Abstract

The paper deals with mathematical modelling of drawing of low-carbon half-round wire using finite element method. Specifically, it covers drawing of hot rolled round wire C9D with the diameter of 6.5 mm to obtain a semicircular cross-section with the height of $H = 4.025$ mm, width $D = 5.8$ mm and a rounding diameter of $r = 0.2$ mm. The drawing process consists of two passes. The shape of the wire after pre-drawing is characterized by the rounding diameter of $R$. It allows the material to flow more easily into small-diameter corners in the final pass. These products find their application particularly in automotive industry as control button stems in dashboards. The computer simulation was carried out using the software package Forge 2009® developed by French Transvalor. Rhinoceros 3D was employed for developing the objects used in Forge 2009®. The total of 5 variants of drawing of the half-round wire was explored. The variants varied in the rounding diameter $R$ in the pre-drawing pass. The rounding diameters $R$ were 5.730 mm, 7.540 mm, 11.525 mm, 18.280 mm and infinitely large in the last variant. Mathematical modelling was used for exploring the impact of the rounding diameter $R$ of the pre-drawing cross-section upon the final shape of the wire. Strain, strain rate and axial stress distributions were studied as well. In addition, normalized Cockroft-Latham fracture criterion (NCLC) was monitored as well, indicating the probability of formation of defects in the forming process. The influence of the diameter $R$ upon final dimensions of the drawn wire was confirmed. Results also reveal considerably non-uniform distributions of strain, strain rate and axial stress across the wire cross-section, as reflected by non-uniform distribution of values of the Cockroft-Latham criterion.

Key words: finite element method, drawing, shaped wire, normalized Cockroft-Latham fracture criterion

1. INTRODUCTION

Drawing is a forming process, in which stock, typically a round section, is pulled through an opening in a drawing die. The products often possess high dimensional accuracy and high-quality finish. Drawing changes mechanical properties of the material: tensile strength increases, whereas plasticity declines. In wire drawing, the plastic deformation takes place at temperatures, at which the effects of work hardening persist.

Among the first to use mathematical modelling to simulate drawing of shaped wires were Avitzur and Boer [1]. They analyzed drawing of a square-section wire by means of the Upper Bound Method. This method was also used by Prakash [2], who dealt with drawing of regular polygon-shaped wires, and Basily [3], who presented solutions for various incoming and outgoing cross-sections. This method, however, lacked the capability to determine internal stresses and strains during forming. It could only be used for determining the upper bounds of the examined parameters. This was useful for dimensioning drawbenches, but insufficient for obtaining more accurate results. This fact, combined with the ever increasing performance of computers, led to transition to the more advanced finite element method (FEM). Simulations of drawing shaped wires based on finite element method were conducted by Kim [4] and Wang [5]. These authors prepared an analysis of drawing hexagonal, triangular and rectangular-section wires from round stock. Analyses of drawing of square wire and twisted square wire were carried out by Knap [6] and Suliga [7] as well. Comparison of the analytical solution for wire drawing and the solution obtained using FEM was given by Luis in his study [8].
2. INDUSTRIAL FORMING PROCESS

The incoming stock is hot-rolled steel wire C9D with the diameter of 6.5 mm. The chemical composition of C9D steel used is shown in Table 1.

Table 1 - Chemical composition of C9D steel (upper limit in 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>Mo</th>
<th>Cu</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.60</td>
<td>0.30</td>
<td>0.035</td>
<td>0.035</td>
<td>0.25</td>
<td>0.25</td>
<td>0.08</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>

The final dimensions of the drawn wire are \( H = 4.025 \) mm, \( D = 5.8 \) mm and \( r = 0.2 \) mm. With regard to the overall reduction, this wire is drawn to the final dimension in two passes in two straight wire-drawing machines. No other operations are used between the passes. The round cross section of the stock is converted into the pre-drawing form which, in turn, is changed into a semicircular shape (Fig. 1). The deformation itself takes place in a tungsten drawing die, i.e. in its reducing zone with the approach angle of \( 2\alpha \). One of the most important factors for the resulting shape (particularly the filling of the \( r \) radius in the final shape) and for other properties of the product is the magnitude of the radius \( R \) in the pre-drawing shape. The speed of movement of the wire in the pre-drawing and final passes is \( 3 \) m.s\(^{-1}\) and \( 0.8 \) m.s\(^{-1}\), respectively.

3. FEM ANALYSIS

The mathematical analysis was performed with the aid of the software Forge 2009. As the arrangement is symmetrical with respect to the \( x-z \) plane, only one half of the wire was considered in the analysis.

3.1 Mesh Element Size

As the problem is symmetrical with respect to \( x-z \) plane, only one half of the stock was considered in the simulation. The finite elements in the mesh were assigned non-uniform sizes in order to reduce the computing time and maintain sufficient precision. In those locations of the stock which were only held between grips and underwent no deformation, the size of the element was set as 1 (the initially reduced part). The size of elements on the surface, i.e. the area in contact with the drawing die, was set at 0.3. In the rounded spot \( r \), an even lower value of 0.1 was selected for more faithful description. The mesh in the wire interior had elements of 0.8 size. This layout of the mesh allowed sufficient computing precision to be achieved, while keeping the computing time at reasonable level. The computing time was up to 16 hours, depending on the type of the problem (pre-drawing pass/final pass). The mesh is shown in Fig. 2.
3.2 Boundary and Initial Conditions

Models for friction between the drawing die and the wire are based on either Coulomb approximation or the Tresca friction law:

\[ \tau_i = \mu \cdot \sigma_i \] (1)
\[ \tau_i = m \cdot \tau_{i,\text{max}} \] (2)

where \( \tau_i \) is the shear stress, \( \tau_{i,\text{max}} \) is shear stress level required to cause plastic deformation of the material, \( \sigma_i \) is the normal stress, \( m \) is the friction factor and \( \mu \) is the friction coefficient. The friction factor in this simulation was \( m = 0.02 \) and the friction coefficient value was \( \mu = 0.05 \).

The flow stress in steel is given by the Spittel equation:

\[ \sigma = A \cdot \exp(m_1 \cdot T) \cdot e^{m_2} \cdot \exp \left( \frac{m_3}{e} \right) \cdot e^{m_4} \] (3)

where \( A = 701.7, m^1 = -0.00124, m^2 = 0.22701, m^3 = 0.01026, m^4 = 0.00196 \).

The coefficient \( \alpha_c \) of heat transfer to the drawing die, as well as the coefficient of heat transfer to the environment \( \alpha_{ok} \) were defined as constants (\( \alpha_c = 1,000 \text{ W.m}^{-2}\text{.K}^{-1}, \alpha_{ok} = 10 \text{ W.m}^{-2}\text{.K}^{-1} \)). The initial temperature of the workpiece was 20°C in all cases.

3.3 Experimental Conditions

Mathematical analysis of the total of 5 variants of cold drawing of half-round wire was conducted. The difference between the variants lay in the pre-drawing radius \( R \). Rounded corner radii \( R \) in individual pre-drawing dies were 5.73 mm, 7.54 mm, 11.525 mm and 18.28 mm. In the last variant, the rounding radius was infinite \( R = \infty \) (i.e. there was no rounding). The reduction zone angle in pre-drawing pass was 10 °. In final pass, this angle was 22° on the straight side and 18° on the rounded side. The length of the conical reducing zone was 2.5 mm in both cases.

The obtained results were used for further analysis of the following parameters: distribution of accumulated stress intensity, longitudinal stress \( \sigma_l \) and NCLC given by the equation [9]:

\[ \int_0^{\epsilon_{eff}} \left( \frac{\sigma^*}{\sigma_{ef}} \right) d\epsilon_{ef} = C \] (3)

where \( \sigma_{ef} \) is the effective stress, \( \epsilon_{ef} \) is the effective strain in the fracture and \( (\sigma^*/\sigma_{ef}) \) is non-dimensional factor of the stress concentration, which represents the most tensile stress influence \( \sigma^* \).

4. DISCUSSION OF RESULTS

4.1 Shape of the wire after pre-drawing and the final pass

The chart in Fig. 3. presents the comparison between shapes of the wire after the pre-drawing pass in all considered variants. With increasing radius \( R \) the ability of the material to fill the area of the radius \( r \) decreases. As seen in the shape upon the final pass (Fig. 4), this is the only area where the shapes differ. The situation practically reversed and this radius was best filled upon the pre-draw variant \( R = \infty \), whereas it was worst for \( R = 5.73 \text{ mm} \). The difference was below 0.3 mm.
3.5 Distribution of Thermomechanical Parameters across the Reduction Zone

Fig. 5 and Fig. 6 show the equivalent strain distribution on sections through the reduction zone between the entry and exit planes in both pre-drawing and the final pass for the variant $R = 11.525$ mm. The strain field is very non-uniform. The maximum strain level in the pre-drawing pass can be found on the flat side, left of the symmetry plane. In the final pass, the maximum strain intensity region is in the rounded area of the drawing die ($r$). In both cases, the increased strain intensity is due to shear strain.

Figs. 7 through 9 show a comparison of the variants in terms of equivalent strain, longitudinal stress and NCLC. As we attempt to optimize the process of drawing half-round wire in regard to the probability of presence of cracks, we focus on maximum values of individual parameters. The strain intensity field is shown in Fig. 7. At the pre-drawing stage, the situation is straightforward: with increasing radius $R$ the strain increases. At the final pass stage, the strain magnitudes in most areas of the cross section are virtually
equal. The greatest difference can be found in the region of maximum strain (rounding \( n \)), where the maximum strain definitely increases with increasing radius \( R \) (in pre-drawing).

\[ \text{Fig. 7.} \quad \text{Distribution of equivalent strain } e_{eq}, \text{final pass- input plain} \]

\[ \text{Fig. 8.} \quad \text{Distribution of longitudinal stress } \sigma_l, \text{final pass- input plain} \]

\[ \text{Fig. 9.} \quad \text{Distribution of normalized Cockroft-Latham fracture criterion NCLC, final pass- input plain} \]

\[ \text{Fig. 8.} \] shows longitudinal stresses \( \sigma_l \) in the exit plane. In pre-drawing the increase in \( R \) has a positive impact on the maximum value of \( \sigma_l \) (for \( R = \infty \) the value of \( \sigma_l \) is the smallest). However, at the final pass stage, the situation turns around and for \( R = \infty \) the value \( \sigma_l = 345 \) MPa, which is the highest value found. However, this fact does not correspond with values of the NCLC (\[ \text{Fig. 9.} \] - the situation here is an opposite). The reason is that the criterion captures the full stress-strain forming history in the given pass. According to NCLC, the probability of crack formation in pre-drawing increases with the radius \( R \). However, in the final pass the situation is reversed. Moreover, all other variants (\( R = 5.73 \) to 18.28 mm) lead to higher NCLC values than the highest one in pre-drawing (\( R = \infty \)). Hence, in order to identify the optimum variant, the results were converted into graphs (see \[ \text{Fig. 10.} \]). After examining the graphs in \[ \text{Fig. 10.} \] one can say that despite the highest stress \( \sigma_l \) and highest strain intensity in the final pass, the optimal variant from the NCLC standpoint is the one with \( R = \infty \).
5. CONCLUSION

Mathematical analysis was used for optimizing the process of drawing half-round wire. By altering the pre-drawing geometry, a variant with the lowest probability of crack formation during drawing was sought. Here we obtained the best variant with $R = \infty$.

Despite this, results of the simulation suggested that variants with lower radii $R$ ($R = 5.73$ and $7.54$ mm) offer an indisputable advantage in higher strain uniformity across the cross-section of the resulting wire. In addition, they lead to more favourable state of stress on most of the cross-section than those with higher radii $R$. Their only weakness is the NCLC value being too high in the vicinity of the rounded region ($r$) of the final drawing die. At present, mathematical simulation of drawing of half-round wire is conducted in order to eliminate this weakness by modifying the geometries of both pre-drawing and final drawing dies (rounding radius $r$, reduction zone angles $\alpha$, etc).

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REFERENCES


