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AN ANALYSIS AND MODELLING OF SPINNING PROCESS WITHOUT WALL-THICKNESS REDUCTION

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Through the spinning process it is made the different axial-symmetrical parts by acting spinning roller on blank of sheet metal, which is shaped through a chuck. In the paper is shown an analyse of stressed and strained state, as well as forming force components of spinning process. On the ground of experimental results it is made mathematical modelling of spinning forming force. The obtained mathematical model describes enough accurate and reliable (P = 0,98) the spinning forming force.

Key words: *modelling, spinning, forming force*

Analiza i modeliranje procesa rotacijskog tiskanja bez stanjenja debljine stjenke. Rotacijskim tiskanjem se dobiju različiti osnosimetrični dijelovi djelovanjem pritisnog valjka na pripremak, koji pri deformiranju prijanja uz rotirajući trn. U radu je prikazana analiza napregnutog i deformacionog stanja, kao i komponenata sile procesa rotacijskog tiskanja. Na osnovi eksperimentalnih rezultata izvedeno je matematičko modeliranje deformacijske sile tiskanja. Dobiveni matematički model dovoljno točno i pouzdano (P = 0,98) opisuje silu procesa rotacijskog tiskanja.

Ključne riječi: *modeliranje, rotacijsko tiskanje, deformacijska sila*

INTRODUCTION

The modelling of spinning process is similarly to the process of deep drawing. The workpiece is flat blank.

It is obtained by this processing through simple pressing roller the parts of complex form of good mechanical characteristics and surface which quality is near to the quality obtained after grinding.

It can be obtained the different axial-symmetrical parts. The working parts are divided to symmetrical, conical with curved drawing and combined parts. The spinning process doesn't enable to produce of unsymmetrical parts [1 - 7].

Tool design that are used for spinning processing is very simple, that secure smaller price and longer the time of explotation life. The same tools can be used for individual operations at the different parts producing.

THEORETICAL BASIS OF SPINNING PROCESS

At the procedure of metal processing through spinning is the main motion circular and it is made by workpiece (5) together with chuck (1) while auxilary motion is made by roller (2) (Figure 1.). The begininng material form for processing is usually circular plate (4) pressed by follower in tailstock (3).

The blank, in this case a plain, sheet-metal disc, is concentrically clamped against the follower by the tailstock and driven via the main spindle. Rotating at high speed, the workpiece is then formed by the spinning roller following a pre-set path to produce a series of strokes or passes. Direction of the material flowing speed (v_m) during deformation process is the same to the axial speed (v) of pressed roller.

Geometry of spinning procedure

It is obtained by spinning the cylindrical hole parts with bottom as is shown at the Figure 2. The part is made from more operations by the different chucks if it isn't able to get desired cylindrical part from one operation (Figure 2.).

Between chuck and pressed roller (Δ) (Figure 1.) depending on clearance size, the cylindrical parts can be made by reduction and without reduction of wall thickness. The wall thickness and cylinder bottom are the same ($s_1 = s_0$) in the first case and in the second case the wall thickness is smaller than bottom thickness, that is preparing part thickness ($s_1 < s_0$).

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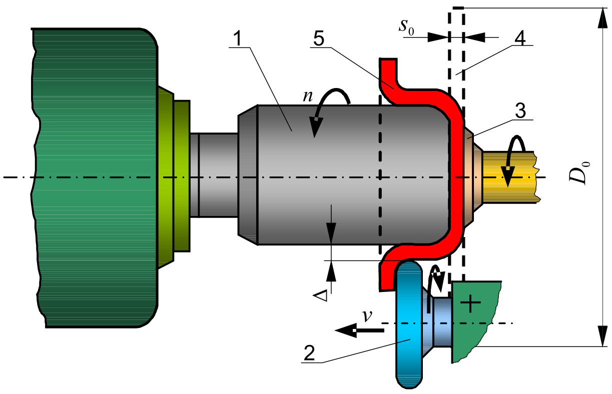

Figure 1. **Schema of spinning process**
Slika 1. **Shema procesa rotacijskog tiskanja**

Stress - strain state

The spinning process (Figure 1.), is very similar to deep drawing process to tools at the press. The process is carried out in one pass from circular plain preparing part. For full

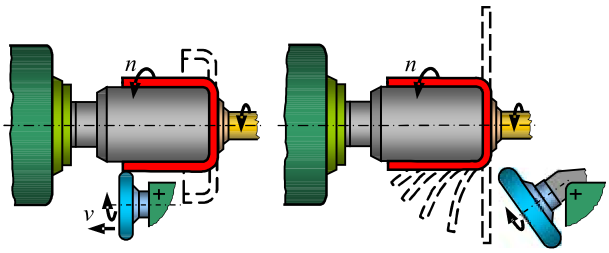

Figure 2. **Spinning process**
Slika 2. **Proces rotacijskog tiskanja**

analysing of strained and stressed state at the spinning it is needed to divide workpiece into several different zones (Figure 3.) at which are occured different schemes of strain and stress [4, 7].

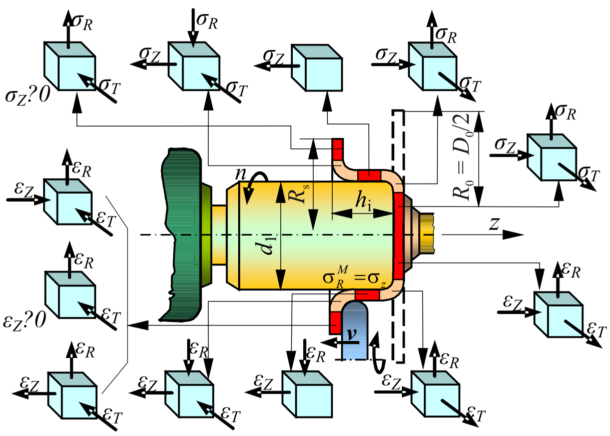

Figure 3. **Strain and stresses distribution by spinning process**
Slika 3. **Raspodjela deformacija i naprezanja kod procesa rotacijskog tiskanja**

The stress state is treated as flat at the element wreath, where it is considered that forming of material is acted by absence of normal stress σ_Z=0. This stress state is unlike in according to radial stress (σ_R) positive and normal stress at the tangent direction is negative (σ_T).

In the element wreath for an analyse of strain and stress is used the method of common soluting of plasticity conditions in the form:

$$\sigma_R - \sigma_T = \pm \beta k, \tag{1}$$

and balance equation:

$$\rho \frac{d\sigma_R}{d\rho} + \sigma_R - \sigma_T = 0, \tag{2}$$

so that we get differential equation:

$$\rho \frac{d\sigma_R}{d\rho} + \beta k = 0. \tag{3}$$

We get through soluting of differential equation (3) for boundary conditions ($\rho = R_S$, $\sigma_R = 0$) radial stressed component that incites plastic deformation at the element wreath:

$$\sigma_R = \beta \cdot k_{sr} \ln \frac{R_S}{\rho} \tag{4}$$

where is:

k_{sr} - the average value of specific flow stress,
R_S - the immediate value outsideed wreath radius of cylinder (from r_1 to R_0),
ρ - radius inside of intervals $r_1 \le \rho \le R_0$.

It is getting through involving of express (4) with condition of plastic flow (1) the normal stress at the tangent direction:

$$\sigma_T = \beta \cdot k_{sr} \left(\ln \frac{R_S}{\rho} - 1 \right). \tag{5}$$

At the spinning of cylindrical elements without reducing of wall thickness the maximum axial stress is defined helping expression:

$$\sigma_{Z_{max}} = \left(1,1 k_{sr} \ln \frac{R_S}{r_1} + k_{sr} \frac{s_0}{2\rho_w + s_0} \right) (1 + 1,6\mu) \tag{6}$$

where:

$$R_S = 0,5 \sqrt{D_0^2 - 4 d_{1sr} \left[h + 0,57 \left(\rho_w + R + s_0 \right) \right]}.$$

Maximum axial stress $\left(\sigma_{Z_{\max}}\right)$, obtained by $h = 0$.

Degree of deformation

The fitted relative strain at the element wreath are:
- at the tangent direction:

$$\varepsilon_T = \frac{\rho}{\sqrt{R_0^2 + \rho^2 - R_S^2}} - 1, \tag{7}$$

- at the radial direction (direction of sheet of metal thickness):

$$\varepsilon_R = \frac{1 - 2\ln\dfrac{R_S}{\rho}}{2 - \ln\dfrac{R_S}{\rho}} \cdot \varepsilon_T, \tag{8}$$

- at the axial direction:

$$\varepsilon_Z = -\left(\varepsilon_T + \varepsilon_R\right). \tag{9}$$

At the immediate strained zone it is normal strains under pressed roller:

$$\varepsilon_T = \frac{d_1}{a_i} - 1,$$
$$\varepsilon_R = \varepsilon_S = \frac{s_1 - s_0}{s_0} \approx 0,$$
$$\varepsilon_Z = \varepsilon_h = \frac{2h_i - \left(a_i - d_1\right)}{a_i - d_1}. \tag{10}$$

where:

$a_i = \sqrt{d^2 + 4d_1\left(h_i + 0,75R\right)}$ - the immediate value of workpiece diameter which was deformed in the cylinder of h_i height.

Logarithmic strain at the part under pressed roller are defined by expressions:

$$\varphi_T = \ln\frac{d_1}{a_i}, \quad \varphi_R = \ln\frac{s_1}{s_0} \approx 0, \quad \varphi_Z = \ln\frac{2h_i}{a_i - d_1}. \tag{11}$$

Forming forces of the spinning process

The axial components of force is determined by expression:

$$F_Z = F_A = \sigma_{Z_{\max}} \cdot A_Z, \tag{12}$$

unless the contact surface of axial force:

$$A_Z = 2ls_0 = 2s_0\sqrt{d_w \cdot \frac{v}{n}}. \tag{13}$$

On the basis of plastic flowing condition the maximum radial strain expresses:

$$\sigma_{R_{\max}} = \sigma_Z + 1,15k_{sr} \tag{14}$$

and

$$A_R = 2\frac{v}{n}\sqrt{d_w \cdot \frac{v}{n}} \tag{15}$$

or the maximum component of force is:

$$F_{R_{\max}} = \sigma_{R_{\max}} \cdot A_R. \tag{16}$$

Owing to simplifying the state of deformation it is taken into account the plane state of deformation and the tangent stress is:

$$\sigma_{T_{\max}} = \frac{\sigma_Z + \sigma_R}{2} = \frac{1,15k_{sr}}{2} \tag{17}$$

and tangent components of force:

$$F_{T_{\max}} = \sigma_{T_{\max}} \cdot A_T \tag{18}$$

where the contact surface is:

$$A_T = \frac{1}{2}s_0\sqrt{2\rho_w \cdot \frac{v}{n}}. \tag{19}$$

The experimental researchings are shown that the maximum radial force occurs immediatelly at the end of spinning of cylindrical part. The axial stress in this moment equals zero ($\sigma_Z = 0$). Total force:

$$F = \sqrt{F_A^2 + F_R^2 + F_T^2}. \tag{20}$$

THE EXPERIMENTAL ANALYSIS OF THE PROCESS

The experimental analyse of spinning process is made in the aim of measuring the forming forces which are used for modelling and simulation ot the spinning process (Figure 4.).

The experimental tool for measuring spinning force components

In Figure 5. is given the presentation of force compo-

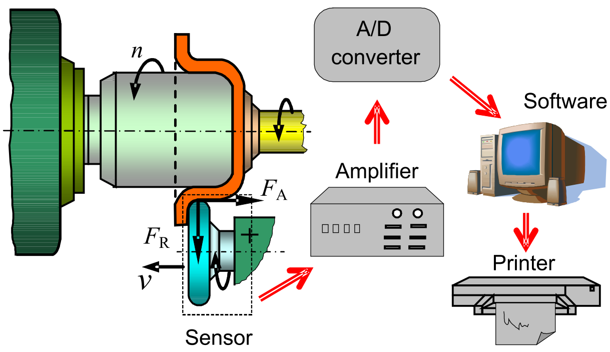

Figure 4. **Presentation of measuring system**
Slika 4. **Prikaz mjernog sustava**

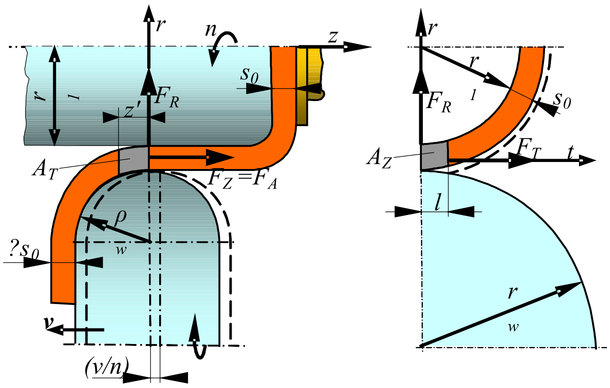

Figure 5. **The spinning force components**
Slika 5. **Komponenate sile procesa rotacijskog tiskanja**

nents at the spinning and Figure 6. is shown the experimental tool for measuring spinning force components.

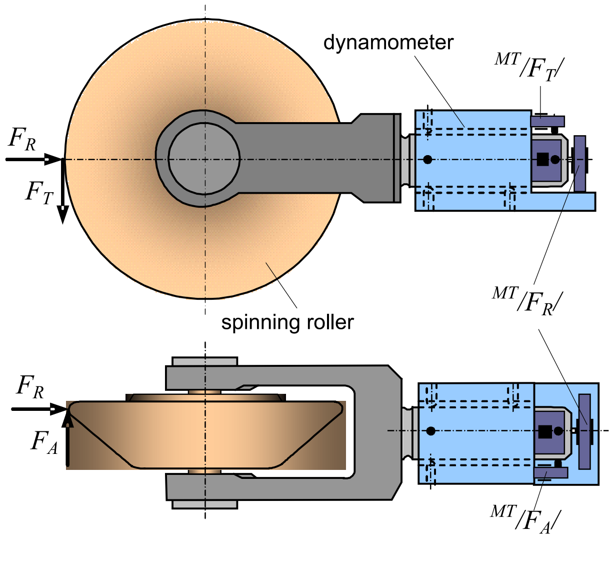

Figure 6. **The experimental tool with built-in force sensors [2] F_A, F_R and F_T**
Slika 6. **Eksperimentalni alat s ugrađenim senzorima sila [2] F_A, F_R i F_T**

The experimental results

On the basis of acquired data for material, revolutions numbers of the main spindle, the feed of pressed roller, roller diameter, lubrication means are obtained the values of force components depends on roller motion (Table 1.).

Table 1. **The experimental results of spinning forces**
Tablica 1. **Eksperimentalni rezultati sile rotacijskog tiskanja**

Trial N_j	The physical variables of processes			The experimental values of forces			
	v / mm/min	s / mm	h / mm	F_A / N	F_R / N	F_T / N	F / N
1	100	1,0	5	127	129	33	184
2	200	1,0	5	160	157	44	228
3	100	2,0	5	215	222	57	314
4	200	2,0	5	252	255	69	365
5	100	1,0	25	199	358	56	413
6	200	1,0	25	241	441	71	508
7	100	2,0	25	326	580	95	672
8	200	2,0	25	371	673	111	776
9	150	1,5	15	402	233	102	476
10	150	1,5	15	378	220	95	448
11	150	1,5	15	408	218	98	473
12	150	1,5	15	409	228	106	480

In the Figure 7. are given the obtained experimental values for Č0148 (DIN St14) and s_0 = 1 mm.

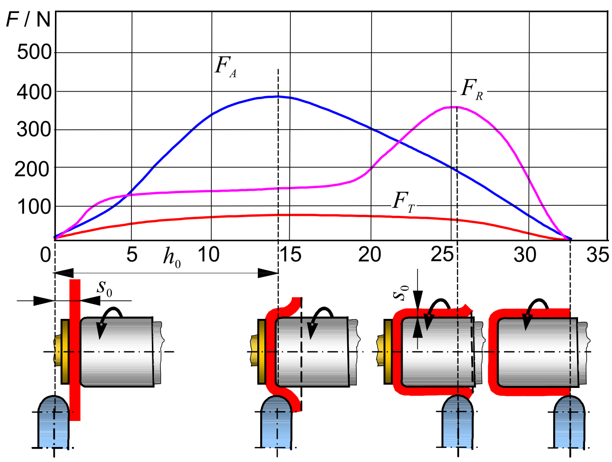

Figure 7. **Force components of spinning**
Slika 7. **Komponentne sile rotacijskog tiskanja**

Analyzing recorded diagrams it can be concluded the following:

- the pressed roller moves during the process by constant speed,
- the tangent component has nearly constant value during the process,
- the maximum value of radial force occurs at the end of the process,
- the decreasing of axial force after reaching of maximum is stepped (at the cylindrical parts obtained through combined action) but at the parts obtained without reducing the decreasing of axial force is extended.

FORCE MODELLING

The parameter choosing of spinning process

On the basis of the experimental results is made a modelling of spinning force (Table 1.).

The varying parameters are defined over input variables of process which define the experiment conditions varying at the three levels: axial speed of pressed roller, v /(mm/min), wall thickness of the blank, s /mm and pressed roller path, h /mm.

The constant parameters of process are: material of preparing part, radius of cycled tools, diameter and product, etc. [1].

Table 2. **The physical and coded values of process parameters**
Tablica 2. **Fizikalne i kodirane vrijednosti parametara procesa**

Influencing parameters	The coded and physical values of input parameters			
Coded parameters	X_i	–1	0	1
Physical parameters	$X_1 = v$	100	150	200
	$X_2 = s$	1,0	1,5	2,0
	$X_3 = h$	5	15	25

The defining of mathematical model

The number of experiment needed for modelling is defined by expression:

$$N = 2^k + n_0 = 2^3 + 4 = 12,$$

where:

N - the total experiment number,
k - number of parameters,
n_0 - the replied experiment number at the central point of a plan.

The force function of spinning is modelled by following polynom function at the coded form:

$$Y = F = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + + b_{23} X_2 X_3 + b_{13} X_1 X_3 + b_{123} X_1 X_2 X_3 \qquad (21)$$

The further modelling action understand the determining coefficients of mathematical model to expression:

$$b_0 = \frac{1}{N}\sum_{j=1}^{N} y_j,$$
$$b_i = \frac{1}{N-n_0}\sum_{j=1}^{N} X_{ij} y_j, \ \text{za} \ i = 1,2,...,k,$$
$$b_{im} = \frac{1}{N-n_0}\sum_{j=1}^{N} X_{ij} X_{mj} y_j, \ \text{za} \ 1 \le i < m < k. \qquad (22)$$

where:

b_0, b_i, b_{im} - coefficients of mathematical model,
X_{ij}, X_{mj} - coded values.

The values of the coefficient of mathematical models are:

$b_0 = 442$; $b_1 = 37$; $b_2 = 99$; $b_3 = 160$;
$b_{12} = 2{,}078$; $b_{23} = 32{,}58$; $b_{13} = 13$; $b_{123} = 0{,}481$.

Taking in attention only significant coefficients of regression, the mathematical model of force has the form:

$$Y = F = 442 + 37 X_1 + 99 X_2 + + 160 X_3 + 32{,}58 X_2 X_3 \qquad (23)$$

Table 3. **The experimental and calculated force values (23)**
Tablica 3. **Eksperimentalne i izračunate vrijednosti sile (23)**

Trial N_j	Coded variables of proces			The numerical results of the spinning force / N	
	X_1	X_2	X_3	The experimental values $Y_j = F_j$	Calculated values
1	–1	–1	–1	184	179
2	1	–1	–1	228	253
3	–1	1	–1	314	311
4	1	1	–1	365	385
5	–1	–1	1	413	433
6	1	–1	1	508	507
7	–1	1	1	672	697
8	1	1	1	776	771
9	0	0	0	476	442
10	0	0	0	448	442
11	0	0	0	473	442
12	0	0	0	480	442

The coefficient of multiple regression R = 0,993 shows very good correlation between varying X_i and spinning force F_j.

The mathematical model (23) enough correctly and reliable (P = 0,98) describes the process force of spinning inside the space of applied experiment what shows the comparing of experimental and calculated values (Table 3.).

Encoding the mathematical model (23) is obtained the physical mathematical model of the spinning force in the form of:

$$Y = -59,39 + 0,74v + 100,26s + 6,226h + 6,516s \cdot h \quad (24)$$

CONCLUSIONS

In according to deep drawing this procedure has defined advantages:
- enable producing of complex products,
- deformation is made in the part under pressed roller, unless at deep drawing at the whole volume of part countour,
- the tools are more simple design than the tools of deep drawing,
- the tool life is longer and tool costs are smaller,
- smaller forming force,
- the tool is flexibile because the same can be used for different parts producing.

The ground failures are:
- unsymetrical parts cann't be produce,
- smaller production in according to deep drawing.

The mathematical modelling of the force of spinning enough correctly and reliable describes forming force, that are confirmed by obtained model of the that has reliability P = 0,98 and the coefficient of multiple regression R = 0,993.

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List of symbols

n	- revolutions numbers of chuck /min^{-1}
v	- axial speed of pressed roller /(mm/min)
v_m	- the material flowing speed /(mm/min)
D_0	- diameter of workpiece (blank diameter) /mm
d_1	- diameter of rotary chuck (chuck diameter) /mm
r_1	- chuck radius /mm
d	- diameter of finished product /mm
s	- wall thickness /mm
s_0	- initial sheet thickness /mm
d_w	- diameter of pressed roller /mm
ρ_w	- roller radius /mm
h	- pressed roller path /mm
l	- spinning length /mm
d_{1sr}	- the immediate diameter of workpiece wreath /mm
R_0	- blank radius /mm
R_S	- the immediate value outsideed wreath radius of cylinder (from r_1 to R_0) /mm
a_i	- the immediate value of workpiece diameter which was deformed in the cylinder of h_i height /mm
v/n	- spinning feed of roller /mm·rev^{-1}
k	- number of parameters
k_{sr}	- the average value of flow stress /Pa
Δs	- absolute reducing of wall thickness /mm
α_0	- angle of chuck /°
α	- angle of pressed roller /°
β	- Lode coefficient (β = 1,0 to 1,55)
μ	- coefficient of friction
ρ	- radius inside of intervals $r_1 \leq \rho \leq R_0$ /mm
σ_R, σ_Z, σ_T	- radial, axial and tangent stress /Pa
$\sigma_{R_{max}}$, $\sigma_{Z_{max}}$, $\sigma_{T_{max}}$	- maximum stresses in radial, axial and tangent direction /Pa
ε_R, ε_Z, ε_T	- the relative strains in radial, axial and tangent direction
φ_R, φ_Z, φ_T	- logarithmic strains
F_R, F_Z, F_T	- the force components in radial, axial and tangent direction /N
$F_{R_{max}}$, $F_{Z_{max}}$, $F_{T_{max}}$	- maximum force in radial, axial and tangent direction /N
F	- total force /N
A_R, A_Z, A_T	- the pressed contact surface at the radial, axial and tangent direction / mm^2
X_{ij}, X_{mj}	- coded values
n_0	- the replied experiment number at the central point of a plane
b_0, b_i, b_{im}	- coefficients of mathematical model
N	- the total experiment number
MT	- strain gages