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Maximization of Versatility Indicator of Quality of Drawing Process Including Qualimetric Estimation of Production Parameters

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A method for determining the rational values of controlled technical, technological and (or) the organizational factors that provide maximum possible level of the object complex quality index with quality value of selected unit factors regard and the uncertainty of process description is developed. The method is used at drawing. It can be a basis for improving the production quality management system and the organization in general, particularly, as an effective means of obtaining reliable information when making decisions to satisfy customer requirements.

Keywords: QUALIMETRY, OBJECT QUALITY INDEX, OPTIMIZATION OF CONTROLLABLE FACTORS, DRAWING

General Statement of the Problem and Its Connection with Important Scientific and Practical Problems

Creation and consumption of quality products (services) is important for the society. In this case, the consumer is interested in the highest quality at the lowest price, and the manufacturer is interested in obtaining maximum profit at minimum expenses. This presupposes an optimum of definite quantitative criterion of the product quality, which is usually represented by a *complex indicator of quality* Q [1]. This parameter is formed by a set of n individual quality $y_i\,(1 \le i \le n)$, which is defined by regulations (DSTU, GOST, TS, ISO etc.), as well as by the needs of the consumer and the opportunities of production manufacturers. An important part is also played by the *relevancy* k_i for each y_i, usually defined by an expert method.

As usual for the highest level of product versatility indicator one aims for the highest values of individual parameter that is mathematically represented by the solution of the system [1]

$$\frac{dQ}{dy_1} = 0; \quad \frac{dQ}{dy_2} = 0; \quad \ldots . \frac{dQ}{dy_n} = 0, \qquad (1)$$

where the corresponding values $y_{i\max}$ are found. Nevertheless, the question of rational values $y_{i\max}$ still remains open.

Theoretically, there can be a set of individual parameters. They are defined by a limited quantity of technical, technological, and (or) the organizational factors under specific production conditions. The latter, individually or in groups, can influence both on the individual quality of products (services), and the set these parameters, formally providing their mutual independence.

As a result, for managing the process of quality creation there is a general problem of finding such set m of technical, technological and (or) organizational factors x_j $(1 \le j \le m)$, which would provide acceptable maximum of versatility indicator Q, avoiding explicit consideration of y_i values.

The Analysis of the Latest Achievements and Publications

According to a study [2], the individual quality parameters y_i can be presented by corresponding functions, and a versatility indicator of quality is represented by functional $Q = f(y_1; y_2 \ldots y_i)$, where $y_i = \varphi(x_1; x_2 \ldots x_j)$.

The mentioned relationships can be found in the course of special studies, for example, by regression or correlation analysis with subsequent analytical approximation of the results obtained, in particular, by the expansion of functions in series [3], etc.

Value of Q depending on the process conditions is found as one of the weighted means: arithmetical, geometrical, quadratic or harmonical one [1]. Also it should be noted that the set of rating coefficients, individual quality indicators y_i follows dependence [2]

$$\sum_{1}^{n} k_i = k_1 + k_2 + ... + k_n + c \equiv 1, \qquad (2)$$

where c is an uncertainty of representation of the creation process of products quality.

Alternatively to the concept of "error", here the term "uncertainty" is used in a broader sense, as it characterizes not only measurement error, but also other information related to measurements, for example, variety of reference data, reliability of expert assessments, etc.

Then the versatility indicator of quality with the usage of polynome of z z -degree for average arithmetic mean is represented by an expression [2]

$$Q = \sum_{i=1}^{n} (k_i \sum_{j=1}^{m} \sum_{h=0}^{z} (a_{ji} \cdot x_{ji}^{h})), \qquad (3)$$

where $0 \le h \le z$ are the numbers of functions expansion term into a row, a_{ji} are the coefficients under the corresponding expansion terms, and the system is transformed into:

$$\frac{dQ}{dx_1} = 0; \quad \frac{dQ}{dx_2} = 0; \quad \frac{dQ}{dx_m} = 0, \qquad (4)$$

where the corresponding values $x_{j\max}$ are found.

The corresponding analysis for the two x_j in general view and for the conditions of wire drawing was performed in study [2] in several ways: with a combination of relationships $y_1 = \varphi_1(x_1; x_2)$ and $y_2 = \varphi_2(x_1; x_2)$, each of which had a maximum or a minimum, as well as form of increasing or decreasing two-dimensional function.

Part of a Problem Which Requires Solution and Task Description

The number of possible combination of parameters in the definition of Q rapidly increases with the increase of the quantity of considered y_i and x_j.

Thus, when considering three individual quality indicators y_i such combinations may include: three increasing functions, one increasing and two decreasing functions, two ascending and one descending, three decreasing, and their combination with the functions or the functions themselves, which have, for example, one minimum or maximum or several extremums of one or both types.

Additional complexities level contribute k_i coefficients levels, rating under the functions y_i, uncertainty c of object description, as well as applied form of average mean when representing a quality versatility indicator Q. As a result, the functionality Q may have one or more extremums or may not have them at all. It makes the solution of the stated problem *in general* be of uncertain volume and, as a consequence, leads to the necessity to consider some specific examples which are important for practice in accordance with of the definite algorithm.

In particular, it is necessary to complement the analysis performed in study [2], on the formation of the quality versatility indicator with two single quality indicators (tensile strength σ_B and ultimate elongation δ of the wire), depending on the degree of deformation ε of the metal and the half-angle α of die taper angle, with the additional evaluation of the impact of the third individual indicator: with the energetic expenses during drawing process. It was the issue, which was chosen as a *work objective.*

Presentation of the Basic Materials of the Researches

Initially a formation of versatility indicator of quality Q according to formula (3) by three individual indicators of quality $y_1 = \phi(x_1)$, $y_2 = \phi(x_1)$ and $y_3 = \phi(x_1)$ were considered. These individual indicators were determined by x_1 and were described by a visual combination of various functional dependencies.

For such case with several coefficients of significance k_1, k_2, k_3 and uncertainty $c = 0$:

$$Q = k_1 \cdot y_1 + k_2 \cdot y_2 + k_3 \cdot y_3 .$$

(5)

Graphical interpretation of the part of performed investigations where $k_1 = k_2 = k_3$ is shown on Figure 1.

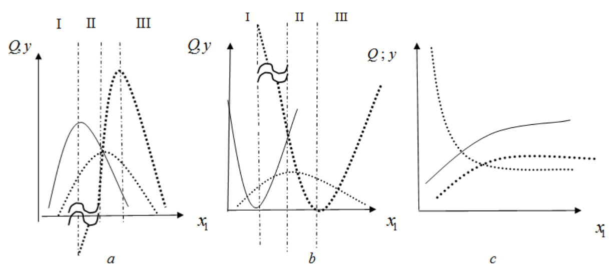

Figure 1. Some combinations of functions of individual quality indicators that form versatility indicator of quality (refer to text)

These data suggest that the simultaneous consideration in accordance with equality (5) of three convex parabolas in the locations of their maximums in the relevant sections I, II and III (see Figure 1) the appearance of the maximum of their amount is problematic. The abscissa of such characteristic location (and, therefore, rational value of x_1) depends on the shape of a parabolas and will be in a section between I and III similarly to the study [2]. Moreover, at the location of the maximum of the parabola (for example, in the section I) there can be formed a *minimum* of the sum of three studied functions; also there can be several extremums.

Corresponding opposite situation is observed on Figure *1b*: the ordinate of the sum of three functions in section I, which is characteristic for the *minimum* of the first function, it may be the greatest. There may also take place a few extremums of both kinds.

Figure 1*c* shows a situation in which the occurrence (or absence) of the maximum of ordinate functions sum depends on the intensity of their change.

If one considers that the list of individual quality indicators and levels of their significance coefficients are determined by the expert method, then on the total curve Q (not shown in the graphs) may take place some maximums and minimums with the excess of the absolute value of one of the *minimums* Q of its other *maximum* values. In all cases, an analysis of the possibility of putting into practice the x_j values found by the analytic representations is required.

Turning to specifics, let us consider the formation of the versatility indicator Q of quality of the drawing process in the formulas (2) - (4) by a combination of the three individual quality indicators: the tensile strength σ_B, relative elongation and energy consumption for metal deformation depending on ε and α (of course, in reality, the formation of Q may be caused also by other factors.)

Required dependencies $\sigma_B = \varphi_1(\varepsilon, \alpha)$ and $\delta = \varphi_2(\varepsilon, \alpha)$ are taken according to I. Yukhvets (Fig. 2), taking into account that

$$\varepsilon = \ln \frac{1}{1-\gamma}, \qquad (6)$$

where γ is a relative degree of metal deformation in the pass, and E. Siebel's formula was used as energy consumption characteristic for determination of drawing stress σ, giving the extremum (minimum) of this value under definite value of α [4]

$$\sigma = \sigma_{\text{Âñð}}(1 + f/\alpha) \cdot \varepsilon + 0{,}667 \cdot \alpha \;, \qquad (7)$$

σ_{Bcp} is an average limit of deformed metal yield in the deformation zone; f is the friction ratio.

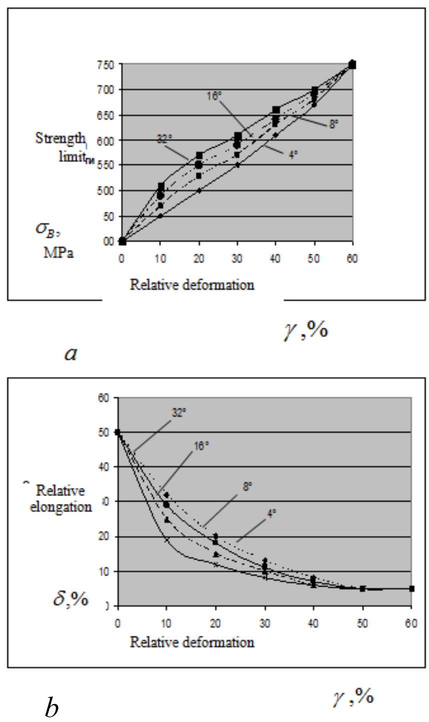

Figure 2. Dependence of tensile strength (a) and relative elongation (b) of the wire on conditional degree of deformation and taper angle of the die during wire drawing [4]

According to the provisions of qualimetry [1] there was considered that increase of σ_B, δ and reduction of energy consumption, and also the necessity of nondimensional representation relatively to 1 of all values of initial parameters should correspond to the increase of versatility quality indicator.

The latter was provided with the division of the current values σ_B and δ according to Figure 2 by 750 MPa and 50% respectively, and the individual indicator of quality, responsible for energy consumption according to the formula (7) was represented as the following

$$U = \frac{\sigma_{Bcp}}{\sigma} = \frac{1}{(1+f/\alpha) + 0{,}667 \cdot \alpha}. \quad (8)$$

On the basis of (3) taking into account (2) (if $c \neq 0$) the versatility indicator of quality was expressed as

$$Q = k_1 \cdot S + k_2 \cdot \Delta + (1 - k_1 - k_2 - c) \cdot U, \quad (9)$$

for which after computer approximation taking into account the data from Figure 2 the functions of individual quality indicators were determined for the following features:

- metal break point

$$S = 0{,}508 + 0{,}514 \cdot \varepsilon^{0.643} + 0{,}14 \cdot \alpha^{1{,}237}; \quad (10)$$

- relative metal elongation

$$\Delta = \frac{1}{-2{,}786 + 9{,}53 \cdot \varepsilon^{0{,}542} + 5{,}01^{0{,}4827}}; \quad (11)$$

- energy consumption (on the basis of formula (8) if $f = 0{,}08$)

$$U = \frac{0{,}667 \cdot \alpha}{(1 + \frac{0{,}08}{\alpha}) \cdot \varepsilon + 0{,}667 \cdot \alpha}. \quad (12)$$

Each of the represented individual quality indicators depends on 2 factors, one of which is a half angle of die taper α and can be conditionally referred to the technical factors, and the second is a metal deformation degree ε and can be referred to the technological (organizational) ones. These values are also developed to the nondimensional representation: ε according to the formula (6), and the angle α into the radian.

In the analysis one should take into account the peculiarities of the actual process of drawing. Thus, the single degree of deformation in the die ε should stay in the limits of 0.1 – 0.5. Going below the lower limit results in intensified wear of dies; going above the higher limit results in wire rapture. Half angle α of the die in the dry drawing usually equals 0.05-0.15. Going above the given limits is followed by the increase of drawing power and energy consumption for process performance [4].

In this particular example, formally, the application of transactions (4) to the expressions (10)-(12) did not reveal the presence of extremums. In such situation, a search for rational values of technical, technological, and (or) the organizational factors should be performed by direct calculation.

It is expedient to carry out the virtual (computational) experiments using the methods of planning, for example, orthogonal Latin squares in order to reduce the amount of work and to facilitate the analysis of the obtained results, while preserving their statistical significance. The positive side of application of this method is the possibility of taking into account both qualitative and quantitative levels of the independent variables. In this case the order of the corresponding square is chosen by one unit more than the quantity of initial effective factors or can be equal to it. Likewise, the level number of changes of these factors is determined [5].

In this example five independent variables $(\varepsilon, \alpha, k_1, k_2, c)$ were marked for which the orthogonal square of 5th order was chosen (Figure 3). Levels of these variables for which determination of Q was performed according to formulas (9) - (12) are listed in the table.

12345	23451	34512	45123	51234
24153	41532	15324	53241	32415
45231	52314	23145	31452	14523
53412	34125	41253	12534	25341
31524	15243	52431	24315	43152

Figure 3. The matrix of orthogonal Latin square of 5th order

In each w-th cell of calculation experiment plan (see Figure 3) a set of figures is represented. Number location refers to the variable number, and its value refers to the level of each variable according to the table data. For example, a group of figures "45231" in the 11th cell corresponds to a value of $Q = 0{,}4312$ (calculated separately), which is obtained if $\varepsilon = 0{,}35; \alpha = 0{,}45; k_1 = 0{,}25; k_2 = 0{,}3; c = 0$.

Table. Levels of the effective factors (of the variables)

Variable No.	Variables	Variables Levels				
		1	2	3	4	5
1	ε	0,05	0,15	0,25	0,35	0,45
2	k_1	0,15	0,25	0,3	0,35	0,4
3	α	0,05	0,15	0,25	0,35	0,45
4	k_2	0,15	0,25	0,3	0,35	0,4
5	c	0	0,025	0,05	0,075	0,1

Partial dependences of Q on each variable (Figure 4) were obtained after calculating the values of the versatility indicator of quality for all cells of the matrix, their logarithmation, averaging of the data for each level of each variable, and potentiation (according to known procedures of treatment [5]).

According to the applied planning methodology, the value of Q is determined by the following formula [5]

$$Q = N \cdot Q_1(\varepsilon) \cdot Q_2(\alpha) \cdot Q_3(k_1) \cdot Q_4(k_2) \cdot Q_5(c), \tag{13}$$

where $Q_{1.....}$ Q_5 are the ordinates on the graphs for the chosen values of the arguments.

Approximization of the data obtained is represented by the trends on the graphs and by the analytical dependences given below:

- for metal deformation degree (Figure 4*a*):

$$Q_1(\varepsilon) = \frac{1}{3{,}08 - 0{,}15 \cdot \varepsilon^{-0{,}591}}; \tag{14}$$

-for die taper angle if $\alpha \geq 0{,}05...0{,}21$ (Figure 4*b*):

$$Q_2(\alpha) = -7{,}88 \cdot \alpha^2 + 2{,}23 \cdot \alpha + 0{,}26; \tag{15}$$

if $\alpha \geq 0{,}21$;

$$Q_2(\alpha) = 4{,}79 \cdot \alpha^2 - 2{,}88 \cdot \alpha + 0{,}77; \tag{16}$$

- for the k_1 significance coefficients under characteristic of S limit of metal hardness (Figure 4*c*)

$$Q_3(k_1) = 0{,}485 \cdot k_1 + 0{,}2416; \tag{17}$$

- for the k_2 significance coefficients under characteristic of relative metal elongation for $\geq 0{,}15...0{,}275$ (Figure 4*d*)

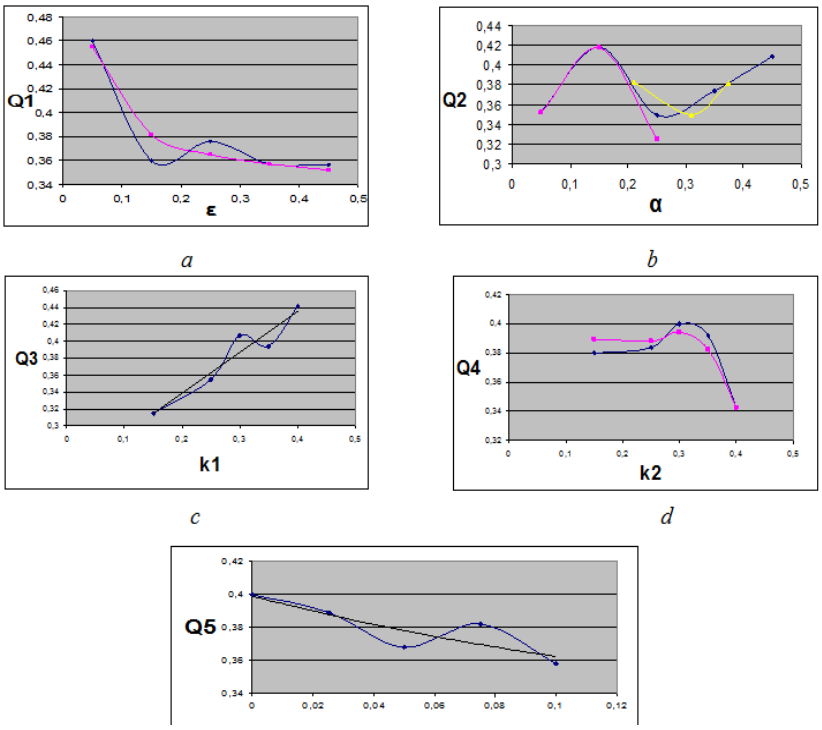

Figure 4. Partial dependences of Q versatility indicator of quality on the degree of deformation (*a*), half angle of die taper (*b*), quality value (*c, d*) and uncertainty (*e*)

$Q_4(k_2) = 0{,}392 - 0{,}001626 \cdot k_2$; (18)

for $k_2 \succ 0{,}275$:

$Q_4(k_2) = -5{,}58 \cdot k_2^{\,2} + 3{,}3875 \cdot k_2 - 0{,}1197$; (19)

to characterize the uncertainty of object description (Figure 4*e*)

$Q_5(c) = 1{,}04 \cdot c^2 - 0{,}4676 \cdot c + 0{,}3989$. (20)

In this case the normalizing factor N can be determined by the formula

$$N = \frac{\sum_{1}^{w} N(w)}{w}, \quad (21)$$

where the values of N_w for every w th cell of the square are determined taking into account the trends of the Figure 4 and are calculated according to the following expression:

$$N_w = \frac{Q_w}{Q_1(\varepsilon) \cdot Q_2(\alpha) \cdot Q_3(k_1) \cdot Q_4(k_2) \cdot Q_5(c)}, \quad (22)$$

where Q_1-Q_5 are the ordinates of the represented partial dependences, which correspond to the variables values according to the numerical code of the variables in the square (see Figure 3) and their values in the table, and Q_w is the calculated values of quality versatility indicator for the corresponding square cells.

Taking into account the average value of N, the set of N_w values allowed to determine the accuracy of data processing by calculation of their average quadratic deviation and the corresponding coefficient of variation. For the considered example N is equal to 47,71 with the variation coefficient ~0,12 under probability of 95%.

When taking into account the possibility of implementation of the chosen set of technical, technological, and (or) organizational factors, the use of these data allows to select such values, which correspond to the highest possible level of the Q versatility indicator of the process quality. In this example, the following values correspond to it:

- the degree of single deformation in the die $\varepsilon \le 0.15$ (see Figure 4*a*), due to reduce of energy costs for the drawing process (in case of necessity to increase the deformation degree $\varepsilon \approx 0{,}25$ can be a recommended value);
- die taper half-angle $\alpha \approx 0{,}15$ (see Figure 4*b*), which corresponds to the minimum of the energy consumption amount for process performance and drawing practice;
- it is recommended to take steps to increase the value of k_1 (see Figure 4*c*)and k_2 (see Figure 4*d*).

It's natural that the reduction of uncertainty (*c*) of process description results in increase of *Q* (see Figure 4*e*).

Comparison of the analysis results with the same materials published in the study [2] showed the dependence of recommendations about the methods of improvement of the process quality on a selected set of individual quality indicators. Thus, the integration of a single significant indicator of quality into the consideration, which is "responsible" for the energy consumption, effected on the recommended values ε and α (earlier $\varepsilon \prec 0{,}1$ and $\succ 0{,}3$-$0{,}4$; $\alpha \prec 0{,}1$).

The given materials were compared to the results of the activity of one of Dnipropetrovsk metalware enterprises; it revealed their correlation with the practically applied values of die taper half-angle and the tendency to reduce the partials dependences for reduction of energy costs for drawing process.

Conclusions and Prospectives of Further Investigations

A method for determining the reasonable level of technical, technological and/or the organizational factors that determine the highest possible level of process quality at all stages of its life cycle is developed, taking into account the individual quality indicators selected by expert method, and also their coefficients and the description uncertainties.

For the first time in the framework of the developed method an example of the interaction of three individual quality indicators of the object, forming a comprehensive indicator of its quality, with various combinations of the functional dependences of individual quality indicators on technical, technological, and/or organizational controlled factors is considered. It is shown that this set can ensure the presence of versatility quality factor (which, as a rule, do not coincide with the maximum of these functions), but such an extremum may not even take place. The recommendations for search of rational values of factors by implementing the calculation experiment, using planning techniques are developed for the latter case.

This method is used at drawing. The reasonable values corresponding to the production practice of factors values and allowing to maximize the quality of the process within the selected limits are revealed.

The prospective of research is the introduction into the consideration of additional individual indicators of quality, which will be, for example, responsible for the effectiveness of the equipment, as well as expanding the list of initial factors influencing on the process.

The method can serve as a basis for improvement of control system of the processes and the quality of the organization itself, in particular, as an effective tool for decision-making to meet customer requirements.

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Максимизация комплексного показателя качества процесса волочения с учетом квалиметрической оценки параметров производства

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Разработан метод определения рациональных значений управляемых технических, технологических и (или) организационных факторов, обеспечивающих максимально возможный уровень комплексного показателя качества объекта с учетом коэффициентов значимости выбранных единичных показателей качества и неопределенности описания процесса. Метод использован в сфере волочения. Он может послужить основой для улучшения системы управления качеством производства и самой организации, в частности, как эффективное средство получения достоверной информации при принятии решений для удовлетворения требований потребителей.