Examination of Complex Optimization Objective Functions of Parameters of Multi-Step Wire Drawing Technology

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Abstract: In this paper, the algorithmic realization of complex optimization objective functions of parameters of multi-step wire cold drawing technology is described. As a result of utilizing two types of optimization, either identical optimum cone-angles can be obtained in each pass or the (variable) optimum cone angles having an optional size in each pass can be obtained. The calculation time of objective functions was investigated, as it is one of the most important factors of non-linear optimization. The optimum technological parameters obtained by using the two types of objective functions were compared, and the cases in which it is worth using the complex optimization having a shorter calculation time were defined.

Keywords: analytical explicit model; drawing force; drawing temperature; multi-step wire drawing; complex optimization; technology planning

1 Introduction

The main aspects of planning industrial technology can be divided into three main groups. In the first group, the quality of the product is adjusted in accordance with the requirements prescribed by the buyer, and any damage and defects arising are eliminated or decreased to a minimum extent. The objective functions minimizing the specific costs belong to the second group; here the functions minimizing the specific power consumption necessary for a given drawing operation are extremely important. Productivity is maximized by the third, very important group of objective functions, so the highest possible hourly output can be realized by using this group of objective functions.

The technological planning method of multi-step wire drawing was investigated taking into consideration the aforementioned aspects. Wire drawing is one of the most widely used processes to produce wires, strands, ropes, or welding rods. The technological parameters of multi-step wire drawing can be described by

analytical methods as well as by finite element methods. In the course of planning the technology, an optimization is realized so that the quantities belonging to the given aspects of planning are maximized or minimized. The non-linear optimization method must be used for multi-step drawing on the basis of the types of functions describing the different parameters.

In addition to the theoretical solution of the tasks, nowadays the presence of the advantageous properties of resolving algorithms and software is a very important aspect as well (e.g. the shortest possible time necessary for the calculations and the lowest possible memory capacity, the increase in size limits, and programs that can be handled and changed easily). Therefore, it can be concluded that in the case of non-linear optimization, the computer implementation of algorithms as well as experimentation are very significant factors, in addition to the mathematical examination of the tasks and resolving algorithms.

Both drawing force and forming energy have been used to optimize wire drawing in [1-3]. Many authors have used different ductile damage or fracture criteria to investigate central burst or other defects and tried to avoid or minimize damage [4-6]. Other studies [7-9] investigate microscopic criteria, based on characteristics of voids and defects, e.g. Kuboki et al. [10] used the void index, based on Oyane's criterion, to evaluate the void fraction during multipass wire drawing.

Automatic optimization processes for wire drawing have been described in [11-15]. The authors have focused on the minimization of the drawing force or/and the forming energy, on the minimization of damage, on the maximization of the wire reduction per pass, on the heterogeneity of the strains or stresses, and on the shape of the inner surface: and they have tended to use optimization algorithms directly coupled with the FEM calculation, each iteration corresponding to one (or several) FEM evaluation(s).

Although these improved optimization processes describe well the real optimums and explain the universal use of angles in the range [4°-8°], these algorithms can be time consuming because they are coupled with FEM evaluations. For instance, the optimal solution of Roy et al. [12] was found after about 100 FEM simulations, in 10 CPU hours. The second disadvantage concerns multi-step wire drawing: these algorithms do not calculate with back tension drawing force in any of the passes. Finally, in most of the articles, the materials are assumed to obey flow rules with no strain hardening.

In [16] a complex model was chosen from among the published models described by explicit analytical formulas on the basis of measurement data. The best approximation of the measured data is given by this complex model, as well as the most important parameters of planning the technology (the wire drawing force, the maximum drawing stress arising in the wire, and the temperature of the wire) are included in this model. The chosen complex model takes into consideration the back tension forces and the flow rules with strain hardening of the materials.

Our earlier research found that a value of exactness similar to the finite element method (FEM) can be obtained by using the analytical method for wire drawing [17].

In order to perform fast calculation of the optimization, it is necessary to choose a model to describe the technological parameters, which requires an exact and a short-time calculation. This requirement is met by the complex model described in [16], as it is very exact, and moreover the time necessary for calculating the analytical models is much shorter than that needed for FEM.

In [17], an optimization objective function is defined which calculates the number of passes by taking into consideration most of the aspects of planning, the geometry of dies and the extent of deformation to be realized up to an intermediate heat treatment (annealing).

Complex optimization differs from standard optimization in that the domain of variability of optimum values is not determined by the equations but rather is determined by another optimization objective function. Owing to this complexity, the time of calculation will become a very important factor, in addition to the exactness of the optimization process. In this paper, the complex optimization objective function described in [17] and a version of it further extended by us are compared by estimating the difference between the optimum values and the length of time necessary for their calculation.

Nomenclature

A_1, A_2	entry and exit wire area of cross section in a pass (mm^2)
b	penetration depth of heat due to friction (m)
c	wire specific heat capacity ($Jkg^{-1}K^{-1}$)
D_0, D_1, D_2	initial diameter, entry and exit wire diameter in a pass (mm)
F, F_{back}	drawing force and back tension drawing force in a pass (N)
k_f	deformation strength (Nmm^{-2})
$k_{f1}, k_{f2}, k_{fk}=(k_{f1}+k_{f2})/2$	entry and exit wire and mean deformation strength in a pass (Nmm^{-2})
$k_{k,back}$	deformation resistance in the case of back drawing force in a pass (Nmm^{-2})
R_M	maximum tensile stress of the exit cross-section of the wire (Nmm^{-2})
t, t_{def}	time and deformation time, i.e. the time spent in the die by the wire (s)
v_1, v_2, v_{mean}, v	entry and exit and the mean wire axial velocity in a pass (ms^{-1}), velocity of drawing (ms^{-1})
v_{diff}	difference between the circumferential velocity of the capstan and the velocity of the coiled wire on the capstan (ms^{-1})
W	specific deformation work (Nmm^{-2})
α	die semi-cone-angle (rad)
$\Delta A = A_1 - A_2$	difference of the entry and the exit wire area of cross section (mm^2)

ΔT	increase in temperature within a pass (K)
λ	thermal conductivity ($Wm^{-1}K^{-1}$)
μ	Coulomb friction coefficient (-)
ν_{def}	distribution coefficient of the heat of the volumetric deformation, i.e. the part of the heat developed owing to the deformation remaining in the wire (-)
$\nu_{friction}$	distribution coefficient of the heat of the friction, i.e. the part of the friction heat remaining in the wire (-)
ρ	density of the wire (kgm^{-3})
$\sigma_{back}=2*F_{back}/(A_2+A_1)$, σ_{max}	back tension drawing stress and maximum value of the drawing stress distribution of the exit cross-section of wire (Nmm^{-2})
$\varphi=\ln(A_1/A_2)$	logarithmic plastic stain (-)
ξ, ζ	average relative drawing stress; maximum relative drawing stress (-)
$\eta_{drive\_efficiency}$	coefficient of efficiency of the drive of the capstan (-)
i, s	sequence number of drawing pass; sequence number of drawing sequence
N_{seq}	number of drawing sequences
$N_{pass,s}$	number of drawing passes in the s-th drawing sequence
x,y, N	data calculated by identical-angle complex optimization; data calculated by variable-angle complex optimization; number of data

2   Determination of the Complex Optimization Objective Functions

First of all, it is necessary to define the model describing exactly the parameters of multi-step wire-drawing technology in order to calculate the complex optimizing method. This model, described in [16], yields exactness identical with the exactness of FEM, but a much shorter time is necessary for its calculation. The model is as follows:

Wire drawing force:

$$F = k_{k,back} \cdot \Delta A \cdot \left(1 + \frac{\mu}{\alpha}\right) + 0{,}77 \cdot A_2 k_{fk} \cdot \alpha + F_{back} \tag{1}$$

$$k_{k,back} = \frac{k_{fk}(1 - 0{,}385\alpha) - \sigma_{back}}{1 + \dfrac{\Delta A}{2A_2}\left(1 + \dfrac{\mu}{\alpha}\right)} \tag{2}$$

Maximum stress arising in the wire:

if $\varphi \geq 0.3$:

$$\sigma_{max} = k_{k,back}\left(\frac{\Delta A}{A_2}\right)\left(1+\frac{\mu}{\alpha}\right) + k_{fk}\alpha\left(1,27 + \frac{A_2}{\Delta A\left(1+\frac{\mu}{\alpha}\right)}\right) + \sigma_{back}, \tag{3}$$

if $\varphi < 0.3$:

$$\sigma_{max} = k_{k,back}\left(\frac{\Delta A}{A_2}\right)\left(1+\frac{\mu}{\alpha}\right) + k_{fk}\alpha\left(1,27 + \frac{A_2}{\Delta A\left(1+\frac{\mu}{\alpha}\right)}\right) \cdot \left(\frac{\varphi}{0,3}\right)^{1,5} + \sigma_{back} \tag{4}$$

Temperature of wire:

$$\Delta T = k_{fk}\,v_{def}\,\frac{\varphi + \alpha}{\rho c} + \frac{1 - \left(1 - \frac{2b}{D_2}\right)^2}{3}1,22v_{friction}\mu k_{fk}\,v_{mean}\left(\frac{t_{def}}{\lambda c \rho}\right)^{\frac{1}{2}} \tag{5}$$

The complex optimization objective function defined in [17] 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. (6)) and maximum (Eq. (7)) relative drawing stresses have been introduced, the values of which shall be set between 0.5…0.55.

$$\xi = \frac{F}{A_2 k_{f2}} \tag{6}$$

$$\zeta = \frac{\sigma_{max}}{R_M} \tag{7}$$

The specific power consumption is minimized by the second optimization objective function. The specific deformation work described by Eq. (8) is minimized by the above function in such a way that it selects the suitable value of $\varphi_{annealing}$. The $\varphi_{annealing}$ determines the extent of deformation at which the intermediate heat-treatment (annealing) process shall be performed on the wire.

$$W = \int_0^{\varphi_{annealing}} k_f(\varphi)d\varphi + \int_0^{\varphi - \varphi_{annealing}} k_f(\varphi)d\varphi \tag{8}$$

The specific power consumption is also minimized by the third objective function. All the power consumption described by Eq. (9) is minimized by this objective function by choosing the optimum cone angles of passes.

$$P = \sum_{s=1}^{N_{seq}} \sum_{i=1}^{N_{pass,s}} \frac{F_i v_i + (F_i - F_{back,i}) v_{diff,i}}{\eta_{drive\_efficiency,i}} \tag{9}$$

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.

The complex optimizing objective function can be obtained by including the optimizing objective functions of utilizing factors as well as the optimizing objective functions determining the place of heat treatment in the condition system of optimization relating to all the power consumption. Eventually, the complex optimizing method also examines the holding of the temperature limit. An additional condition is also determined in the complex optimizing objective function described in [17], namely, that the optimum values of cone angles shall be identical in each pass.

In this paper, the complex optimizing objective function is extended in such a way that the process is allowed to take an optional value of cone angle in each pass. It is obvious that all the power consumption obtained by using this extended objective function as well as the number of passes are less or equal to the result of the complex objective function having identical cone angles. We next investigate the difference between the two results as well as the difference between the lengths of time necessary for the calculations.

3   The Development of the Complex Optimizing Objective Functions Using Computer Technology

The algorithmization of a calculation method belonging to the two complex optimization objective functions and its software realization are necessary for determining the length of time of calculation and the differences between the complex optimums. First of all, the algorithm of the objective function searching for the identical cone angles in each pass was described from the complex optimizing methods, and software was developed for it. The flowchart of the algorithm of objective function searching for the identical cone angles in each pass is demonstrated in Fig. 1.
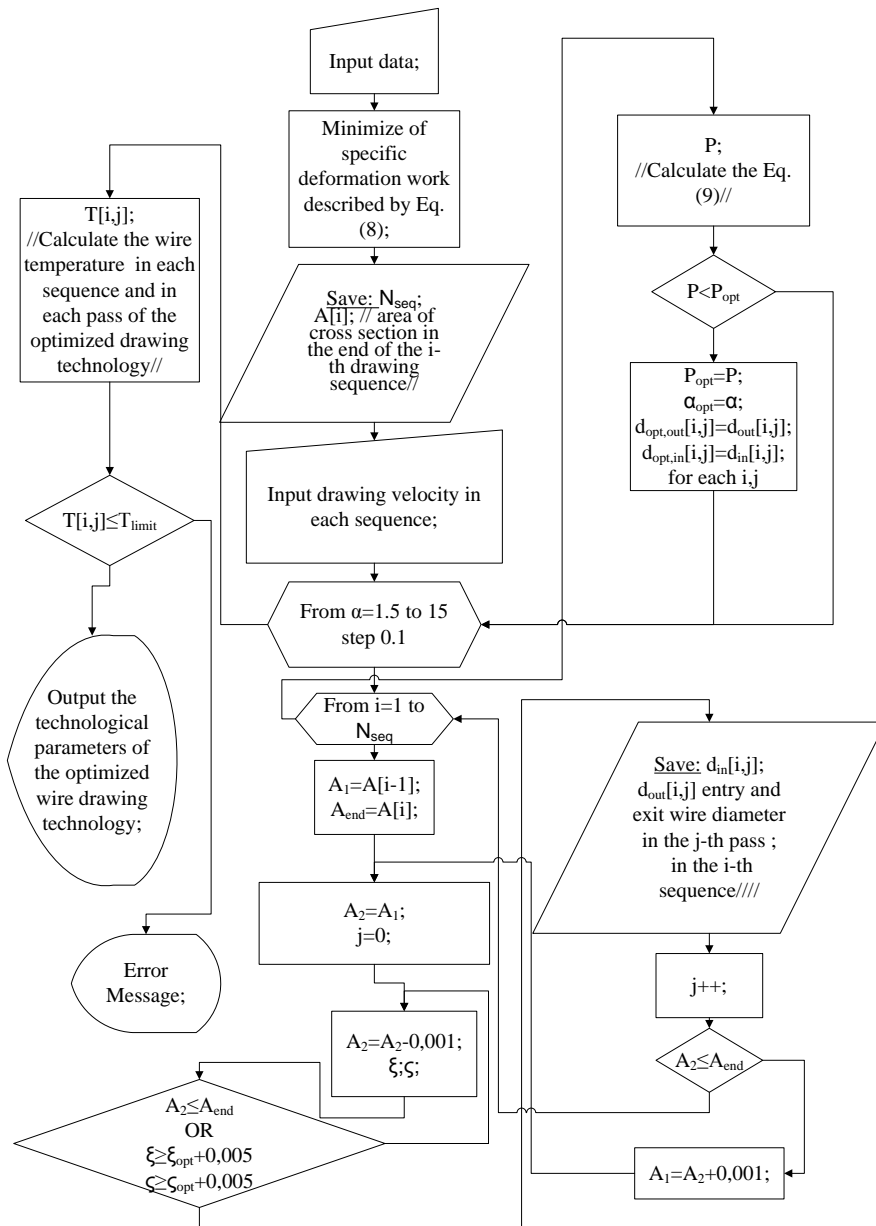
Figure 1

The flowchart of the algorithm of objective function searching for the identical cone angles in each pass

This algorithm has been developed in a software program that treats a group consisting of three different material grades and supposes wet lubrication.

The algorithm requests the suitable material quality and the yield law belonging to it: then the initial diameter of input coarse wire and later the final diameter of the product are given. The algorithm receives the basic parameters of the drawing machine; the most important parameter is whether back drawing force occurs in the individual passes or not.

The pre-determined interval for the cone angle intervals is a set of values between 3° and 30°. The values of the cone angles were determined only to an exactness of one decimal because the fact that the cone angles can be developed in the practice was taken into consideration. In this way, the set of optional angles was decreased to a value of 271, thus decreasing the length of time necessary for the calculation of the algorithm. After a value is chosen by the algorithm from a pre-determined interval of cone angles, the algorithm optimizes by using the relative drawing stresses.

It is necessary to use the modified optimization condition in order to decrease the length of time necessary for the calculation. Instead of a definite value, a safety zone is determined for the relative drawing stresses within which their optimum values must fall. In the computer program, the (lower and upper) limits of the safety zone differ from the pre-fixed (0.5….0.55) values by a value of ±0.005. The two relative drawing stresses would still have a small chance of falling at the same time within the safety zone expected by the objective function, and therefore it is reasonable to use an attenuated condition. In accordance with the new optimization condition, only one of the relative drawing stresses is expected to fall within the safety zone, while it is enough if the value of the other factor is lower than the upper limit of the zone. The cone angle has a strong influence on the dominance of one of the relative drawing stresses and whether it falls falling within the safety zone at a time when the value of the other factor is lower than it.

All of the 271 cone angles are examined by the algorithm. At the end of the process, the complex optimization parameters consisting of the saved values of cone angles belonging to the drawing sequences, the values of reduction in each pass, and the values of power consumption are obtained. Finally, the algorithm calculates the wire temperature in each pass and indicates if the upper limit corresponding to the lubrication is exceeded.

The algorithm realizing a complex optimizing objective function allowing different cone angles in each pass is more complicated, and therefore the time necessary for the calculation is longer.

The flowchart of the algorithm realizing a complex optimizing objective function allowing different cone angles in each pass is demonstrated in Figs. 2 and 3.
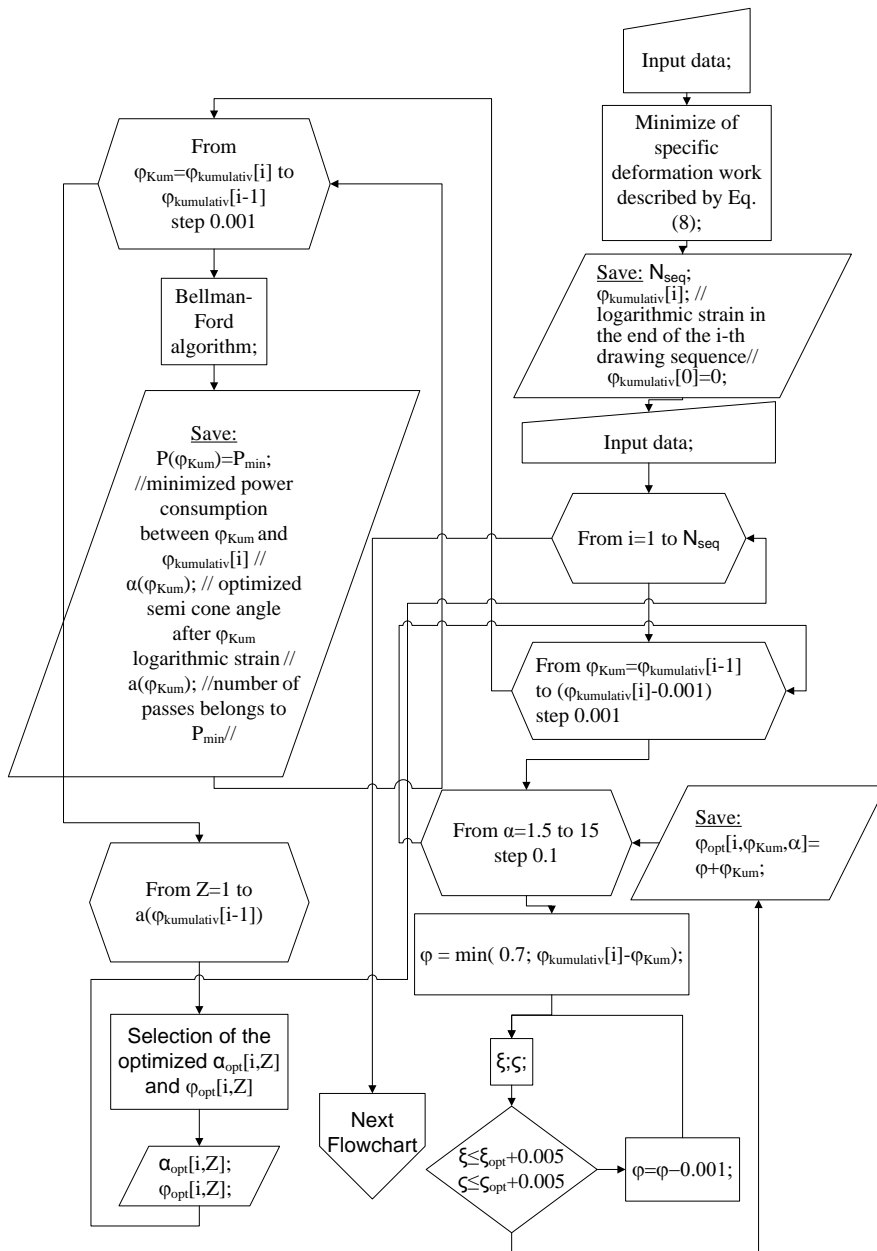
Figure 2

The flowchart of the algorithm realizing a complex optimizing objective function allowing different cone angles in each pass. Part I
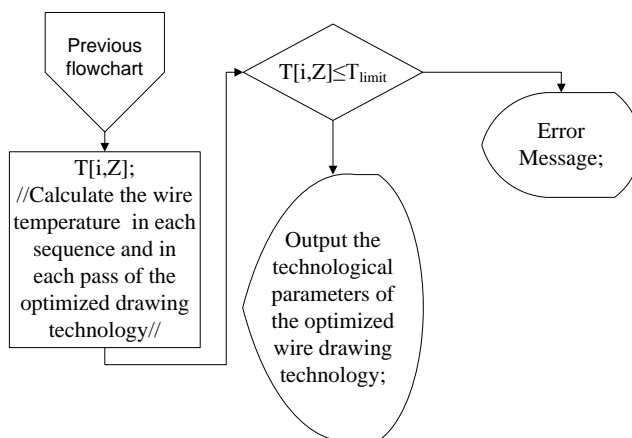
Figure 3

The flowchart of the algorithm realizing a complex optimizing objective function allowing different cone angles in each pass. Part II

The length of time necessary for the calculation is very long, even if the resources of the algorithm theory are used here. The calculation of the values of angle-reduction pairs arising following all of the possible deformations can increase the calculation time by at least 3 orders of magnitude compared to the calculation time necessary for the complex optimization with identical angle. We need this calculation, as the extent of the previous deformation of wire in the individual passes is not indicated preliminarily during the drawing sequence optimized by the relative drawing stresses. In the next step, it is necessary to carry out a searching action in order to create a drawing sequence from the angle-reduction pairs whose power consumption is the lowest. Only the number of these pairs is larger by at least 2-3 orders of magnitude than the length of time necessary for the calculation of complex optimization having identical angles. The number of "routes" that can be realized on these pairs is of an astronomical order of magnitude; this indicates well how complicated this task is.

The first steps of the algorithm are identical with the algorithm realizing the optimization of identical angles: the request for data and the determination of the number and places of heat treatments.

Following the above procedure, the angle-reduction pairs are calculated. This procedure can be considered as the construction of a map where the algorithm determines the edges coded by the angle-reduction pairs initiating from the point indicated by the deformation occurring up to the given point. So the adjacency created by the edges directing outwards from the given points, as well as the length of route between them (i.e. the value of power consumption), can be obtained.

Further information was collected about the optimum parameters as the algorithm further decreased the length of time of the calculation. The function of the formula

describing the explicit average utilization factor was investigated for the values of technological parameters applied in industrial circumstances. On the basis of this investigation, it can be stated that the value of logarithmic deformation carried out in one pass cannot be higher than 0.7 under any circumstances because, in this case, the value of the factor can only be higher than 0.5…0.55. A value of 0.02 can be chosen as the lowest value of deformation, which reduces a rod with a diameter of 100 mm only by 1 mm. As a consequence of the decreasing behaviour of Eqs. 3 and 4, the relative drawing stresses can by no means reach the values of 0.5…0.55 at any of the technological parameters below this deformation range. This means that the range of deformation that can be accepted in one pass is between 0.02…0.7. Owing to the exactness of workability of dies, this range has also been divided into discrete values where the difference between the adjacent reductions is 0.001. With this, the selectable reduction set was decreased to a value of 681. So the algorithm must examine merely a maximum of 681 values if it searches for the optimum value of utilization factor at a given angle-value, so the time necessary for the calculation of constructing the map will be a maximum of 681 times more than the calculation time of optimization.

Afterwards the algorithm searches for the shortest route between the initial and end-points from the short sections of route. The shortest route-set (having the lowest power consumption) is found from the route-set with a number of astronomic orders of magnitude by the clever Bellman-Ford algorithm [18, 19]; the calculation time for this searching procedure does not have a longer order of magnitude than the machine time of making a map. Therefore, it can be concluded that the calculation time of complex optimum with variable angles is longer only by 2 to 3 orders of magnitude, as compared to the version having identical angles; so this algorithm can calculate the objective function even using current computer capacity.

4   Comparison of the Complex Optimization Objective Functions

It can be seen in the previous section that there is a significant difference in calculation time lengths of the algorithms realizing the two complex optimization objective functions. In the case of a multi-step wire drawing, the time necessary for the complex optimization of searching for the identical cone angle is between 5 minutes and 1 hour, while the time necessary for finding the variable angles lasts for days. On the other hand, the complex optimization method with identical angles can never result in an optimum value having lower power consumption than the method with variable angles.

On the basis of the above arguments, it was necessary to compare the two optimum values for the most possible parameter values in order to decide what the

extent of error is during the process to search for the identical angle with a short calculation time as compared to the complex optimization with variable angles. The results obtained in the course of running the algorithm with variable angles for ten weeks was compared to the method of identical angles.

The complex optimizations were carried out by using the following three material grades: **Al99.5**; **CuE**; **C10**. The individual optimization processes were started by using different initial wire diameters: the highest value was **20 mm,** while this value was decreased by 0.6 mm down to **0.2 mm** in the course of the further runs. The complete deformation of a multi-step drawing process was equal to the value of approximate deformability of the given material. Though heat treatment is not prescribed in the drawing technology in this case, the two complex optimizing objective functions can well be compared. In addition to changing of the initial wire diameter, the drawing velocity was also changed. The final velocity of drawing was **1, 4** and **7 m/s.** The two complex optimums were calculated for a total of 102 technological adjustments as a function of the velocities, initial wire diameters and material grades. These parameters cover the greatest part of the technological value set applied during wire production, and consequently, a good approximation of the behavior of complex optimums is given for an optional multi-step drawing.

The semi-cone angles belonging to the passes of complex optimums are demonstrated in Fig. 4.
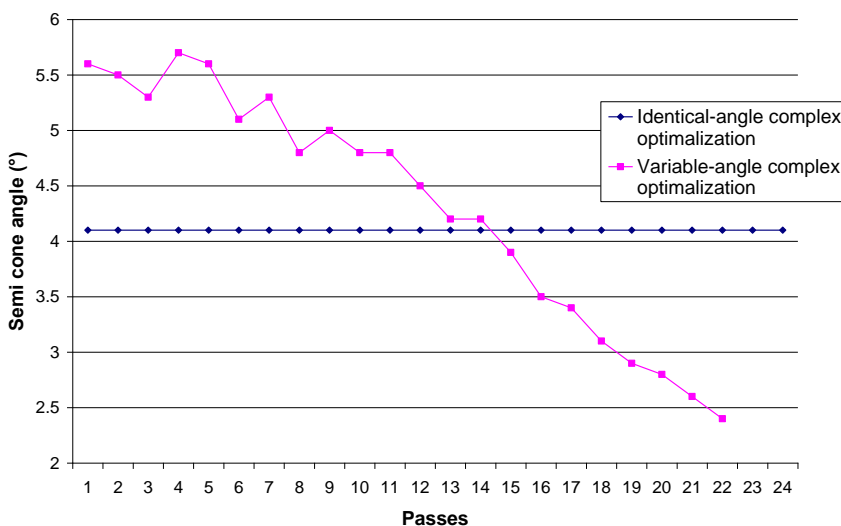

Figure 4

The change of cone angles as a function of the complex optimizing objective functions when the initial wire diameter is 20 mm, the diameter of ready-made wire is 2.58 mm, the final velocity of drawing is 7 m/s and the grade of material is Al99.5

As a result of the complex optimization with variable angles, drawing sequences were obtained consisting of 1 or 2 passes fewer than those in the results of optimization with identical angles (as can be seen in Fig. 4). Independent of the drawing velocity and wire diameter, a decreasing trend can be observed concerning the semi-cone angles if the number of passes increases and the wire diameter decreases when using the version with variable angles, although this change cannot be considered monotonous.

In addition to comparing the number and geometry of dies, the most important task is to compare the value of power consumption of the multi-step wire drawing machine in order to perform the complete deformation.

The absolute error-norm (10) introduced in [16] was used for digitizing the difference between the two objective functions; as input, it substitutes the values for power consumption obtained by the complex optimizations belonging to the identical technological adjustment to the place with identical index.

$$\left\| . \right\|_1 = \sum_{j=1}^{N} \frac{\left| x_j - y_j \right|}{N * y_j} \tag{10}$$

The value of error norm obtained for the 102 adjustments (samples) is **0.0396.** This value can be considered infinitesimal, so it can be stated that, as far as power consumption is concerned, the difference between the complex optimization with identical angles and the complex optimization with variable angles is not too significant, independent of the cross section, drawing velocity and material grade.
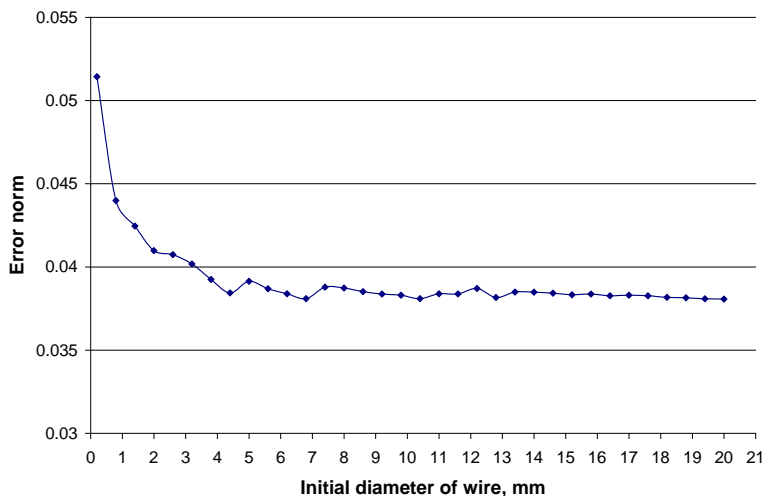

Figure 5

The difference between the power consumption values belonging to the complex optimums expressed by absolute error norms as a function of the initial diameter of wire. The drawing procedure has been carried out up to the limit of deformability for each material grade.

The behaviour of error norms was investigated as a function of the initial wire diameter, the final velocity of drawing and the material grade. The results of these investigations are demonstrated in Figs. 5, 6 and 7. It can be seen in Fig. 5 that the error-norm of power consumption is constantly below 0.04 in the case that the initial diameter is more than 3 to 4 mm. The error norm starts growing in the case of lower values of initial diameters. The angular coefficient of increase becomes significant below 1 mm, though here the value of error norm is still less than 0.045. As was described earlier in the section dealing with the development of the model, the closed analytical relationships installed in some complex optimizing objective functions are not relevant in the case of the finest gauge drawing; therefore, optimization below a wire diameter value of 0.5 mm is not suggested using the optimizing processes described here. However, a small and constant difference can be found between the complex optimizations in the accepted range; therefore, it seems to be reasonable to use an algorithm with identical angles, which has a shorter time of calculation, for the technological planning.

By investigating the difference between the complex optimums as a function of velocity (Fig. 6), it can be stated that the error-norm increases if the final velocity of drawing increases, and the relationship can be approximated by a power function with an exponent with a value of less than 1, in spite of the fact that direct proportionality cannot be observed between them. On the basis of the behavior of the function, it can be predicted that the error norm will not exceed the range of 0.07 to 0.08, even in case of a drawing velocity value of 10 m/s.
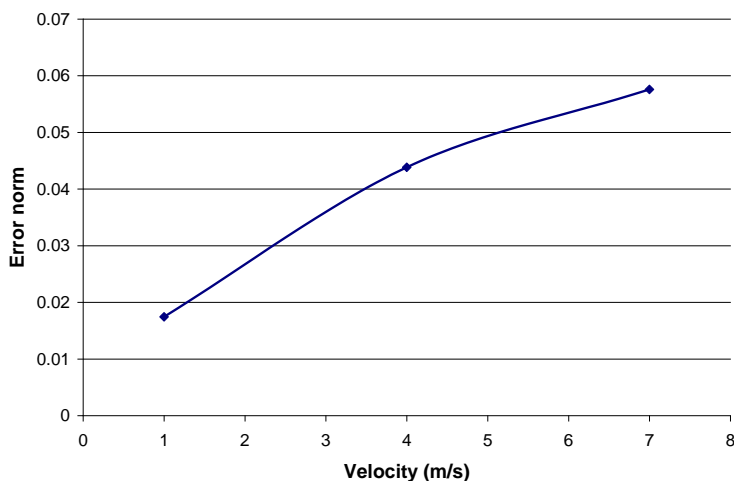

Figure 6

The difference between the power consumption values belonging to the complex optimums expressed by error norms as a function of the final velocity of drawing. The drawing has been carried out up to the limit of deformability in case of each material grade.

By investigating the differences as a function of the three material grades, it can be stated that the n-value of the material influences the value of the error norm. The higher the hardening reaction of the material to the deformation is, the higher the difference is between the power consumption values of complex optimums. However, the effect of material quality is not significant. It can be seen in Fig. 7 that the highest difference between the error norms is only around 0.01 and the error norm is much less than 0.045 in the case of copper.

It can be concluded that the difference between the results of complex optimization with identical angles and complex optimization with variable angles is sensitive to the initial diameter and to the material grade only to a small extent.

However, the drawing velocity has a more significant effect on the error norms belonging to the complex optimums. In the case of coarse drawing machines, medium drawing machines and fine drawing machines, the result of the complex optimization objective function with identical angles is accepted as a drawing-technological line with a minimum error up to a final velocity of 10 m/s, which is the best drawing-technological line from the point of view of material grade, quantity and cost effectiveness. In order to increase the effectiveness, a complex optimization objective function with variable angles can be offered on the basis of the trend of error norms if the final velocity of drawing is higher than 10 m/s.
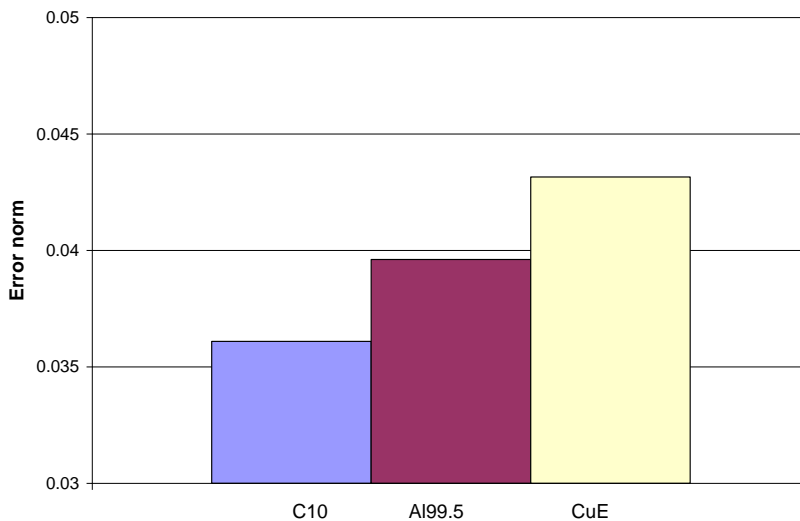

Figure 7

The difference between the power consumption values belonging to the complex optimums expressed by absolute error norms as a function of the material grades. The drawing has been carried out up to the limit of deformability in the case of each material grade.

Conclusions

In the present paper, a complex optimization objective function concerning multi-step wire drawing technology is described and is also interpreted on a complex model. A method has been developed by which the technological planning can be carried out quickly by means of calculations. Therefore, it has become possible to determine the most advantageous optimum technology for the task in a cheaper and faster way.

The objective function focused on in this paper has been extended from a version in which cone angles are identical. In the new objective function, the values of the cone angles are independent of each other in the individual passes. The two versions were compared. The difference between the lengths of time necessary for the calculation of the two objective functions was determined by the algorithmization of the complex optimization processes. It was found that the difference between the length of time necessary for the calculations is of about 2 orders of magnitude, i.e. 100 times higher for the complex optimization with variable angles (e.g. the length of time can be some minutes versus a complete day).

The complex optimization methods were realized using software as well. The differences between the complex optimums were determined by comparing the results of software runs considering the power consumption of the drive and the total number of passes. The absolute error norm of differences is less than 0.04; this means that the two kinds of complex optimization show good conformity.

As a result of the more detailed investigations, it can be concluded that the optimization method with identical angles, due to its significantly shorter calculation time, is suitable for the most effective realization of the planning of an industrial technology – independent of the quality of material – in the case of fine, medium and coarse wires (a diameter of 0.5 to 20 mm) at a final velocity of less than 10 m/s. However, the optimization method with variable angles is suggested for planning the multi-step drawing technology if the velocities are above 10 m/s. Our purpose is to increase the effectiveness of industrial technology; the next step is to test this approach in an industrial setting.

Acknowledgement

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