CHARACTERIZATION OF COMPLEX OPTIMIZATION OF MULTISTEP WIRE DRAWING BASED ON A SPECIFIC INDUSTRIAL TECHNOLOGY

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ABSTRACT

In this paper, objective functions of complex optimization of multi-step wire cold drawing technology is introduced and applied for an industrial DHCF 17 multistep wire technology. Two types of complex objective function are presented with either identical optimum cone-angles in each pass or variable optimum cone-angles being able to differ between the drawing passes. Through this calculation, the results of the complex optimization were characterized and the results are compared with the original operating parameter values.

INTRODUCTION

The main aspects of industrial technology design can be divided into three main groups. The first group sets the quality of the product according to customer requirements and eliminates or minimizes any damage or defects. The second group includes objective functions that minimize specific costs, among which the functions that minimize the specific energy consumption of a given operation occupy a very important place. The third is also a very important objective function class that maximizes productivity, allowing the factory to maximize its hourly performance. Considering these aspects, we studied the possibilities of improving the technology planning process for a wire drawing process.

A complex optimization process was built, which simultaneously takes into account the optimization objective functions for drawing force, stress distribution, temperature, and heat treatment in order to meet the above criteria of technology design. This complex optimizing procedure was used to improve the technology applied on DHCF 17 multistep drawing machine used in industry and to compare the results of the complex optimum with the original operating values.

In order to perform complex optimization efficiently, first, the precise thermomechanical coupled model of the multi-step wire drawing is needed, which has the least possible computational requirement. For this purpose, in [1] we have shown that in the case of wire drawing modelling, closed analytical methods using explicit formulas can achieve the same accuracy as finite element analysis, but in turn the process can be simulated faster. In [2], we selected a coupled model based on measurement data and models described by explicit analytical formulas previously published in the literature. This coupled model gives the best approximation to the measured data and includes methods describing the most important parameters of technology design, such as the Geleji wire drawing force,

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the modified Geleji model of maximum tensile stress in the wire and derived Siebel model of the wire temperature.

Figure 1 – Longitudinal cross-section view of the forming process in one step

The main equations of this coupled model are [2]:

- Hajduk’s equation for the $k_f$ yield strength (plastic flow curve):

$$k_f = k_{f0}K_T K_\phi K_\psi = k_{f0}K_T C_2 \phi^{n_2} C_3 \phi^{n_3}$$  \hspace{1cm} (1)

where $k_{f0}$ is the initial value of the yield strength, $K_T$ is the temperature dependent factor of the model, $C_2$ is constant for the strain dependent factor and $n_2$ is the hardening exponent, $C_3$ is constant and $n_3$ is exponent for the strain rate dependent factor.

- Geleji’s equations for the multistep wire drawing force ($F$) for a step:

$$F = k_{k, Ellen} \cdot \Delta A \cdot \left(1 + \frac{1}{\alpha}\right) + 0.77 \cdot A_2 k_{f, k} \cdot \alpha + F_{Ellen}$$  \hspace{1cm} (2)

$$k_{k, Ellen} = \frac{k_{f, k} \left(1-0.385\alpha\right) - \sigma_{Ellen}}{1 + \frac{\Delta A}{2A_2} \left(1 + \frac{\mu}{\alpha}\right)}$$  \hspace{1cm} (3)

where $A_1$ is the inlet cross-section, $A_2$ is the outlet cross-section of the wire, $\Delta A = A_1 - A_2$, $\alpha$ is semi-cone angle, $\mu$ is the Coulomb’s friction coefficient, $k_{f, k}$ is the average value of the $k_f$ function of wire for examined step, $F_{Ellen}$ is the backward drawing force (Fig. 1), $\sigma_{Ellen}$ is the averaged backward drawing stress.

- Geleji’s modified model of maximum tensile stress in the wire $\sigma_{\text{max}}$: 
where $\varepsilon$ is the engineering strain, while the other notation is the same as in the previous models.

- Wire temperature increase model derived from Siebel’s equation for a step ($\Delta T$):

$$
\Delta T = k_a \left( \phi + \alpha \right) \rho c + \frac{1 - \left( 1 - \frac{2b}{D_z} \right)^2}{3} t_{al} \ln \left( \frac{t_{al}}{\lambda c p} \right)
$$

where $\phi$ is the logarithmic strain in a step, $\rho$ is density, $c$ is specific heat capacity, $\lambda$ is thermal conductivity of the wire, $D_z$ is the outlet diameter, $v_1$ is the inlet velocity of the wire, $v_2$ is the outlet velocity of the wire, $v_{al} = (v_1 + v_2)/2$, $t_{al}$ is time of material point on symmetry axis passing through the die, while the other notation is the same as in the previous models.

Between the steps of the wire drawing process, the cooling of the wire was calculated based on the following convective heat transfer coefficient ($u$):

$$
u = 675 \cdot \ln(v_2 + 3) \quad [W/(m^2 \text{ K})] \quad (7)$$

For the specific DHCF 17 technology MOL FORTILMO AWD 150 Special wire drawing lubricant used of which Coulomb’s friction coefficient’s velocity ($v$) dependency is the following:

$$
\mu(v) = 0.0072 + \frac{1}{6.93 \cdot v + 5.1}
$$

COMPLEX OPTIMIZATION PROCEDURE

Based on the type of functions describing each technological parameter in case of multistep wire drawing, nonlinear optimization is used as defined by the extremum equation Eq.(9) and the conditions Eq.(10) that define the domain of optimization. In the course of technological designing, we want to enforce the different optimization objective functions together. For this purpose, a complex
The objective function was defined that results in a conditional extremum, where the domain narrowed by the condition is also an extremum of another target function. Thus complex optimization applied differs from the nonlinear case in that the domain of the optimum is not determined by equations and inequalities as in Eq.(10), but determined by another optimizing objective function.

\[
\text{ext} \left\{ f(x) \right\} \\
g_j(x) \geq 0, \\
j = 1, \ldots, m \\
h_k(x) = 0, \\
k = 1, \ldots, p \\
x \in \mathbb{R}^m, 
\]

where \( f(x) \) is the function to be optimized, \( g_j(x) \) and \( h_k(x) \) are the condition functions.

Our aim is to define a complex optimizing objective function that calculates the number of steps, the geometry of the dies and the extent of strain, taking into account as many design aspects as possible, which must be done until intermediate annealing.

During complex optimization, the optimum sizes of the cone angles of the tools were searched, provided that strain belonging to die is also optimal: according to the objective function defined by the utilization factors and the location of the heat treatment in the technological line. This complex optimizing objective function, while ensuring product quality, minimizes production costs and increases productivity by reducing the number of steps.

The complex optimization objective function defined in [3] consists basically of 3 optimization objective functions and of a temperature limit relating to the optimum places.

The extent and size of deformation is maximized (i.e., the number of stages is minimized) by the first optimization objective function in order to ensure the suitable high quality of the product, i.e. ruptures, surface failures and other damage cannot be found in the ready-made wire. In order to avoid damage and failures, the average (Eq. (11)) and maximum (Eq. (12)) relative drawing stresses have been introduced, the values of which shall be set between 0.5…0.55.

\[
\xi = \frac{F}{A_j k_{f2}} \\
\zeta = \frac{\sigma_{\text{max}}}{R_m} 
\]

where \( \xi \) is the average relative stress, \( k_{f2} \) is the yield stress in the outlet side of the step, \( \zeta \) is the maximum relative drawing stress, \( \sigma_{\text{max}} \) is the
maximum drawing stress acting in the wire, \( R_M \) is the ultimate tensile strength.

The specific power consumption is minimized by the second optimization objective function. The specific deformation work described by Eq. (13) is minimized by the above function in such a way that it selects the suitable value of \( \phi_{\text{annealing}} \). The \( \phi_{\text{annealing}} \) determines the extent of deformation at which the intermediate heat-treatment (annealing) process shall be performed on the wire.

\[
W = \int_0^{\phi_{\text{annealing}}} k_f(\phi) d\phi + \int_0^{\phi - \phi_{\text{annealing}}} k_f(\phi) d\phi
\]  

(13)

where \( W \) is specific deformation work, \( \phi \) is the logarithmic strain.

The specific power consumption is also minimized by the third objective function. All the power consumption described by Eq. (14) is minimized by this objective function by choosing the optimum cone angles of passes.

\[
P = \sum_{s=1}^{N_{\text{pass}}} \sum_{i=1}^{N_{\text{seq}}} \left( F_i v_i + (F_i - F_{\text{back},i}) v_{\text{diff},i} \right) \eta_{\text{drive efficiency},i}
\]  

(14)

where \( P \) is power consumption, \( v_{\text{diff}} \) is the velocity difference between the wire and drawing reel, \( N_{\text{seq}} \) is the total number of the drawing sequences, \( N_{\text{pass}, s} \) is the total number of the passes in the \( s \)-th sequence, \( \eta \) is the drive efficiency.

As far as the average value of wire temperature is concerned, an upper temperature limit of 60-70 °C is prescribed for the wet drawing and an upper temperature limit of 250-300 °C is prescribed for the dry drawing. This limit gives the upper boundary value when choosing the drawing velocity.

Two complex optimization objective functions were defined, where in one case the procedure gives the identical cone angles in each step, while in the other case it is allowed to obtain variable angles. These are represented by Eq.(15) and Eq.(16):

\[
\min \left\{ P \mid \max(\phi|\xi = (0.5 \ldots 0.55), \zeta = (0.5 \ldots 0.55)); \min(W); T_{\text{wire}} \leq T_{\text{limit}}; \forall s \in \{1 \ldots N_{\text{seq}}\} \forall i, j \in \{1 \ldots N_{\text{pass},s}\}; \alpha_i = \alpha_j \right\}
\]  

(15)

\[
\min \left\{ P \mid \max(\phi|\xi = (0.5 \ldots 0.55), \zeta = (0.5 \ldots 0.55)); \min(W); T_{\text{wire}} \leq T_{\text{limit}} \right\}
\]  

(16)
First, the procedure defined by the complex optimizing object function calculates the desired location of the annealing in the technology using the integral equation Eq. (13). The Hajduk yield strength model described in Eq. (1) makes this calculation easy to handle. Thus the extent of the strain to be performed in each draw sequence can be determined.

The next step in the process is to find the cone angles of drawing steps (passes) for the minimum of power consumption in each drawing sequence, while, according to domain bounding objective function, the extent of the reduction in each step results from optimization with the utilization factors in Eq. (11,12).

The domain of cone angles is between 3°-30°. At smaller angles, the required drawing force increases in hyperbolic manner (see Eq.(4)). If the cone angle were larger, then V-shaped tears would be created along the surface of several creators of the surface. On the other hand, the phenomenon of the central burst, as well as the dead corner and shaving, would be almost 100% likely [4].

In the case of complex optimization for variable cone angles, the optimization with the utilization factor was weakened, and only made sure that both values of the utility factors were lower than the upper bound of the security bands and at least one was in the security band. This will ensure that the optimum reduction related to the product quality always exists in each pass.

As a final step in the process, the method examines the wire temperature and provides a limit for speed as described above.

Based on the studies carried out in [5], we found that the difference between the computation times is at least two orders of magnitude, i.e. 100 times. Comparing the results of the software runs, the differences between the complex optima by comparing the power demand of the drive and the total number of passes were established. We found that there is a good agreement between the two complex optimizations. After more detailed studies, it was concluded that in the case of diameter: 0.5 to 20 mm, less than 10 m/s final velocity, regardless of the material quality, the identical cone angle optimization process with a much shorter computing requirement is the most effective way of designing an industrial technology. In case of different speeds and diameters, variable angle complex optimization is recommended for the design of the multistep wire drawing technology.

CHARACTERIZATION OF COMPLEX OPTIMIZATION BASED ON DHCF17 TECHNOLOGY

The identical cone-angle complex optimization method is presented to the drawing technology of DHCF 17 based on [6]. The final velocity is 8.5 m/s, the wire’s initial diameter is 1.4 mm, the finish diameter is 0.35 mm, the material quality is C10 steel. Passes total number is 17. The drawing process can be carried out in one sequence, no intermediate annealing is required.

It is noteworthy that at this material quality (C10) only 0.1% specific deformation work can be achieved by optimally installed annealing in the technology compared to annealing applied at the end of the drawing sequence. In
contrast, this number is higher almost two orders of magnitude in the case of Al99.5.

Figure 2 – Semi cone angle dependent power consumption of complex optimized DHCF 17 technology where the cone angles are the same in each step

Figure 3 – Semi cone angle dependent power consumption in case of one step wire drawing technology

In the case of a given industrial technology, the cone-angle dependent power requirement optimized by utilization factors can be seen in Fig. 2. Comparing with cone angle optimum of one step wire drawing (Fig. 3.) we can state that in one step only one global minimum exists, while in case of complex optimization there are several local minimum. This also makes the searching of the complex optimum
more complicated, because of this property simple analytical methods or even a greedy algorithm do not find the searched global minimum. In addition, the result is modified compared to the one-step case.

Compared to the original industrial technology, we can see that power consumption can be reduced from 3550W to 3150W, which saves 11.3%.

The outlet diameters for industrial technology passes were compared with the values indicated by the complex optimum. In the Fig. 4 can be seen that the complex optimum allows larger reductions, not only in comparison to industrial technology, but also in comparison to the optimum calculated only with Eq. (11-12) utilization factors. On the basis of the only utilization optimum, it reaches the finish diameter in 16 steps, while the complex optimum needs only 13 degrees.

![Complex optimization](image)

**Figure 4 – Comparison of outlet diameters of industrial (DHCF 17) and complex optimized technology**

In Fig. 5 can be seen the industrial and complex optimized drawing force for each pass. It can be seen that the majority of the steps require less drawing force, so not only the quality of the product is guaranteed, but the power requirement decreases and the wear lifetime of the drawing dies is also increased.

As a final step in complex optimization, the wire temperature limit was examined. The average wire temperature of the complex optimized technology can be seen in Fig. 6. The technology was wet-lubricated, so adjustment at the drawing velocity is not necessary, as even the average wire temperature does not cross the 60-65 °C limiting band for wet lubrication as shown in the diagram. So the complex optimized technology can be realized from a thermal point of view with a drawing force of 8.5 m/s.
Figure 5 – Comparison of industrial (DHCF 17) and complex optimized drawing force for each pass

Figure 6 – Averaged wire temperature for the outlets of each pass
CONCLUSIONS

The example shown also shows that the introduced complex optimization objective functions are multi-criteria processes that modify almost every major influencing factor of wire drawing according to the requirements. We can also find that cost-efficiency and even productivity are further improved compared to the optimizing objective functions on their own that considered for technology designing so far.

Based on the above considerations, the presented complex optimization target functions can be recommended for technology design and can be used successfully in our opinion. To facilitate design in an industrial environment, complex optimization should be performed with the help of wire drawing models that can be written with the selected explicit closed formulas. This minimizes the computational time spent on the design, while at the same time getting the most accurate results from optimizing models of similar structure.

REFERENCES


