DODATNI NAPONI ZBOG SAVIJANJA U PROCESU DUBOKOG IZVLAČENJA

THE EXTRA STRESS BECAUSE OF THE BENDING IN THE PROCESS THE DEEP DRAWING

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REZIME

Opšte rješenje, problema u uslovima ravninskog stanja deformacije za plastično područje, dato je u radu[3]. Ovo rješenje ograničeno je na polarne koordinate i neočvršćavajuće materijale. U radu [4] data su neka pojedinačna rješenja ovakvih ravninskih problema u plastičnom području na bazi opšteg rješenja. Na osnovu prethodno pomenuta dva rada nastao je ovaj rad.

Rezultat ovog rada jeste analitički izraz za izračunavanje dodatnog napona koje se pojavljuje u procesu dubokog izvlačenja zbog savijanja i ispravljanja lima preko radijusa prstena za izvlačenje. Po ovom izrazu, dodatno naprezanje zbog savijanja, u procesu dubokog izvlačenja, direktno je proporcionalno pomjeraju neutralne linije u procesu savijanja lima prema centru savijanja. U stvari, to je vrijednost srednjeg radijalnog napona po debljini lima u procesu savijanja momentima.

Preliminary notes

SUMMARY

The general solution of the plane problem in plastic region was given in the paper [3]. This solution is limited to polar coordinates and the non-hardening material. In the paper [4] are given same individual solutions of problems in the plastics region on the basis of the general solution.

In this paper, on the basis of results of two papers earlier mentioned, the principal normal stresses are calculated in the ideal conditions and polar coordinates, which are the effect of a bending a sheet metal in the process of the deep drawing of rotation caps with a bottom. In this way, the directly calculation of the additional stress because of the bending and the correction of a sheet across a radius of a die for drawing is enabled in mentioned process, which increased stresses in a wall of the cap and a force of drawing.

1. UVOD

Nalaženje sile i deformacionog rada u procesu dubokog izvlačenja rotacionih posuda s dnom vezano je za određivanje ukupnog radnog naprezanja. Kao što je poznato, ovo radno naprezanje dobiva se tako što se na teorijsku vrijednost radijalnog naprezanja dodaju preostala naprezanja koja se pojavljuju u realnim uvjetima.

2. OSNOVNI KOMPONENTNI NAPONI

U uvjetima ravninske deformacije $\varepsilon_z = 0$, za plastično područje je $\nu = 0{,}5$, treće normalno naprezanje $\sigma_z = \dfrac{\sigma_x + \sigma_y}{2} = \dfrac{\sigma_x + \sigma_y}{2} = \sigma_3$ jest i glavno normalno naprezanje.

1. INTRODUCTION

Calculation of the force and deformation work in the process of deep drawing of rotational caps with a bottom is engaged for a determination of the total working stress. As it is known, this working stress is obtained in way that on the theoretical value of radial stress remaining stresses which appears in the real conditions are added.

2. ELEMENTARY COMPONENT STRESS

Under conditions of plane strain $\varepsilon_z = 0$, for plasticity region is $\nu = 0,\ 5$, the third normal stress $\sigma_z = \dfrac{\sigma_1 + \sigma_2}{2} = \dfrac{\sigma_x + \sigma_y}{2} = \sigma_3$ is principal normal stress.

Komponentna naprezanja σ_x, σ_y i τ ($\tau = \tau_{xy} = \tau_{yx}$) mogu se izraziti posredstvom glavnih normalnih naprezanja σ_1, σ_2 i ugla nagiba φ prvog glavnog normalnog naprezanja σ_1 u odnosu na osu x u vidu [1]

The components stress σ_x, σ_y and τ ($\tau = \tau_{xy} = \tau_{yx}$) can be expressed through the principal normal stresses σ_1, σ_2 and the angle of inclination φ of the first principal normal stress σ_1 in respect to axis x as [1]

$$\left.\begin{aligned} \sigma_x &= \frac{\sigma_1+\sigma_2}{2} + \frac{\sigma_1-\sigma_2}{2} cos\, 2\varphi \\ \sigma_y &= \frac{\sigma_1+\sigma_2}{2} - \frac{\sigma_1-\sigma_2}{2} cos\, 2\varphi \\ \tau &= \frac{\sigma_1-\sigma_2}{2} sin\, 2\varphi. \end{aligned}\right\} \tag{1}$$

U ravnini x-y sa

In x-y plane with

$$\sigma = \frac{\sigma_x+\sigma_y}{2} = \frac{\sigma_1+\sigma_2}{2}, \qquad \tau_{max} = \frac{\sigma_1-\sigma_2}{2} \tag{2}$$

određeno je srednje normalno naprezanje σ, koje je invarijantna veličina, i maksimalno tangencijalno (smičuće) naprezanje τ_{max}. Naprezanja σ i τ_{max} djejstvuju na trajektorijama linija klizanja.

the middle normal stress σ, as invariant value and maximal shear stress τ_{max} are defined. The stresses σ, τ_{max} effect on a slide line trajectory.

Po hipotezi najveće deformacione energije utrošene na promjenu oblika (kriterij von Misesa), uvjet početka plastičnog tečenja za ravninsko stanje deformacije izražava se u vidu [2]

According to the hypothesis of the largest deformation energy consumed to the change a shape (criterion of von Mises), the condition of the plasticity flow beginning for plain state of deformation is expressed by [2]

$$\tau_{max} = \frac{\sigma_1-\sigma_2}{2} = \frac{1}{2}\sqrt{(\sigma_x-\sigma_y)^2+4\tau^2} = k_s, \tag{3}$$

gdje je zbog jednostavnijeg izražavanja uvedena reducirana vrijednost k_s specifičnog deformacionog otpora k ($2\, k_s = \frac{2}{\sqrt{3}} k$).

Iz (1), uzimajući u obzir (2) i (3), dobiva se

where for the purpose of simple expression reduced value k_s of specific deformation resistance k ($2k_s = \frac{2}{\sqrt{3}}k$) is introduced. From (1), with the using (2) and (3), system of the differential equations is obtained

$$\left.\begin{aligned} \sigma_x &= \sigma + k_s\, cos\, 2\varphi \\ \sigma_y &= \sigma - k_s\, cos\, 2\varphi \\ \tau &= k_s\, sin\, 2\varphi \end{aligned}\right\} \tag{4}$$

sistem jednadžbi koje zadovoljavaju uvjet plastičnog tečenja. Radi toga kod daljnjeg razmatranja problema i operiranja sa sistemom (4) nije potrebno uzimati u obzir i uvjet plastičnog tečenja, jer će ovaj uvjet biti zadovoljen za proizvoljne vrijednosti ugla φ.

This system satisfies the condition of the plastic flow. In order to a further consideration of the problem and an operation with system (4) the condition of the plastic flow is not needed to take into consideration, because this condition will be satisfied for an arbitrarily value of an angle φ.

3. TRANSFORMACIJA JEDNAČINA RAVNOTEŽE

Polarni sistem koordinata (O; r, φ) postavlja se tako da se podudara (poklapa) s glavnim pravcima normalnih naprezanja σ_1, σ_2. Drugim riječima, polarne koordinate r, φ su i glavni pravci normalnih naprezanja $\sigma_1 = \sigma_r$, $\sigma_2 = \sigma_\varphi$. Tada je veza osnovnih x, y i polarnih koordinata r, φ dana sa

$$x = r \cos \varphi, \quad y = r \sin \varphi. \qquad (5)$$

Diferencijalne jednadžbe ravnoteže elementa koji se nalazi u uvjetima ravninskog stanja, uz zanemarivanje inercionih (zapreminskih) sila može biti predstavljena u vidu

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau}{\partial y} = 0, \; \frac{\partial \tau}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0. \qquad (6)$$

U idealnim uvjetima plastičnog tečenja (bez očvršćavanja) $k_s = const.$, jednadžbe (6), u polarnom koordinatnom sistemu r, φ, transformiraju se u jednadžbu [3]

$$r\frac{\partial \sigma}{\partial r} + \frac{\cos\varphi - \sin\varphi}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s. \qquad (7)$$

Jednadžba (7) je linearna, nehomogene i prvog reda.

3. TRANSVORMATION OF EQUATIONS

Polar system coordinates (O; r, φ) are arranged that coincide to the principal directions of normal stresses σ_1, σ_2. In other words, polar coordinates r, φ are also principal directions of the normal stresses $\sigma_1 = \sigma_r$, $\sigma_2 = \sigma_\varphi$. Then, the connection between elementary x, y and polar coordinates r, φ are given by

$$x = r \cos\varphi, \quad y = r \sin\varphi. \qquad (5)$$

Differential equations of equilibrium of an element which is situated under plane state conditions, ignoring the inertia (volume) force can be presented by

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau}{\partial y} = 0, \quad \frac{\partial \tau}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0. \qquad (6)$$

In ideal conditions of plastic flow (without hardening) $k_s = const.$, in polar system of coordinates r, φ, equation (6) are transformed to equation [3]

$$r\frac{\partial \sigma}{\partial r} + \frac{\cos\varphi - \sin\varphi}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s. \qquad (7)$$

The equation (7) is linear, non homogenous and first order.

4. OPĆE RJEŠENJE

Za jednadžbu

$$r\frac{\partial \sigma}{\partial r} + \frac{\cos\varphi - \sin\varphi}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s \quad (\sigma_r > \sigma_\varphi)$$

prvi nezavisni integrali dani su sa [3]

$$\left.\begin{array}{l} \ln r + \ln(\cos \varphi - \sin \varphi) = C_1 \\ \sigma - 2k_s \ln(\cos \varphi - \sin \varphi) = C_2. \end{array}\right\} \qquad (8)$$

Za jednadžbu

$$r\frac{\partial \sigma}{\partial r} - \frac{\sin\varphi - \cos}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s \quad (\sigma_r < \sigma_\varphi)$$

prvi nezavisni integrali dani su sa [4]

$$\left.\begin{array}{l} \ln r + \ln(\sin \varphi - \cos \varphi) = C_1 \\ -\sigma - 2k_s \ln(\sin \varphi - \cos \varphi) = C_2. \end{array}\right\} \qquad (9)$$

4. GENERAL SOLUTOIN

For equation

$$r\frac{\partial \sigma}{\partial r} + \frac{\cos\varphi - \sin\varphi}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s \quad (\sigma_r > \sigma_\varphi),$$

the first independent integrals is given by [3]

$$\left.\begin{array}{l} \ln r + \ln(\cos \varphi - \sin \varphi) = C_1 \\ \sigma - 2k_s \ln(\cos \varphi - \sin \varphi) = C_2. \end{array}\right\} \qquad (8)$$

For equation

$$r\frac{\partial \sigma}{\partial r} - \frac{\sin\varphi - \cos}{\cos\varphi + \sin\varphi}\frac{\partial \sigma}{\partial x} = -2k_s \quad (\sigma_r < \sigma_\varphi),$$

the first independent integrals is given by [4]

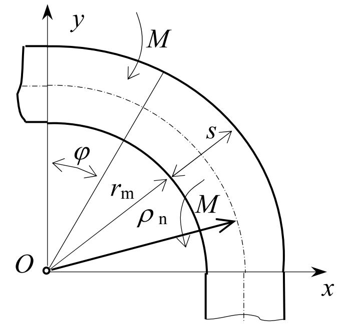
$$\left.\begin{array}{l} \ln r + \ln(\sin \varphi - \cos \varphi) = C_1 \\ -\sigma - 2k_s \ln(\sin \varphi - \cos \varphi) = C_2. \end{array}\right\} \qquad (9)$$

5. SAVIJANJE MOMENTIMA

U procesu dubokog izvlačenja preko zaobljene ivice prstena za izvlačenje polumjera r_m (slika 1) lim se savija. Ako se pretpostavi da se u procesu ne koristi držač lima, zanemari trenje između alata i radnog dijela može se uzeti da se savija momentima u plastičnom području.

5. BENDING WITH MOMENTS

In the deep drawing process over a round rim of the drawing die with radius r_m (Figure 1) a sheet is bent. If it is supposed that in the process of drawing the blank holder does not use, the friction between a tool and a piece of work is neglected, then can be suppose that it is buckled with moments in the plastic region.



Slika 1. *Savijanje momentima*
Figure 1. *Bending and correcting with the moments*

Glavno radijalno naprezanje σ_r po čitavom presjeku je tlačno. Glavno obimno naprezanje σ_φ tlačno je u zoni $r < \rho_n$ i vlačno za $r > \rho_n \leq r_m + s = R_1$, gdje je ρ_n polumjer neutralnog vlakna. Treće glavno normalno naprezanje $\sigma_\theta = \frac{\sigma_r + \sigma_\varphi}{2}$, pod uvjetom da se proces odvija u uvjetima ravninskog deformiranja.

Uz pretpostavku da nema očvršćavanja, postavljanje pravouglog koordinatnog sistema u centar polumjera r_m, tačaka O, prstena za izvlačenje omogućava korištene općih rješenja danih u radovima [3,4].

U zoni $r > \rho_n$ prvo glavno normalno naprezanje je obimno naprezanje σ_φ $(\sigma_r < \sigma_\varphi)$. Srednje normalno naprezanje $\sigma = \sigma_\theta$, za plastično deformiranu oblast, dano je sa [4]

$$\sigma = k_s\left(1 - 2\ln\frac{R_1}{r}\right). \tag{10}$$

Koristeći uvjet plastičnog tečenja i definiciju srednjeg normalnog naprezanja σ

$$\left.\begin{aligned} \sigma_\varphi - \sigma_r &= 2k_s \\ \sigma_r + \sigma_\varphi &= 2\sigma, \end{aligned}\right\} \tag{11}$$

dobivaju se vrijednosti druga dva glavna normalna naprezanja

The principal radial stress σ_r around a complete cross-section is compressive stress. The principal circumferential stress σ_φ in the zone $r<\rho_n$ is compressive stress and tensile stress for $r > \rho_n \leq r_m + s = R_1$, where the ρ_n is radius of the neutral surface. The third principal normal stress is given by $\sigma_\theta = \frac{\sigma_r + \sigma_\varphi}{2}$, under the condition the process is evolved in the condition of plane deformation state.

Under the suppose that the process is evolved in non hardening condition, putting the rectangular coordinate systems in the center of the radius r_m, the point O of the drawing die, enable the application of the solutions given in the papers [3, 4].

In the zone $r > \rho_n$ the first principal stress is circumferential stress σ_φ $(\sigma_r < \sigma_\varphi)$. The middle normal stress $\sigma = \sigma_\theta$, in the plastic region, is given by [4]

$$\sigma = k_s\left(1 - 2\ln\frac{R_1}{r}\right). \tag{10}$$

Using the condition of plastic flow (3) and definition of the middle principal normal stress σ

$$\left.\begin{aligned} \sigma_\varphi - \sigma_r &= 2k_s \\ \sigma_r + \sigma_\varphi &= 2\sigma, \end{aligned}\right\} \tag{11}$$

the values of other normal stresses are obtained as

$$\left.\begin{aligned}\sigma_r &= -2k_s \ln\frac{R_1}{r}\\ \sigma_\varphi &= 2k_s\left(1-\ln\frac{R_1}{r}\right).\end{aligned}\right\} \quad (12)$$

U zoni r < ρ_n sva tri glavna normalna naprezanja su naprezanja pritiska. Prvo glavno normalno naprezanje je radijalno naprezanje σ_r ($\sigma_r > \sigma_\varphi$). Srednje normalno naprezanje $\sigma = \sigma_\theta$, za plastično deformiranu oblast, dano je sa [4]

$$\sigma = -k_s\left(1+2\ln\frac{r}{r_m}\right). \quad (13)$$

Koristeći uvjet plastičnog tečenja i definiciju srednjeg normalnog naprezanja

$$\left.\begin{aligned}\sigma_r - \sigma_\varphi &= 2k\\ \sigma_r + \sigma_\varphi &= 2\sigma,\end{aligned}\right\} \quad (14)$$

dobivaju se vrijednosti druga dva glavna normalna naprezanja koja djejstvuju u uzdužnim ravninama

$$\left.\begin{aligned}\sigma_r &= -2k_s \ln\frac{r}{r_m}\\ \sigma_\varphi &= -2k_s\left(1+\ln\frac{r}{r_m}\right).\end{aligned}\right\} \quad (15)$$

6. DODATNO NAPREZANJE ZBOG SAVIJANJA

Ukupno naprezanje, pri proračunu sile u procesu dubokog izvlačenja, sadrži i naprezanje zbog savijanja i ispravljanja lima preko zaobljene ivice prstena za izvlačenje. Prema slici 2 srednja vrijednost obimnog naprezanja $\sigma_{\varphi s}$ po debljini lima na mjestu savijanja i također na mjestu ispravljanja lima (slika 1) može se izraziti sa

$$\left.\begin{aligned}\sigma_r &= -2k_s \ln\frac{R_1}{r}\\ \sigma_\varphi &= 2k_s\left(1-\ln\frac{R_1}{r}\right).\end{aligned}\right\} \quad (12)$$

In the zone r < ρ_n every three the principal normal stresses are compressive stress. The first principal normal stress is radial stress σ_r ($\sigma_r > \sigma_\varphi$). The middle normal stress $\sigma = \sigma_\theta$, in the plastic region, is given by [4]

$$\sigma = -k_s\left(1+2\ln\frac{r}{r_m}\right). \quad (13)$$

Using the condition of plastic flow (3) and definition of the middle principal normal stress

$$\left.\begin{aligned}\sigma_r - \sigma_\varphi &= 2k\\ \sigma_r + \sigma_\varphi &= 2\sigma,\end{aligned}\right\} \quad (14)$$

values of other two principal normal stresses acting in longitudinal planes are obtained as

$$\left.\begin{aligned}\sigma_r &= -2k_s \ln\frac{r}{r_m}\\ \sigma_\varphi &= -2k_s\left(1+\ln\frac{r}{r_m}\right).\end{aligned}\right\} \quad (15)$$

6. THE EXTRA CIRCUMFERENTIAL STRESS

Total strain, when calculating the forces in the process of deep drawing, includes a strain due to bending and straightening the sheet over the rounded edges of the pull ring. According to Figure 2, the mean value of extensive stress $\sigma_{\varphi s}$ by the thickness of the sheet at the point of bending and also at the point of correcting plate (Figure 1) can be expressed with.

$$\sigma_{\varphi s} = \frac{1}{s}\int_{r_m}^{R_1}\sigma_\varphi dr = \frac{1}{s}2k_s\left(\int_{\rho_n}^{R_1}(1-\ln\frac{R_1}{r}) - \int_{r_m}^{\rho_n}(1+\ln\frac{r}{r_m})\right)dr .$$

Nakon integracije dobiva se

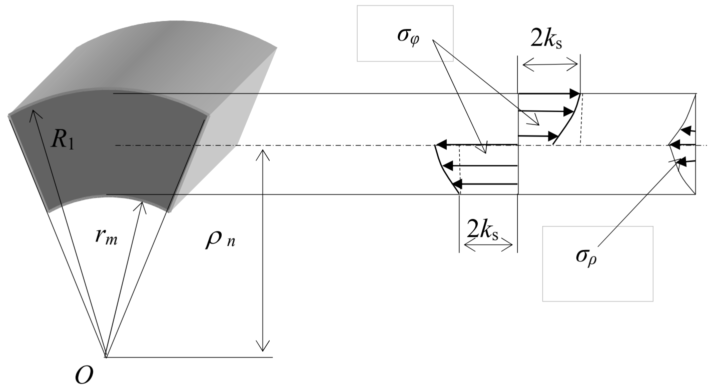
After integration an expression can be given by

$$\frac{1}{s}\int_{r_m}^{R_1}\sigma_\varphi dr = \frac{1}{s}2k_s(R_1 - 2\rho_n + r_M + \rho_n \ln\frac{R_1 r_M}{\rho_n^2}) .$$

Ako se za polumjer neutralne linije uzme vrijednost [ ] $\rho_n = \sqrt{R_1 r_M}$ dobiva se

If the radius of the neutral axis takes the value [6] $\rho_n = \sqrt{R_1 r_M}$ a relation is given as

$$\sigma_{\varphi s} = \frac{2k_s}{s}(R_1 - 2\sqrt{R_1 r_M} + r_M) = \frac{4k_s}{s}(\frac{R_1 + r_M}{2} - \rho_n) . \quad (16)$$



Slika 2. *Dijagrami naprezanja*
Figure 2. *Diagram of the stresses*

U izrazu (16) na lijevoj strani u zagradi pojavljuje se razlika između vrijednosti srednjeg polumjera $\rho_s = \frac{R_1 + r_m}{2}$ i neutralnog polumjera $\rho_n = \sqrt{R_1 r_m}$ savijenog lima. Prema tome, kod savijanja lima momentima pojavljuje se i obimna sila, što je suprotno od dosadašnjih shvaćanja da kod savijanja lima momentima ova sila ne postoji.
Prema slici 1 u prvoj operaciji procesa dubokog izvlačenja pojavljuje se dodatno naprezanje $\Delta\sigma_\rho$ zbog savijanja i ispravljanja lima s vrijednošću dva puta većom od $\sigma_{\varphi s}$ iz (16), tj. $\Delta\sigma_\rho = \frac{2k_s}{s}\left(\frac{R_1 + r_m}{2} - \sqrt{R_1 r_m}\right)$, odnosno

$$\Delta\sigma_\rho = 2k_s \frac{\rho_s - \rho_n}{s}. \qquad (17)$$

In the expression (16) on the left in parentheses appears the difference between the value of the middle radius $\rho_s = \frac{R_1 + r_m}{2}$ and neutral radius $\rho_n = \sqrt{R_1 r_m}$ of bended sheet. Thus, in the case of the sheet bending with moments appear circumferential forces also, what is opposed to the current understanding that in the case of the sheet bending with moments this force does not exist. Referring to Figure 1 in the first operation of deep drawing process occurs additional stress $\Delta\sigma_\rho$ due to bending and correction of sheet with a value greater twice than $\sigma_{\varphi s}$ from (16), i.e $\Delta\sigma_\rho = \frac{2k_s}{s}\left(\frac{R_1 + r_m}{2} - \sqrt{R_1 r_m}\right)$,

$$\Delta\sigma_\rho = 2k_s \frac{\rho_s - \rho_n}{s}. \qquad (17)$$

7. ZAKLJUČAK

Rezultat ovog rada jest analitički izraz (17) za izračunavanje dodatnog naprezanja $\Delta\sigma_\rho$ koje se pojavljuje u procesu dubokog izvlačenja zbog savijanja i ispravljanja lima preko polumjera r_M prstena za izvlačenje. Po ovom izrazu, dodatno naprezanje zbog savijanja $\Delta\sigma_\rho$ direktno je proporcionalno pomjeraju neutralne linije, $\rho_s - \rho_n$, u procesu savijanja lima prema centru savijanja.
Ustvari, to je vrijednost srednjeg obimnog naprezanja $\sigma_{\varphi s}$ (16) po debljini lima u procesu savijanja momentima. Ovo je suprotno od dosadašnjih shvaćanja da u procesu savijanja momentima srednje obimno naprezanje $\sigma_{\varphi s}$ je jednako nuli kod ne očvršćavajućih materijala [5].

7. CONCLUSION

The result of this paper is the analytical expression (17) for the calculation of additional stress $\Delta\sigma_\rho$ which is appeared in the process of deep drawing because of the bending and correcting a sheet across the rim of the draw-die. According to this expression, the additional stress because of the bending $\Delta\sigma_\rho$, in the process of deep drawing, is directly proportional to the neutral line shift, $\rho_s - \rho_n$, to center of bending a sheet.
In fact, it is the value of the mean circumference stress $\sigma_{\varphi s}$ (16) by the thickness of the sheet in the process of bending with moments. This is contrary to previous understanding that in the process of bending with moments mean circumference stress $\sigma_{\varphi s}$ is equal to zero for no-hardening materials [5].

U dosadašnjoj praksi smatralo se da dodatno naprezanje, u procesu dubokog izvlačenja zbog savijanja lima, nastaje na dijelu trase prstena gdje se pojavljuje skokovita izmjena njegovog polumjera. Na toj ideji dolazilo se do ovog dodatnog naprezanja posredstvom izjednačavanja radova obimne sile i momenta savijanja [6]. Pri tome se kod izračunavanja momenta M za polumjer neutralne linije koristio izraz $\rho_n = \sqrt{R_1 r_m}$, a kod izračunavanja dodatnog naprezanja $\Delta\sigma_p$ koristio se izraz $\rho_n = r_m + 0{,}5\, s$.

In the to date practice it is supposed that the additional stress, in the process of deep drawing because of the bending a sheet, rises on the part of die where exists a significant change of its curvature. On this idea, the calculation of this additional stress was done through the process of equalization the works of the forces and moment of the bending on the neutral line. In the same time, for the calculation of the moment M for radius of neutral line the expression $\rho_n = \sqrt{R_1 r_m}$ is used and for the calculation of additional stress $\Delta\sigma_p$ an expression $\rho_n = r_m + 0{,}5$ s is used.

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