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INFLUENCE OF THE VARIABLE CHARACTER OF ANIZOTROPY ON THE HARDENING CURVES IN HYDRAULIC BULGING TEST OF COPPER SHEET[4]

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Abstract: *The study of sheet material of biaxial tensile test gives, as is known, additional useful information for the material at elevated deformation rates. One of the widely used modern methods of biaxial testing is hydraulic buljing test (HBT). Usually the hardening curves in biaxial tensile test in one or another degree differ with the respective curves of one axial tensile test. In the present study an attempt was made to introduce a correction by using an equation for anisotropy variation in function of the degree of deformation in order to match the one axial tensile and biaxial tensile curves. Copper sheet material was investigated and as a result were obtained hardening curves for one axial tensile test and HBT, as well as data for the variation of planar and normal anisotropy within the deformation interval. Satisfactory result gives the correction by introducing a functional dependence of anisotropy on the deformation in the Hill equation by 1948 year.*

Keywords:*,Tensile test, Sheet Metal, biaxial Tensile Straining, Hydraulic Bulging test, anisotropy*

INTRODUCTION

In the research of metal sheet materials of two-dimensional tension, we can use many equations from different authors. One of the problems is related to the divergence of the obtained curves from the one-dimensional tensile stretching with those obtained by the two-dimensional tension [1-5]. In order to resolve this problem are offered coefficients taking into account: the anisotropy of the material and the hardening coefficient of the material or constants characterizing the material. However, no universal solution has been found to achieve a common curve welding of one-dimensional and two-dimensional tensile obtained by experimental and mathematical models [6-18].

In prior studies [19-22] of metal sheet materials, an attempt was made to introduce correction in the hardening equations, with satisfactory results for steel and aluminum.

The object of this research is to check up the possibility of ensuring satisfactory compatibility for the two types of hardening curves by accounting the change of anisotropy during the process of plastic deformation of copper sheet material.

MATERIALS AND EXPERIMENTAL PROCEDURES

To carry out the research we used a copper sheet material with thickness of 0.9 mm. The sheet material was cut into sample bodies for one-dimensional and two-dimensional stretching (fig.1.a and b).

The test units for one-dimensional tension test were cut in three directions relative to the direction of rolling - parallel (0 °), perpendicular (90 °) and under angle of 45 °. The test units were divided into two groups - to determine the mechanical properties in the three directions and to determine the change of the normal and flat anisotropy in the deformation process. The one-dimensional tension test was carried out on a universal machine Instron 3384. The mechanical properties were determined by three samples in each direction. For the determination of the

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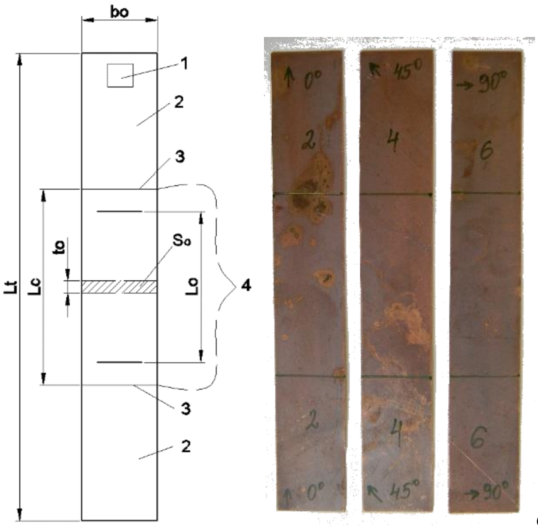
changing anisotropy in the deformation process we used a contact dynamic extensometer „2620-601“ fixed to the test body with a fixed base of 50 mm (fig.2.b).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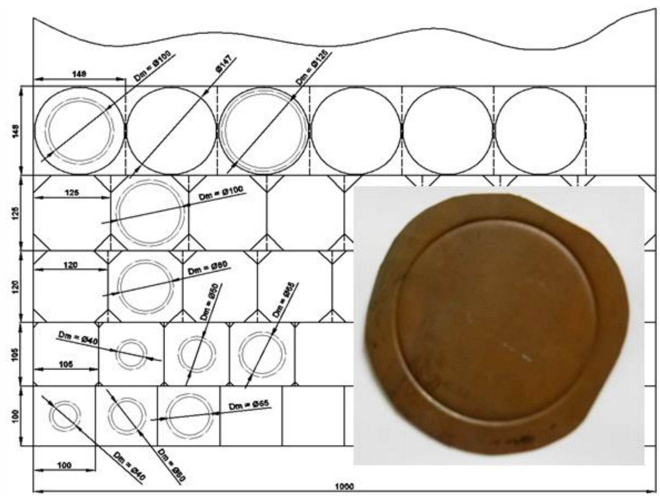
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Fig.1. Shape and meazurement of models for:
a) one-dimensional tensile test, b) two-dimensional tensile test

To determine the private and average values of normal and flat anisotropy, the test bodies were tested to standard deformation of 20 %. The determination of the varying private factors of normal and flat anisotropy were done through identical equal intervals of elongation of size 2.5 mm, measured by an extensometer to reach the loss of resistance.

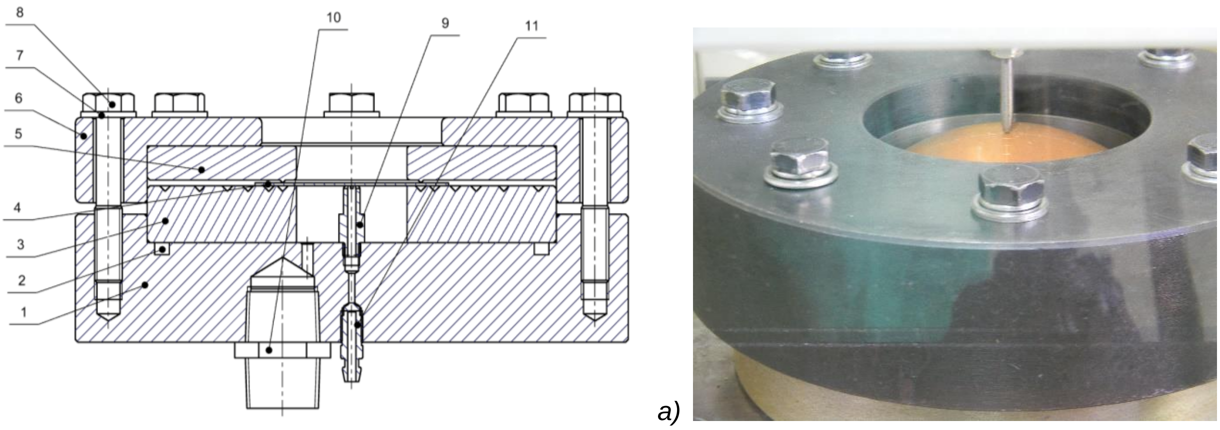
The test bodies for the two-dimensional tensile test were prepared for matrix testing of 100 mm.


a)

b)

Fig.2. Fixed test model of copper for: a) determination of mechanical indexes,
b) determination of presence of anisotropy with an attached extensometer

The two-dimensional tension test was conducted with the developed equipment (fig.3) and methodology of hydraulic bulging in the laboratory of plastic deformation in the Department of Material Science and Technology, protected by dissertation work [19]. The installation for hydraulic bulging was digitized with a controller of NI-6008 for real-time data collection, through software designed to monitor and control the process. The change of the pressure and the height of the inflation were recorded in real-time. On another installation was obtained geometry data set of the bulged sample using a developed 3D scanning system „David Laserscanner 3"(fig.4.a).



a) b)

Fig. 3. Testing by hydraulic blowing of copper: a) with circular molds [19, 21, 22], b) general appearance of the hydraulic bulging

To determine the geometric parameters such as the shape, the radius of the bulging surface and the thickness at the sample pole was developed a software product SA-3DSC (fig.4.b). For correctness in the construction of the hardening curves, it was accepted to use the average radius by the thickness of the sample, which is determined by measuring the outer and inner radii of the scanned sample after establishing the sphericity. The data for the changing of middle radius of the hemisphere and the thickness at the pole were taken sequentially through a set bulging height of 5 mm until the loss of resistance was reached, indicator of which was the moment when the pressure was dropping.

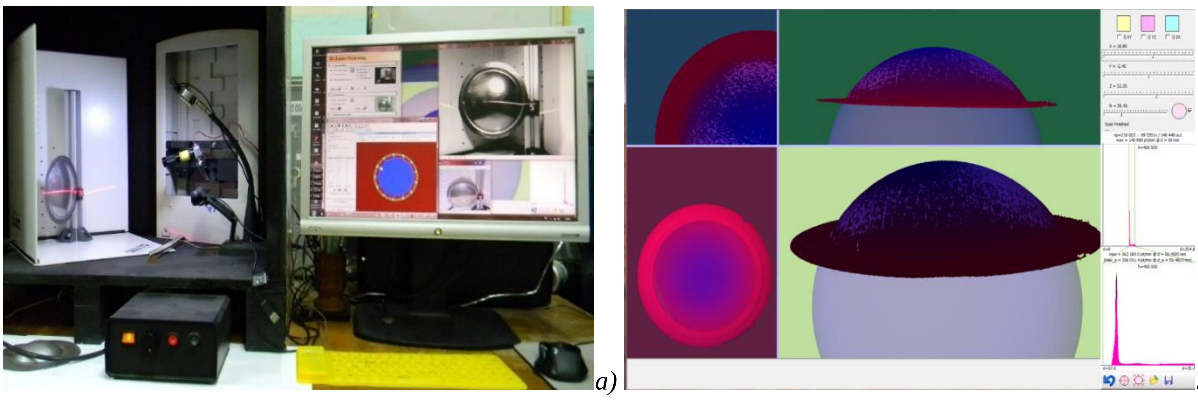

a) b)

Fig. 4. System for analysis of hydraulically bulged model: a) General appearance of the 3D scanning system [19], b) Panel of the software product SA-3DSC for spherical analysis, determining the radius of the digital image and the thickness at the pole

The obtained experimental data was necessary to establish the equations for radius change and the thickness at the pole as a function of the height of the bulge to build the hardening curves. This approach differs from the commonly used method, in which the thickness at the pole is determined analytically by formulas proposed by various authors ( ), and for radius is accepted the radius of the outer spherical surface of the test sample.

RESULTS AND DISCUSSIONS

For researching of the chemical composition of the copper sheet is used GDOES analysis. The obtained results show that the test material is 99,9% copper (table.1). For comparison, in the same table are also presented the literature data on the chemical composition of similar copper sheet materials.

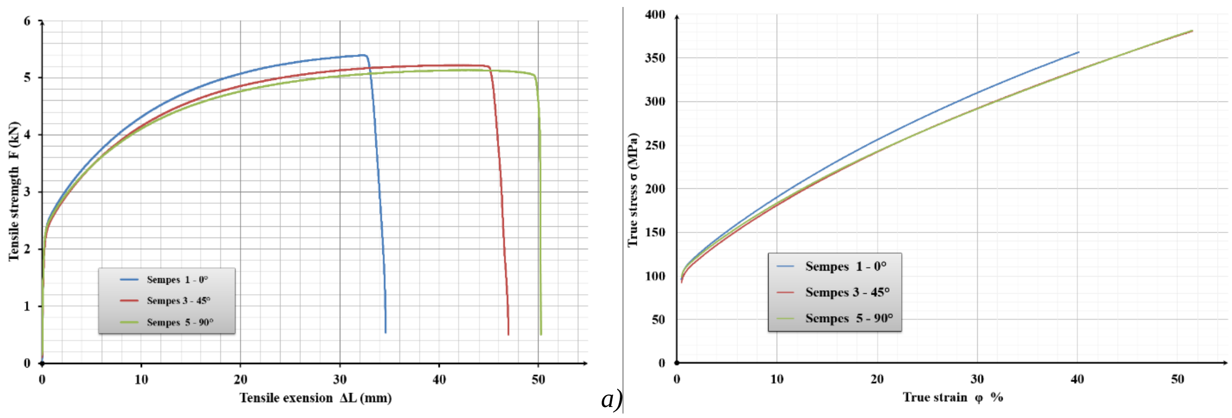
Table 1. Chemical composition of copper sheet in %, with thickness 0.9 mm

Chemical elements		Fe	Ni	S	As	Pb	Zn	O	Sb	Bi	Sn	Cu
Percentage content	min	-	-	-	-	-	-	-	-	-	-	99,9
	max	0,005	0.002	0.004	0.002	0.005	0.004	0.05	0,002	0,001	0,002	-
Analysis obtained from „GDOES“ analiz		0,0043	0,003	0,003	0,0016	0,0045	0,003	<0,045	0,0017	0,001	0,0018	99,9

From the initial study was found a significant difference in the relative extensions of the test bodies in the different directions (fig.5.a). The test models tested in the direction 45º and 90º with respect to the direction of rolling are showing significantly longer elongation than the sample in direction 0º. The probable cause for this behaviour is related to the reorientation of the grains when loading in different directions relative to the exit texture of the material. Previous metallographic studies on rolled materials indicate reorientation and grain shredding under a favorable loading direction [14, 17, 18, 19].

The resulting indicator diagrams of one-dimensional stretching are transformed in charts of true strains and deformations (fig.5.b). From the location of the obtained hardening curves for the three directions is visible, that when is 0° the stress values across the entire study range are higher of those at 45° and 90°. As the degree of strain increases, the difference in the stress raises. The hardening curves at 45° and 90° practically coincide. The reached maximum degree of deformation in both directions 45° and 90° is significantly higher (with over 20%) than in 0°. It should be noted that the maximum degree of deformation with one-dimensional tension reaches 50%. The resulting hardening curve of one-dimensional stretching further on will serve as a comparative analysis with the hardening curve of two-dimensional tension.

The results of the study of the mechanical properties of one-dimensional tension are presented in table 2 together with their limit values according to the literature data. The comparison shows that the obtained experimental data correspond to the literature data for the studied material. The test data indicate the presence of anisotropy. The analysis of the results of the three strands shows, that there is no definite relationship between R_{02} and R_m. For example, while R_m decreases continuously by changing the directional angle relative to the rolling direction, R_{02} has a minimum value at 45°, but in directions 0° and 90° the values are practically identical. The relative elongation A correlates with Rm, while increasing as the test angle changes from 0° to 90°.



a) b)

Fig. 5. Diagrams of the tested specimens of one-dimensional tensile: a) primary indicators, b) true strains and true stress

Table 2. Mechanical characteristics of copper sheet with a thickness 0.9 mm

Index		**R_{02} (MPa)**	**R_m (MPa)**	**A (%)**	**HV**
According to literature data	Min	54	224	20	49
	Max	270	314	65	87
Measured in directions	0º	98,52	239,92	49,51	61,83
	45º	91,98	232,38	63,87	61,83
	90º	98,51	227,83	65,05	61,83

Determination of the anisotropy of the material of one-dimensional tensile test to a deformation degree of 20 % is shown in table 3. Calculation of the private factors R_i and the mean value of normal anisotropy R_{cp} has been performed in the known formulas of V. Lankford (1, 2). For their calculation, are used the full reading values of the extensometer for thickness, width and length (in table 3 are shown their rounded values).

Table. 3. Normal and flat anisotropy

Output dimensions of the test pieces of copper sheet									
Room temperature 25.5°C		Load speed		Working length L_c		Starting width b_0		Starting thickness t_0	
		5 mm/min		65 mm		25 mm		0.9 mm	
Results from the determination of normal anisotropy									
Direction	Deformation degree	Starting width	Starting thickness	Current width	Current thickness	φ_b	φ_t	R_i	R_{cp}
	ε %	b_0 (mm)	t_0 (mm)	b (mm)	t (mm)	-	-	-	-
0°	20	25.08	0.9	24.22	0.85	0,034892	0,057158	0,610443	**0,656155**
45°	20	25.45	0.9	24.2	0.83	0,050363	0,080969	0,622004	
90°	20	25.16	0.9	24.62	0.87	0,021696	0,028171	0,770168	
Results from the determination of flat anisotropy									
Direction	Deformation degree	Starting width	Starting thickness	Current width	Current thickness	φ_b	φ_l	R_i	ΔR_{cp}
	ε %	b_0 (mm)	l_0 (mm)	b (mm)	l (mm)	-	-	-	-
0°	20	25.08	65	24.22	78.85	-0.03489	-0,19311	0,180685	**0,226885**
45°	20	25.45	65	24.2	78.08	-0.05036	-0,1833	0,274765	
90°	20	25.16	65	24.62	73.46	-0,0217	-0,12235	0,177324	

The values of normal anisotropy, which correspond to the literature data on copper, indicate a pronounced anisotropy with a value less than one.

$$R_i = \varphi_b / \varphi_t = \ln\left(\frac{b}{b_0}\right) / \ln\left(\frac{t}{t_0}\right), \quad (1)$$

$$R_{cp} = (R_{0^\circ} + 2R_{45^\circ} + R_{90^\circ})/4 \quad (2)$$

Information about correct evaluation of the behavior of the material in plastic deformation, as it is known, can be obtained by calculating the private factors $\widehat{R}_i$ (3), taking into account the ratio of true width deformation to the true deformation along the length of the sample and the value of the mean plane anisotropy $\Delta\widehat{R}_{cp}$ (4).

$$\widehat{R}_i = \varphi_b / \varphi_l = \ln\left(\frac{b}{b_0}\right) / \ln\left(\frac{l}{l_0}\right) \tag{3}$$

$$\Delta\widehat{R}_{cp} = (\widehat{R}_{0^\circ} - 2.\widehat{R}_{45^\circ} + \widehat{R}_{90^\circ})/2 \tag{4}$$

From the conducted experiment is visible, that the values of the private coefficients of anisotropy, as well as the average coefficient of flat anisotropy are less than one and lower than normal anisotropy. Literature data for the flat anisotropy of the test material, required to compare the obtained results were not found.

At two-dimensional tense state for adjusting the hardening curves usually is taken into account the value of the normal mean anisotropy. Due to the complexity of the deformation by hydraulic bulging should be considered also in the case of hydraulic anisotropy. Additionally, when adopting permanent coefficients of anisotropy for correction we do not account for their alterations in the process of deformation, which can lead to unacceptable results on the hardening curves at two-dimensional tension test. In connection with the need to take account of the change of normal and flat anisotropy was conducted a study with one-dimensional stretching at even intervals of extension of size 2.5 mm. The obtained results are summarized and presented graphically for private factors (fig.6.a) and for the mean values of normal and flat anisotropy (fig.6.b).

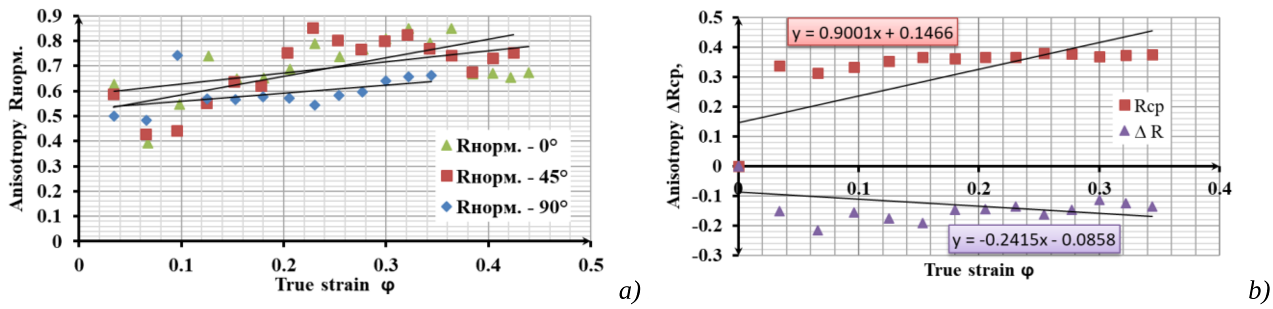


Fig. 6. Dependency of: a) normal anisotropy $R_{i.}$ of the degree of deformation in the three directions of testing, b) mean normal anisotropy R_{cp} and mean flat anisotropy $\Delta \widehat{R}_{cp}$ of the degree of deformation.

The results show, that with increasing the degree of deformation the private factors in all three directions are changing, having a increasing character. A similar pattern is found in the mean normal anisotropy, while the mean flat anisotropy has a decreasing character. To determine the changing of normal anisotropy $R_{cp.}$ in the deformation process was derived an equation (fig.6.b), which will be used for adjusting the hardening curve from two-dimensional tension by introducing it in the proposed equations by Hill from 1948 year (5), from 1978 year (6) and Smith and colleagues (7).

$$\bar{\sigma}_{аниз.} = \bar{\sigma}_{изотр.} \{(r_0 + r_{90})/[r_{90} \times (r_0 + 1)]\}^{1/2} \tag{5}$$

$$\bar{\sigma}_{аниз.} = \bar{\sigma}_{изотр.} \sqrt{2/(1 + R_{cp.})} \tag{6}$$

$$\bar{\sigma}_{аниз.} = \bar{\sigma}_{изотр.} \{2 - [2 \times R_{cp.}/(R_{cp.} + 1)]\}^{1/2} \tag{7}$$

The adjustments should not exclude the influence of the flat anisotropy, which may be included in the above-mentioned equations instead of normal anisotropy.

To correct the equivalent deformations by accounting the anisotropy, established equations for normal and flat anisotropy are introduced into the Smith and colleagues equation [Smit] for deformation, where was made a correction in the numerator, in which the digit 2 in the original equation is replaced by the digit 1[19].

$$\bar{\varphi}_{аниз.} = \bar{\varphi}_{изотр.} / \{2 - [2 \times R_{cp.}/(R_{cp.} + 1)]\}^{1/2} \tag{8}$$

Hill's equation (9) for deformations at two-dimensional tension does not account the difference between anisotropic and isotropic material.

$$\overline{\varphi}_{изотр.} = \ln(t_0 / t) \tag{9}$$

The main equation for calculating the equivalent tension in the pole for the case of isotropicity, known as Hill's equation is:

$$\overline{\sigma}_{изотр.} = (P \times R_{ПС})/(2 \times t) \tag{10}$$

Equivalent tensions $\overline{\sigma}_{изотр.} = \overline{\sigma}$ and deformations $\overline{\varphi}_{изотр.} = \overline{\varphi}$ in the equations (5) ÷ (8) under the premise of isotropy are calculated from the experimentally established equations for the thickness at the pole, the average radius of the dome (hemisphere) and the pressure in function of the height of the bulging. The obtained curves and their variations, together with the corresponding equations (11, 12) are shown in fig.7.a and fig.7.b:

$$R_{ПС} = 901.43 \times h_{ПС}^{-0.827} \tag{11}$$

$$t = -2E - 05 \times h_{ПС}^3 + 0.0003 \times h_{ПС}^2 - 0.0081 \times h_{ПС} + 0.9059 \tag{12}$$

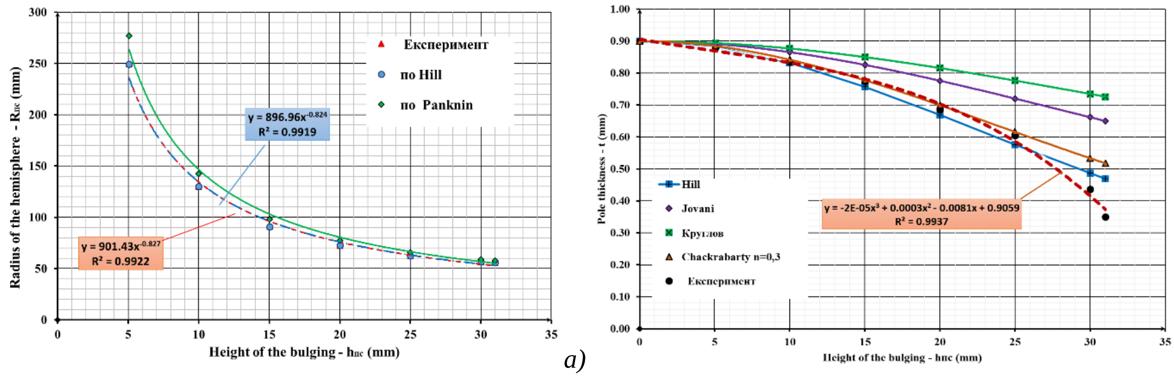


Fig. 7. *Dependency of: a) radius of the hemisphere, b) the thickness at the pole in function of the height of the bulge.*

For comparison on fig.7.a are presented the results of applying the equations of Hill and Pankin (13, 14).

$$R_{ПС} = \frac{\left(\dfrac{d_м}{2}\right)^2 + h_{ПС}^2}{2 \times h_{ПС}} \tag{13}$$

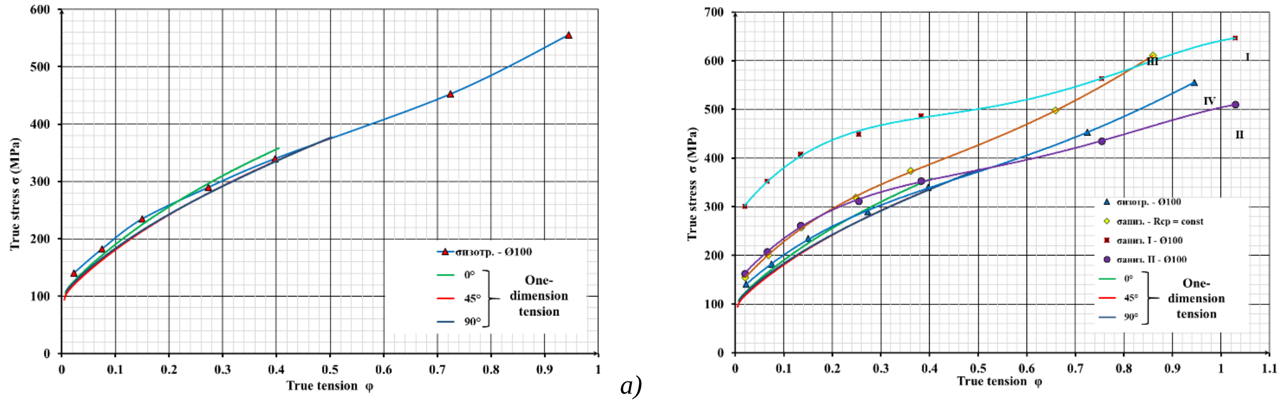
$$R_{ПС} = \frac{\left(\dfrac{d_м}{2} + R_f\right)^2 + h_{ПС}^2 - 2 \times R_f \times h_{ПС}}{2 \times h_{ПС}} \tag{14}$$

As you can see, the curve, according to Hill's equation, almost overlaps with experimentally established curve (the red dashed line). Pankin's equation gives higher values for the radius, especially at smaller heights of bulging. This behavior of moving away to higher values at Pankin's equation is also found for other materials [19]. It is related to the member Rf that he introduced, taking into account the radius of roundness of the matrix in the area of the sample attachment. Higher values of Rпс at low altitudes will lead to displacement of the hardening curve to a higher unreal values of the equivalent strains at the low degree of deformation.

About the change in the thickness of the pole the comparison of the experimentally obtained curve with the curves obtained according to the equations of the mentioned authors shows significant deviations, as in the direction of increase (Kruglov, Jovani), so in the direction of decrease (Hill and Chakrabarti) with the increasing of the bulging height (fig.5.b). These deviations will reflect strongly on the change of the hardening curve. On one side logarithmically calculated true deformation (9) will increase or decrease several times. On other side the equivalent tension (8), will change vastly, as the thickness, which is in the denominator in the equation is multiplied by 2.

On fig.8.a are shown the actual tensions of one-dimensional tension in the three directions of research and the hardening curve of two-dimensional tension with the premise for isotropy, built on the basic equation of Hill (10), where $R_{пс}$ and t are replaced with the equations obtained from the experimental data (11, 12).

The two-dimensional tensile curve is very close to the one-dimensional tensile curves. She is shown as natural extension of the one-dimensional tensile curves at directions 45° and 90°. To degree of deformation of 0.4, the two-dimensional tensile curve shows slightly higher values of tension towards the directions 45° and 90° from the one-dimensional tension (which, as noted above overlap). The tensions from one-dimensional tensile test in direction 0° in the begining have slightly lower values from tensions of two-dimensional tension and after reaching deformation of 0.2 they start to weakly surpass them.



a)

b)

Fig.8. *Curves of true tensions and true stress: a) with the premise for isotropy, b) with corrections for anisotropy.*

On fig.8.b. are shown: the experimental curve of hardening (IV), the curve I built on an equation (5), the curve II built on an equation (6) and the curve III built on an equation (6) with a constant factor for anisotropy.

The largest deviation from the experimental curve (IV) has the curve I, which is built on an equation (5), taking into account equations for the changing of anisotropy in both directions 0° and 90°. The curve II, which was built on Hill's equation (6), accounting for the third direction (45°), is moved equidistantly relative to the curve I to lower tensions and crosses the experimental curve. At the same time,the character of curve II differs than that of the one-dimensional tensile curves, as at the low degrees of deformation it is located above them, and after deformation of 0.5 the curve has a lower values from the experimental curve IV. The built curve III is moved over the experimental curves of one-dimensional and two-dimensional tension, as the degree of deformation increases the deviations are constantly increasing. These results testify, that the examined cases of different adjustment for anisotropy do not provide a satisfactory result, including the attempts to introduce correction through equations for the changing of anisotropy. However it should be noted, that the use of experimentally established equations for the change of $R_{пс}$ and t instead of values obtained from the surface of the bulged sample for $R_{пс}$ and calculated thickness t in the pole of any formula in the literature, gives better results.

CONCLUSIONS

1. From the examination of one-dimensional tension have been obtained objective data for the change of anisotropy during deformation, which allows to be derived the necessary equations;
2. From the experimentally obtained data of two-dimensional tension are derived equations for the changing of the radius and the thickness at the pole of the samples depending on the height of the bulge.

3. It have been achieved a correction in the equations for equivalent tensions and deformations by introduction of the received from the conducted tests equations, as for the geometric parameters - radius of the hemisphere, thickness in the pole, as well as for anisotropy.
4. The study showed that the first Hill equation from 1948 year (without consideration of anisotropy) corresponds best with the one-dimensional tensile curves, while the second Hill equation from 1978 year (taking into account the anisotropy) gives a significant deviation in the direction of increased tensions.

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