-)	0,728	0,745	0,772	0,738	0,771
A_{80} (%)	34,1	36,6	32,4	33,2	35,1
Z (%)	66,6	69,1	63,5	64,4	67,2
ε_r (-)	0,252	0,274	0,236	0,247	0,251
C (MPa)	514,8	521,9	604,7	518,2	530,3

Tab. 6 Selective averages, selective standard deviations and combined measurement uncertainties of values of mechanical properties of steel strip DD11 (11 320.0) in direction 0° towards rolling direction at application of three and five test bars

Mechanical properties	Application of three test bars			Application of five test bars		
	Selective average	Selective standard deviation	Resulting uncertainty	Selective average	Selective standard deviation	Resulting uncertainty
R_e (MPa)	257,2	9,2	10,3	255,6	5,0	6,9
R_m (MPa)	343,6	7,0	9,4	340,8	3,8	7,3
R_e/R_m (-)	0,748	0,013	0,019	0,748	0,007	0,015
A_{80} (%)	34,3	1,2	1,4	34,1	0,7	0,9
Z (%)	66,4	1,6	2,4	66,2	0,9	1,9
ε_r (-)	0,254	0,011	0,011	0,252	0,006	0,006
C (MPa)	547,16	29,6	29,6	530,3	16,2	16,2

Tab. 7 Values of mechanical properties of steel strip DD11 (11 320) in direction 45° towards rolling direction

Mechanical properties	Test bar No. 1	Test bar No. 2	Test bar No. 3	Test bar No. 4	Test bar No. 5
R_e (MPa)	304,6	301,6	266,1	278,5	298,4
R_m (MPa)	359,9	359,4	333,8	340,7	350,4
R_e/R_m (-)	0,846	0,839	0,797	0,768	0,924
A_{80} (%)	26,7	31,3	30,4	28,7	29,6
Z (%)	62,5	63,9	64,4	62,9	63,4
ε_r (-)	0,249	0,221	0,236	0,231	0,243
C (MPa)	605,6	602,4	553,5	600,3	590,8

Tab. 8 Selective averages, selective standard deviations and combined measurement uncertainties of values of mechanical properties of steel strip DD11 (11 320.0) in direction 45° towards rolling direction at application of three and five test bars

Mechanical properties	Application of three test bars			Application of five test bars		
	Selective average	Selective standard deviation	Resulting uncertainty	Selective average	Selective standard deviation	Resulting uncertainty
R_e (MPa)	290,8	12,4	13,5	289,8	6,8	8,6
R_m (MPa)	351,0	8,8	10,8	348,8	4,8	8,0
R_e/R_m (-)	0,828	0,015	0,022	0,828	0,008	0,017
A_{80} (%)	29,5	1,4	1,5	29,3	0,8	0,9
Z (%)	63,6	0,6	1,7	63,4	0,3	1,7
ε_r (-)	0,215	0,013	0,013	0,22	0,007	0,013
C (MPa)	587,1	17,0	17,0	590,5	9,3	9,3

Tab. 9 Values of mechanical properties of steel strip DD11 (11 320) in direction 90° towards rolling direction

Mechanical properties	Test bar No. 1	Test bar No. 2	Test bar No. 3	Test bar No. 4	Test bar No. 5
R_e (MPa)	290,1	329,2	293,9	300,6	296,7
R_m (MPa)	353,3	351,6	354,6	352,8	353,3
R_e/R_m (-)	0,821	0,936	0,829	0,768	0,924
A_{80} (%)	27,3	26,1	26,8	27,1	25,7
Z (%)	61,5	61,5	62,9	61,7	62,2
ε_r (-)	0,241	0,239	0,240	0,241	0,239
C (MPa)	622,1	544,0	595,3	592,3	570,4

Tab. 10 Selective averages, selective standard deviations and combined measurement uncertainties of values of mechanical properties of steel strip DD11 (11 320.0) in direction 90° towards rolling direction at application of three and five test bars

Mechanical properties	Application of three test bars			Application of five test bars		
	Selective average	Selective standard deviation	Resulting uncertainty	Selective average	Selective standard deviation	Resulting uncertainty
R_e (MPa)	304,4	12,5	13,7	302,1	7,0	8,9
R_m (MPa)	353,2	0,9	6,5	353,3	0,5	6,4
R_e/R_m (-)	0,862	0,037	0,040	0,862	0,020	0,026
A_{80} (%)	26,7	0,4	0,1	26,6	0,2	0,5
Z (%)	62,0	0,5	1,7	62,0	0,3	1,6
ε_r (-)	0,240	0,001	0,001	0,240	0,000	0,000
C (MPa)	587,1	23,0	23,0	584,8	12,6	12,6

Tab. 11 Selective averages, selective standard deviations and combined measurement uncertainties of medium values of mechanical properties of steel strip DD11 (11 320.0) for three and five test specimens

Mechanical properties	Application of three test bars			Application of five test bars		
	Selective average	Selective standard deviation	Resulting uncertainty	Selective average	Selective standard deviation	Resulting uncertainty
R_e (MPa)	285,8	8,4	9,9	284,4	6,4	8,24
R_m (MPa)	349,7	3,5	7,3	347,9	1,8	6,6
R_e/R_m (-)	0,817	0,024	0,028	0,816	0,011	0,018
A_{80} (%)	30,0	1,4	1,5	29,8	0,6	0,8
Z (%)	63,9	0,8	1,8	63,7	0,4	1,7
ε_r (-)	0,229	0,011	0,011	0,233	0,006	0,006
C (MPa)	577,1	21,6	21,6	576,0	12,3	12,3

4 EXPERIMENTAL EVALUATION OF PLASTIC ANISOTROPY RATIOS AND DETERMINATION OF MEASUREMENT UNCERTAINTIES

Normal anisotropy of sheet-metal expresses non-uniformity of mechanical properties on sheet-metal plane against mechanical properties in normal orientation on sheet-metal plane, i. e. in orientation of thickness. The normal anisotropy of sheet-metal mechanical properties in given orientation x (0°, 45°, 90°) towards rolling direction of sheet-metal expresses by dimensionless number – plastic strain ratio r_x that is given by the equation:

$$r_x = \frac{\varphi_b}{\varphi_s} = \frac{\ln\frac{b_0}{b_k}}{\ln\frac{s_0}{s_k}} = \frac{\ln\frac{b_k}{b_0}}{\ln\frac{L_0 \cdot b_0}{L_K \cdot b_K}} \quad (-), \tag{6}$$

where φ_b, φ_s – logarithmic deformations in direction of width and thickness, L_0, b_0, s_0 – initial length, width and thickness of tested part of test bar.

For evaluation of anisotropy the plain test bars according to standard ČSN EN ISO 6892-1 are used. Evaluation of plastic plane anisotropy is performed according to ČSN 42 0437. Plastic strain ratio expresses resistance of sheet-metal to thinning during deep drawing process. Higher the value of the coefficient, the higher is the resistance to thinning and thereby is more suitable for deep drawing process. As a criterion of sheet-metal formability the value of weighted average plastic strain ratio is being used according to relation:

$$\bar{r} = \frac{1}{4} \cdot \left(r_0 + r_{90} + 2 \cdot r_{45}\right) \quad (-), \tag{7}$$

where are r_0, r_{45}, r_{90} – plastic strain ratios in directions 0°, 45°, 90° towards sheet-metal rolling direction.

Arising of tips at stampings is judged according to degree of planar anisotropy of plastic strain ratio Δr which is possible to derive from relation:

$$\Delta r = \frac{1}{2} \cdot \left(r_0 + r_{90} - 2 \cdot r_{45}\right) \quad (-) \tag{8}$$

If $\Delta r > 0$, the tips are created in directions 0° and 90° towards sheet-metal rolling direction, i.e. in directions of maximum values of coefficient r_x. If $\Delta r < 0$, the tips are created in directions +45° and –45° towards sheet-metal rolling direction. If $\Delta r = 0$, the tips are not created.

The higher the value of $\bar{r}$, the higher is resistance of sheet-metal against thinning and its suitability for deep drawing.

Guiding values of weighted average of plastic anisotropy ratio $\bar{r}$ for evaluation of sheet-metal formability have not be defined by national standard yet. Neverthless it is possible to use suggested sheet-metal classification concept according to Shawki:

a) low formability $\bar{r} < 1{,}25$,

b) good formability $\bar{r} = 1{,}25 \text{ až } 1{,}60$,

c) excellent formabilitty $\bar{r} > 1{,}60$.

For evaluation of plastic strain ratios of steel strip DD11 (11 320) the results from tensile tests executed according to ČSN ISO 10113 and also standards ČSN ISO 10275 and ČSN EN ISO 6892-1 were used.

Measured values of initial and final length and width of tested part of test bar for evaluation of directional values of plastic strain ratio of steel strip DD11 (11 320.0) are in Tab. 12.

Tab. 12 Measured values of initial and final length and width of tested part of test bar for identification of directional values of plastic strain ratio of steel strip DD11 (11 320.0)

Angle towards rolling direction	Measured value	Test bar No. 1	Test bar No. 2	Test bar No. 3	Test bar No. 4	Test bar No. 5
0°	L_0 (mm)	80,00	80,00	80,00	80,00	80,00
	b_0 (mm)	20,00	19,98	20,00	19,99	19,98
	L_{k0} (mm)	107,30	109,25	105,95	107,50	106,95
	b_{k0} (mm)	18,03	17,83	18,15	17,95	18,05
45°	L_0 (mm)	80,00	80,00	80,00	80,00	80,00
	b_0 (mm)	19,97	20,00	20,05	19,95	20,20
	L_{k45} (mm)	101,35	105,05	104,35	102,40	103,50
	b_{k45} (mm)	18,65	18,20	18,32	17,90	18,10
90°	L_0 (mm)	80,00	80,00	80,00	80,00	80,00
	b_0 (mm)	19,90	20,00	20,05	19,95	19,98
	L_{k90} (mm)	101,85	100,90	101,40	101,23	101,32
	b_{k90} (mm)	18,75	18,97	18,70	18,81	18,75

Selection averages, combined measurement uncertainties of medium values of initial and final length and width of tested parts of test bar at application of three and five test bars were calculated with the use of software MS Excel using statistical method. Calculated values are in Tab. 13.

Tab. 13 Selective averages and combined measurement uncertainties of medium values of initial and final length and width of tested parts of test bar at application of three and five test bars

Angle towards rolling direction	Measured value	Application of three test bars		Application of five test bars	
		Selective average	Measurement uncertainty	Selective average	Measurement uncertainty
0°	L_0 (mm)	80,00	0,00	80,00	0,00
	b_0 (mm)	19,99	0,00	19,99	0,00
	L_{k0} (mm)	107,50	1,03	107,39	0,90
	b_{k0} (mm)	18,00	0,10	18,00	0,10
45°	L_0 (mm)	80,00	0,00	80,00	0,00
	b_0 (mm)	20,00	0,03	20,00	0,02
	L_{k45} (mm)	103,58	1,32	103,43	1,23
	b_{k45} (mm)	18,39	0,15	18,39	0,15
90°	L_0 (mm)	80,00	0,00	80,00	0,00
	b_0 (mm)	19,98	0,05	19,98	0,05
	L_{k90} (mm)	101,38	0,29	101,38	0,28
	b_{k90} (mm)	18,81	0,10	18,80	0,01

The values of plastic strain ratios in directions 0°, 45° and 90° towards sheet-metal rolling direction, value of weighted average of plastic strain ratio $\bar{r}$ and degree of planar anisotropy of plastic strain ratio Δr of steel strip DD11 (11 320.0) were calculated according to equations (6) to (8) with the use of three and five test bars in every direction 0°, 45° and 90° towards sheet-metal rolling direction. Resulting values are in Tab. 14 and Tab. 15.

Tab. 14 Values of weighted average of plastic strain ratio and degrees of planar anisotropy of plastic strain ratios of steel strip DD11 (11 320.0) calculated with the use of three test bars in every directions 0°, 45° and 90° towards sheet-metal rolling direction

r_0	r_{45}	r_{90}	$\bar{r}$	Δr
0,55	0,48	0,34	0,47	-0,04

Tab. 15 Values of weighted average of plastic strain ratio and degrees of planar anisotropy of plastic strain ratio of steel strip DD11 (11 320.0) calculated with the use of five test bars in every directions 0°, 45° and 90° towards sheet-metal rolling direction

r_0	r_{45}	r_{90}	$\bar{r}$	Δr
0,55	0,65	0,34	0,55	-0,09

Mean arithmetical value $\bar{y}$ can be calculated by putting arithmetical means of all values acquired by direct measurement into formula (8) for searched value.

Mean error of measurement $u(y)$ can be enumerated according to equation:

$$u(y)=\sqrt{\left(\left(\frac{\partial f}{\partial x}\right)^{2}\cdot \bar{u}(y)^{2}(x_{1})+\left(\frac{\partial f}{\partial y}\right)^{2}\cdot \bar{u}(y)^{2}(x_{2})+..+\frac{\partial f}{\partial x}\cdot \bar{u}(y)^{2}(x_{\mathrm{n}})\right)} \tag{9}$$

Overall interval of confindence can be written in a form:

$$y=\bar{y}\pm u(y) \tag{10}$$

Relative mean error can be calculated as ratio of absolute error to the magnitude of measured value:

$$u_{\mathrm{r}}(y)=\frac{1}{y}\cdot u(y)\cdot 100 \quad (\%) \tag{11}$$

Relative mean error of measurement of weighted average of plastic strain ratio of sheet-metal can be formulated by applying into equation (9):

$$u(\bar{r})=\sqrt{\left(\frac{\partial \bar{r}}{\partial b_{\mathrm{k0}}}\right)^{2}\cdot u^{2}(b_{\mathrm{k0}})+\left(\frac{\partial \bar{r}}{\partial L_{\mathrm{k0}}}\right)^{2}\cdot u^{2}(L_{\mathrm{k0}})+\left(\frac{\partial \bar{r}}{\partial b_{\mathrm{k45}}}\right)^{2}\cdot u^{2}(b_{\mathrm{k45}})+\left(\frac{\partial \bar{r}}{\partial L_{\mathrm{k45}}}\right)^{2}\cdot u^{2}(L_{\mathrm{k45}})+ +\left(\frac{\partial \bar{r}}{\partial b_{\mathrm{k90}}}\right)^{2}\cdot u^{2}(b_{\mathrm{k90}})+\left(\frac{\partial \bar{r}}{\partial L_{\mathrm{k90}}}\right)^{2}\cdot u^{2}(L_{\mathrm{k90}})}, \tag{12}$$

where in equation written above (12) are:

$$\frac{\partial \bar{r}}{\partial b_{\mathrm{k0}}}=\frac{-1}{4b_{\mathrm{k0}}\cdot \ln\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k0}}\cdot b_{\mathrm{k0}}}}-\frac{\ln\frac{b_{\mathrm{k0}}}{L_{0}}}{4b_{\mathrm{k0}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k0}}\cdot b_{\mathrm{k0}}}\right)^{2}}; \qquad \frac{\partial \bar{r}}{\partial L_{\mathrm{k0}}}=\frac{-\ln\frac{b_{0}}{b_{\mathrm{k}}}}{4L_{\mathrm{k0}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k0}}\cdot b_{\mathrm{k0}}}\right)^{2}};$$

$$\frac{\partial \bar{r}}{\partial b_{\mathrm{k45}}}=\frac{-1}{2b_{\mathrm{k45}}\cdot \ln\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k45}}\cdot b_{\mathrm{k45}}}}-\frac{\ln\frac{b_{\mathrm{k45}}}{L_{0}}}{2b_{\mathrm{k45}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k45}}\cdot b_{\mathrm{k45}}}\right)^{2}}; \qquad \frac{\partial \bar{r}}{\partial L_{\mathrm{k45}}}=\frac{-\ln\frac{b_{\mathrm{k45}}}{b_{0}}}{2L_{\mathrm{k45}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k45}}\cdot b_{\mathrm{k450}}}\right)^{2}};$$

$$\frac{\partial \bar{r}}{\partial b_{\mathrm{k90}}}=\frac{-1}{4b_{\mathrm{k90}}\cdot \ln\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k90}}\cdot b_{\mathrm{k90}}}}-\frac{\ln\frac{b_{\mathrm{k90}}}{L_{0}}}{4b_{\mathrm{k90}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k90}}\cdot b_{\mathrm{k90}}}\right)^{2}}; \qquad \frac{\partial \bar{r}}{\partial L_{\mathrm{k90}}}=\frac{-\ln\frac{b_{\mathrm{k90}}}{b_{0}}}{4L_{\mathrm{k90}}\cdot \ln\left(\frac{L_{0}\cdot b_{0}}{L_{\mathrm{k90}}\cdot b_{\mathrm{k90}}}\right)^{2}}.$$

Mean error of measurement of degree of sheet-metal planar anisotropy can be formulated in the similar way.

By putting of measured values for steel strip DD11 (11 320.0) into equation (12) the weighted average of plastic strain ratio defined at reliability interval was obtained:

a) at application of three test bars $\bar{r}=0{,}47\pm 0{,}12$,

b) at application of five test bars $\bar{r}=0{,}55\pm 0{,}03$.

Degree of planar anisotropy of plastic strain ratio defined at reliability interval:

a) at application of three test bars $\Delta r = -0{,}04 \pm 0{,}07$,

b) at application of five test bars $\Delta r = -0{,}09 \pm 0{,}06$.

From mean values of selective average Δr is apparent that in case of drawing rotational stampings the tips would be created in direction +45° and -45° towards sheet-metal rolling direction.

5 CONCLUSIONS

From the results of experimental evaluation of directional mechanical properties calculated either for three or five test bars in every direction of 0°, 45° and 90° towards sheet-metal rolling direction (see Tab. 6, Tab. 8 and Tab. 10) implies that only small differences exist between selective averages, selective standard deviations and measurement uncertainty values calculated ether for three or five test bars in every orientation of 0°, 45° and 90° towards sheet-metal rolling direction. The values of ratio R_e/R_m calculated with the use of free and five test bars in every orientation of 0°, 45° and 90° towards sheet-metal rolling direction (see Tab. 6, Tab. 8 and Tab. 10) are identical. Because of these reasons it would have been sufficient to ungo measurement only for three test bars in every direction of 0°, 45° and 90° towards sheet-metal rolling direction.

At measurement with the use of three test bars in every direction of 0°, 45° and 90° towards sheet-metal rolling direction in case of significant deviation of any value from selective average (as in example value R_e in Tab. 5, measured by test bar No. 3) which can be detected by expertly judgement or by relative error (in presented example the value is 9,3 %), it is necessary to execute measurements with the use of greater number of test bars, so that selective directive deviation could be cut down as well as resulting uncertainty of mean measured value.

The values of uncertainties contributions given by device, that are recommended to take into account at measurement of material properties, have insignificant influence on final values of measurement uncertainties. Only at tensile strength R_m (see Tab. 10) the selective standard deviation was minimal and contribution of measurement uncertainty of device had extensive influence on resulting measurement uncertainty.

The values of selective averages of weighted average of plastic strain ratio $\bar{r}$ and degree of planar anisotropy of plastic strain ratios Δr calculated with the use of three and five test bars in every directions of 0°, 45° and 90° towards sheet-metal rolling direction (see Tab. 14 and Tab. 15) are different. The difference is in mean values and in resulting uncertainties, whereas resulting uncertainty value with the use of five bars is distinctively lower.

At evaluated steel strip DD11 (11 320.0) the specified uncertainties of values of selective averages of weighted average of plastic strain ratio $\bar{r}$ calculated with the use of three and five test bars in every orientation of 0°, 45° and 90° towards sheet-metal rolling direction do not influence result of judgment of sheet-metal formability because calculated values are not even close to interval boundaries for sheet-metal classification according to Shawki.

At average values of degree of planar anisotropy of plastic strain ratio calculated with the use of three and five test bars in every directions of 0°, 45° and 90° towards sheet-metal rolling direction the mean values and uncertainties are different, whereas mean values are near interval boundaries and that is why it is impossible due to measurement uncertainty to determine in what direction towards sheet-metal rolling direction the tips arise at drawing of rotational stampings. For accurate results in this case it is necessary to use higher number of test bars.

From the measured values of mechanical properties of steel strip DD11 (11 320.0) results that sheet-metal suited requirements on mechanical properties according to ČSN 41 1320. What relates to unconventional criterion of sheet-metal formability, weighted average of plastic strain ratio $\bar{r}$, it is possible with the use of sheet-metal classification concept according to Shawki to classify tested sheet-metal into group with low formability, i. e. with low suitability for drawing operations at which predominate pressure-pull mechanical diagrams of stress. According to mean values of degree of planar anisotropy of plastic strain ratio Δr , it is very likely that during drawing of rotate symmetrical stampings the tips would be created in directions +45° and -45° towards sheet-metal rolling direction.

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