INFLUENCE OF TECHNOLOGICAL CONDITIONS OF DRAWING ON INHOMOGENEITY OF DEFORMATION UNDER CONDITIONS OF HYDRO-DYNAMIC LUBRICATION

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Abstract

At conventional lubrication during wire drawing it is possible to expect the value of the friction coefficient between 0.05 and 0.13. However, according to some authors it is possible to achieve under conditions of hydrodynamic lubrication (for example with use of compressive dies) a friction coefficient $\mu = 0.0005$, it means hundred times lower. Such values already allow us to consider such technological parameters, which would lead at higher friction coefficients to unacceptably large total forces, or to wire breakage. We focus in this paper on the FEM analysis of drawing with small deformation angles of the die and large partial deformations. We will focus on normal cone die. The first part presents a simulation of drawing with use of small deformation angles, for friction value $\mu = 0.0005$. We analyse the influence of the die geometry on the overall drawing force and the inhomogeneity of deformation intensity over the cross section of wire at single pass drawing.

Key words: wire drawing, spring wire, FEM, friction coefficient, Shear strain, drawing power

1. INTRODUCTION

Steel wires with a carbon content ranging from 0.55 to 0.9 wt.% are intended mainly for the manufacture of ropes and cords for tire reinforcements. Due to the fact that these wires are in a rope or in a cord exposed to alternating tension, compression and torsion, they must have in addition to the high tensile strength, drawability and abrasion resistance also high fatigue strength. Although the wire drawing is considered to belong to the simpler forming technologies, the state of deformation in the working part of the die is complicated by the presence of shear stress. This is a consequence of friction and disadvantageous flow of metal near the surface of the wire, when the trajectory of the material point on the wire surface on the input and output plane of the deformation zone is twice expressively wrapped. In these places we can observe as a result of this phenomenon the areas of the maximum strain rate intensity, which surround the area of difficult deformation [1]. The shear stress in the vicinity of the surface causes an inhomogeneity of deformation intensity over the cross-section of wire, and thus also the differences in the material strengthening, in its structure and texture. At the same time it influences the presence of internal stress and the quality of the wire surface.

Numerous theoretical and practical researches [2-10] were devoted to the exploration of the influence of technological parameters of drawing on the inhomogeneity of deformation. It is evident also from our previous works [1, 11, 12] that it is possible to achieve a significant improvement of the homogeneity of the deformation intensity in the drawn wire by an increase of partial reductions (i.e. by reducing the number of passes at otherwise constant total deformation), as well as by the reduction of the deformation angle (approach angle) $2\alpha$.

Although the actual magnitude of friction does not influence significantly the inhomogeneity of deformation [11], at small angles and large partial deformations it increases the total drawing force above the values of the force corresponding to the yield strength of the wire of the given diameter, which ultimately leads to the plastic deformation of the wire behind the die instead in it, and subsequently to the formation of the neck and to wire breakage.
One of the nowadays already commonly used drawing technologies, which dramatically reduce the friction coefficient is wire drawing in conditions of hydrodynamic lubrication with use of pressure dies [13]. Majority of wire drawing mills uses, however, the pressure dies with ordinary deformation angles \((2\alpha = 9 \text{ to } 12^\circ)\) and with standard partial deformations \((Q_d = 18 \text{ to } 25\%)\). These parameters, however, do not lead to significant reduction of shear deformations under the surface of the wire. Some wire drawing mills therefore cease using the pressure drawing dies for the whole set reductions and they serve only in the first passes in order to ensure sufficient capture of lubricant on the wire. According to the works of Avitzur [14], the friction coefficient can drop after achievement of the conditions of hydrodynamic lubrication down even to the values \(\mu = 0.0005\), which is a hundred times less than at normal drawing. Due to the fact that the force for overcoming the friction makes 20% of the total drawing force (at use of the optimum angle of the die), and even up to 60% of the total drawing force (at use of small angles of the die) [7], it is possible to to perform drawing in conditions of hydrodynamic friction with very small deformation angles.

In this work we will perform a FEM simulation of drawing at conditions of hydrodynamic friction, and we will assess the magnitude of shearing strains and total drawing force.

2. FE ANALYSIS

FE analysis of wire drawing from the steel C78 (chemical composition is shown in Table 1). Simulation with the initial diameter \(d_0 = 5.5\) mm was made in the simulation program FormFEM. The simulation was performed in 2D as rotationally symmetrical, without consideration of heating of the wire. Finite element mesh had in the area corresponding to the steady-state higher density, in order to ensure sufficient accuracy of calculation in reasonable computational time. The friction coefficient was \(\mu = 0.0005\) and we made for comparison also simulations with \(\mu = 0.05\). The scope of the analysis is documented in Table 2. At the beginning of the drawing, the microstructure of the wire is fully restored. The flow stress during this cold forming of steel is given by the equation (1) (the equation is valid for the strain of 0.1 and higher):

\[
\sigma = 1011.8 \exp(-0.0069 \cdot T) \cdot \exp(0.00747 \cdot \varepsilon) \cdot \exp(0.00875 \cdot \varepsilon) \cdot \exp(0.22724 \cdot \varepsilon)
\]  

(1)

Table 1 Chemical composition of the C78D steel (wt. %)

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 - 0.80</td>
<td>0.5 - 0.8</td>
<td>0.1 - 0.3</td>
<td>≤ 0.035</td>
<td>≤ 0.035</td>
<td>≤ 0.15</td>
<td>≤ 0.20</td>
<td>≤ 0.25</td>
<td>not specified</td>
</tr>
</tbody>
</table>

Table 2 Parameters of the FE analysis

<table>
<thead>
<tr>
<th>(\mu) (-)</th>
<th>(d_0) (mm)</th>
<th>(\varepsilon_0) (-)</th>
<th>(Q_d) (%)</th>
<th>2(\alpha) (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0005</td>
<td>5.36</td>
<td>0.051</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>5.07</td>
<td>0.051</td>
<td>0.163</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>4.76</td>
<td>0.288</td>
<td>25</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4.43</td>
<td>0.431</td>
<td>35</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>4.76</td>
<td>0.288</td>
<td>25</td>
<td>2</td>
</tr>
</tbody>
</table>

3. ANALYSIS OF RESULTS AND DISCUSSION

3.1 Total drawing force

Figure 1 shows evolution of the recorded total drawing force in time at drawing with the deformation angle \(2\alpha = 12^\circ\) for all deformations. In the area of stabilised plastic flow it is possible to discern an area, especially for smaller deformations, where fine mesh was used. We determined for this area the average value of the total drawing force, which we then used for comparison of all simulations (see Figure 2).
As it is evident from Figure 2 the dependence of the total drawing forces on the deformation angle of the die does not show the local minimum for the used friction coefficient, as we can observe it at normal drawing (see Fig. 3). It means thus that the effect of friction on the total drawing force is in this case negligible. An important role is played only by the influence of homogeneous deformation and by the effect of shear deformation caused by unfavourable metal flow near the surface of the wire. Figure 3 provides a comparison of the total drawing force according in dependence on the deformation angle for the deformation of 25% and for the friction coefficient $\mu = 0.0005$ (hydrodynamic friction) and $\mu = 0.05$ (dry or mixed friction). We see that an increase of the friction coefficient leads to an increase of the total drawing force at use of smaller deformation angles. In the case of the angle of $2\alpha = 2^\circ$ the difference is more than 60%.

### 3.2 Shearing strain

We can see the typical course of real shearing strain in dependence on the distance from the wire centre in the diagram in Figure 4. This diagram shows the values of real shearing strain at drawing with the deformation of 25% and $2\alpha = 26^\circ$ in all points of the FEM mesh from the area of the stabilised plastic flow. The data can be very well fit by the third-degree polynomial. The diagram in Fig. 5 shows then a comparison of the course of real shearing strain in dependence on the distance from the wire centre for $2\alpha = 12^\circ$ for
individual deformations. The course is similar for deformations of 15, 25 and 35%, if we create a ratio of the real shearing strain $e_{xy}$ and of the real linear strain:

$$e_i = \ln \frac{d_0}{d_l},$$

the results for the given deformations would practically not differ ($e_{xy}/e_l$ would not exceed the value of 0.77). The course for the deformation of 5% is exceptional, when the proportion $e_{xy}/e_l = 4.9$. For this reason these small deformations are not used in practice. Results for all simulations are then summarised in the graph in Figure 6, which shows the dependence of the maximum value of the shearing strain (this value was reached on the wire surface or right below it) on the magnitude of the deformation angle and on partial deformation. It is evident that from the perspective of homogeneity of the deformation, it is desirable to use the smallest possible deformation angles. It is obvious from this graph that use of too small deformations in combination with large deformation angle leads to a sharp increase of shearing strain in the surface layers of the wire. This fact is documented even better by the diagram in Figure 7 where we see the dependence of the ratio of the maximum shearing strain and real linear deformation $e_{xy}/e_l$ on the magnitude of the deformation angle and on the partial deformation.

Fig. 4 Course of real shearing stress in dependence on the distance from the wire centre $Q_d = 25\%$ and $2\alpha = 26^\circ$

Fig. 5 Comparison of the course of real shearing strain in dependence on the distance from the wire centre for individual deformations ($2\alpha = 12^\circ$)
4. CONCLUSIONS

The results of our FE analysis have unequivocally confirmed that an improvement of the deformation homogeneity over the wire cross-section can be ideally achieved by the use of the dies with the smallest possible deformation angle. In the case of application of pressure dies, which can ensure conditions of hydrodynamic friction, the use of very small deformation angles is desirable also from the viewpoint of the total drawing force. Further improvement of the deformation homogeneity over the wire cross-section can be achieved by increasing the partial reductions and thus by reducing the number of passes. The reason is that under the conditions of hydrodynamic friction in the die with the deformation angle of $2\alpha = 2^\circ$ the total drawing force at the increase of partial reduction of 25 to 35% increases only by approx. 30% to approx.
5 kN. To this force at the wire diameter of 4.43 mm corresponds the stress of 325 MPa, it means the value, which is significantly lower than the yield strength of the rod from the steel C78. This means that no deformation of wire will occur behind the die and no wire breakage will take place even at the deformation of 35%.

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