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 auxiliary motion is made by roller (2) (Figure 1.). The beginning 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 \( D \) (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 \( s_1 < s_0 \).
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 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].

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 $\sigma_z = 0$. This stress state is unlike in according to radial stress ($\sigma_r$) positive and normal stress at the tangent direction is negative ($\sigma_\theta$).

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

$$\sigma_r - \sigma_\theta = \pm \beta k,$$  

(1)

and balance equation:

$$\rho \frac{d\sigma_r}{d\rho} + \sigma_r - \sigma_\theta = 0,$$  

(2)

so that we get differential equation:

$$\rho \frac{d\sigma_r}{d\rho} + \beta k = 0.$$

(3)

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

$$\sigma_r = \beta \cdot k_w \ln \frac{R_S}{\rho},$$

(4)

where is:

- $k_w$ - the average value of specific flow stress,
- $R_S$ - the immediate value outsideed wreath radius of cylinder (from $r_1$ to $R_S$),
- $\rho$ - radius inside of intervals $r_1 \leq \rho \leq R_w$.

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

$$\sigma_\theta = \beta \cdot k_w \left\{ \ln \frac{R_S}{\rho} - 1 \right\},$$

(5)

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

$$\sigma_{z_{\text{ax}}}= \left[ 1,1k_w \ln \frac{R_S}{r_1} + k_w \frac{s_0}{2\rho_u + s_0} \right] \left( 1 + 1,6\mu \right),$$

(6)

where:

$$R_S = 0.5\sqrt{D_0^2 - 4d_w \left[ h + 0.57\left( \rho_u + R + s_0 \right) \right]}.$$
Maximum axial stress \( \sigma_{Z_{\text{max}}} \), obtained by \( h = 0 \).  

**Degree of deformation**

The fitted relative strain at the element wreath are:
- at the tangent direction:
  \[
  \varepsilon_T = \frac{\rho}{\sqrt{R_0^2 + \rho^2 - R_h^2}} - 1,
  \]
  
- at the radial direction (direction of sheet of metal thickness):
  \[
  \varepsilon_R = \frac{1 - 2 \ln R_s}{2 - \ln R_i} \cdot \varepsilon_T,
  \]
  
- at the axial direction:
  \[
  \varepsilon_Z = - (\varepsilon_T + \varepsilon_R).
  \]

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

\[
\varepsilon_T = \frac{d_i}{a_i} - 1, \\
\varepsilon_R = \varepsilon_S = \frac{s_i - s_0}{s_0} \approx 0, \\
\varepsilon_Z = \varepsilon_h = \frac{2h_i - (a_i - d_i)}{a_i - d_i}.
\]

where:

\[
a_i = \sqrt{d_i^2 + 4d_i (h_i + 0.75R)} - \text{the immediate value of workpiece diameter which was deformed in the cylinder of } h_i \text{ height.}
\]

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

\[
\varphi_T = \ln \frac{d_i}{a_i}, \quad \varphi_R = \ln \frac{s_i}{s_0} \approx 0, \quad \varphi_Z = \ln \frac{2h_i}{a_i - d_i}.
\]

**Forming forces of the spinning process**

The axial components of force is determined by expression:

\[
F_Z = F_A = \sigma_{Z_{\text{max}}} \cdot A_Z,
\]

unless the contact surface of axial force:

\[
A_Z = 2ks_0 = 2s_0 \sqrt{\frac{\nu}{n}},
\]

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

\[
\sigma_{R_{\text{max}}} = \sigma_Z + 1.15k_w
\]

and

\[
A_R = 2 \frac{\nu}{n} \sqrt{\frac{d_w \nu}{n}}
\]

or the maximum component of force is:

\[
F_{R_{\text{max}}} = \sigma_{R_{\text{max}}} \cdot A_R.
\]

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

\[
\sigma_{T_{\text{max}}} = \frac{\sigma_Z + \sigma_R}{2} = \frac{1.15k_w}{2}
\]

and tangent components of force:

\[
F_{T_{\text{max}}} = \sigma_{T_{\text{max}}} \cdot A_T,
\]

where the contact surface is:

\[
A_T = \frac{1}{2} s_0 \sqrt{\frac{2k_w \nu}{n}}.
\]

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:

\[
F = \sqrt{F_A^2 + F_R^2 + F_T^2}.
\]

**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 of the spinning process (Figure 4.).

The experimental tool for measuring spinning force components

In Figure 5. is given the presentation of force compo-
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>
<thead>
<tr>
<th>Trial</th>
<th>( N_i )</th>
<th>( v ) ( \text{mm/min} )</th>
<th>( s ) ( \text{mm} )</th>
<th>( h_i ) ( \text{mm} )</th>
<th>( F_x ) ( \text{N} )</th>
<th>( F_z ) ( \text{N} )</th>
<th>( F_r ) ( \text{N} )</th>
<th>( F ) ( \text{N} )</th>
</tr>
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<tr>
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<td>1,0</td>
<td>5</td>
<td>127</td>
<td>129</td>
<td>33</td>
<td>184</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>1,0</td>
<td>5</td>
<td>160</td>
<td>157</td>
<td>44</td>
<td>228</td>
<td></td>
</tr>
<tr>
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<td>5</td>
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<td>222</td>
<td>57</td>
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<tr>
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<td>5</td>
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<td>255</td>
<td>69</td>
<td>365</td>
<td></td>
</tr>
<tr>
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<td>15</td>
<td>409</td>
<td>228</td>
<td>106</td>
<td>480</td>
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</tbody>
</table>

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

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].

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:

\[
Y = F = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{123} X_1 X_2 X_3
\]

(21)

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

\[
b_0 = \frac{1}{N} \sum_{j=1}^{N} y_j,
\]

\[
b_i = \frac{1}{N-n_0} \sum_{j=1}^{N} X_i y_j, \quad za \quad i = 1,2,...,k,
\]

\[
b_{ij} = \frac{1}{N-n_0} \sum_{j=1}^{N} X_i X_j y_j, \quad za \quad 1 \leq i < m < k.
\]

(22)

where:

- \( b_0, b_i, b_{ij} \) - coefficients of mathematical model,
- \( X_i, X_{ij} \) - coded values.

The values of the coefficient of mathematical models are:

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

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

\[
Y = F = 442 + 37 X_1 + 99 X_2 + 160 X_3 + 32,58 X_2 X_3
\]

(23)
The coefficient of multiple regression $R = 0.993$ shows very good correlation between varying $X_i$ and spinning force $F_i$.

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:

$$Y = -59.39 + 0.74v + 100.26s + 6.226h + 6.516s'h$$  \hspace{0.5cm} (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 counter,
- 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 flexible because the same can be used for different parts producing.

The ground failures are:
- unsymmetrical parts can’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 $R = 0.993$.

**REFERENCES**


**List of symbols**

- $n$ - revolutions numbers of chuck /min
- $v$ - 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
- $r_j$ - chuck radius /mm
- $d$ - diameter of finished product /mm
- $s$ - wall thickness /mm
- $s_0$ - initial sheet thickness /mm
- $d_p$ - diameter of pressed roller /mm
- $\rho$ - roller radius /mm
- $h$ - pressed roller path /mm
- $l$ - spinning length /mm
- $d_{w0}$ - the immediate diameter of workpiece
- $R_b$ - blank radius /mm
- $R_S$ - the immediate value outsideed wreath radius of cylinder (from $r_j$ to $R_b$) /mm
- $\sigma_{r}$ - the immediate value of workpiece diameter which was deformed in the cylinder of height $h$ /mm
- $\sigma_{r}$ - the immediate value of workpiece
- $\sigma_{w0}$ - the immediate diameter of workpiece
- $\sigma_{r}$ - absolute reducing of wall thickness /mm
- $\alpha$ - angle of chuck /°
- $\alpha$ - angle of pressed roller /°
- $\beta$ - Lode coefficient ($\beta = 1.0$ to 1.55)
- $\mu$ - coefficient of friction
- $\rho$ - radius inside of intervals $r_j \leq \rho \leq R_b$ /mm
- $\sigma_{r}$ - radial, axial and tangent stress /Pa
- $\sigma_{r}$ - maximum stresses in radial, axial and tangent direction /Pa
- $\epsilon_r$ - the relative strains in radial, axial and tangent direction
- $\varphi_r$ - logaritmic strains
- $\epsilon_r$ - the force components in radial, axial and tangent direction /N
- $F$ - total force /N
- $A_r$ - the pressed contact surface at the radial, axial and tangent direction /mm²
- $X_{ij}, X_{mj}$ - coded values
- $n_{ij}$ - the replied experiment number at the central point of a plane
- $h_{b1}, h_{b2}$ - coefficients of mathematical model
- $N$ - the total experiment number
- MT - strain gages