Stanisław Płonka[1,*],
Robert Drobina[1],
Dariusz Jędrzejczyk[1],
Jacek Postrożny[2]

[1] University of Bielsko-Biała,
Department of Manufacturing Technology
and Automation,
43-309 Bielsko-Biała, ul. Willowa 2, Poland,
* e-mail: splonka@ath.bielsko.pl

[2] Cavalry Captain Witold Pilecki State University
of Malopolska in Oświęcim,
Institute of Management
and Production Engineering,
32-600 Oświęcim, ul. M. Kolbego 8, Poland,
e-mail: jacek.postrozny@dydaktyk.pwsz-oswiecim.edu.pl

Selection of Optimal Thermochemical Treatment of Steel Guides of Yarn

Abstract

This paper presents a method of selection of an optimal (the best possible) thermochemical treatment of a steel guide of yarn for a ring spinning frame with the use of an optimisation procedure based on assumed criteria, and with consideration of their importance. Yarn guides for a ring spinning frame were manufactured from three brands of steel and were subjected to the following types of thermochemical treatment: 50SiCr4 steel (chrome hardening, diffusion boronising, and titanising); 41CrAlMo7 steel (nitrosulfiding and nitrogen case hardening), and C45 steel (diffusion boronizing). Unit manufacturing costs and six criteria of manufacturing quality: four parameters of surface texture (Rq, Rp, $R\Delta q$, r_w), maximal hardness of the surface layer ($HV_{0,1}$), and the case depth of the surface layer (g_{ww}), were taken as criteria for assessment. Values of the assessment criteria obtained from calculations and measurements were subjected to normalisation. The knowledge of experts and importance matrix B, evaluated with the use of the Saaty method (consisting in pairwise comparison of the successive criteria) were used to determine the importance of the criteria taken for the assessment. Using the Power method, eigenvalues of matrix B were found, as well as corresponding coordinates y_t of the eigenvector, which are simultaneously the weights of the corresponding criteria. Normalised decisions were created in the next step by raising each component of the normalised assessments to a power equal to the corresponding weight. In the last step of the procedure, a single optimal lining-up was created comprising the smallest s-th components of the individual decisions d_1, d_2, ..., d_m. The best variant of the thermochemical treatment was recognised as corresponding to the largest component of the optimal lining-up, which in our case is the diffusion boronizing.

Key words: *optimisation, thermochemical treatment, yarn guide.*

Introduction

The diversity of means and methods of surface treatments, including also heat and thermochemical treatment, can lead to a situation where elements which are identical or similar in shape, dimensions and accuracy are frequently produced according to various manufacturing processes, differing from each other in labour demand and costs; additionally providing different manufacturing quality of workpieces and, in consequence, better or worse functional quality [1, 2]. Therefore there, emerges a complex, multivariant task of the design and selection of the most effective method of heat and thermochemical treatment [3, 4], and gener-

ally the choice of a variant of the manufacturing process for the workpiece. In the case of a ring spinning frame, in the area of the twisting operation, the yarn passes through a guiding eyelet (guide), which generally performs the following functions: changes or maintains the direction of run of the yarn, and generates an appropriate tension of the yarn [5, 6]. During the frictional operation of the mating pair: yarn-guide, the guide generally remains immovable in relation to the yarn sliding on it. While the surface of the guide should comply with the following conditions [5, 6]:

- should feature q low coefficient of friction in cooperation with the yarn, which is mainly dependent on the geometrical structure of the surface (SGP in short), resulting from the method of its treatment,
- should not generate any electrostatic charges or transfer them to the yarn,
- should have sufficient wear resistance.

Conditions of the friction have a decisive effect on the productivity of the process and quality of the textile product. It is known that in the case of the slip of yarn on the guide, the value of friction depends on the tension of the yarn, geometrical structure of the surface (SGP) and physical properties of the objects involved in the friction, as well as on the

external conditions in which the slip occurs [6].

In the majority of studies up to now dealing with analysis of the geometrical structure of the surface in contact with the yarn – to have a more unequivocal assessment – usage of two or more roughness parameters have been generally recommended [7, 10]. This can enable a more accurate assessment of the effects of a brand of raw material, the type of heat treatment as well as thermochemical and finishing treatments on the geometrical structure of the surface. The coefficient of linear correlation R of the SGP parameters or of the 3D surface roughness parameters (topography), with the coefficient of kinetic friction of the yarn μ_k are very helpful in this assessment [10, 11].

Operating conditions of the guide (abrasion) require good abrasion resistance, from the material and, thus, high hardness over a considerable depth of the material. Therefore, it is necessary to take into considerations these physical properties of the surface layer when selecting the type of thermochemical treatment.

The issue of the assessment of a manufacturing processes in respect of two or more criteria has been presented so far in a few publications only [10, 12-15]. The definition of an allowable set of var-
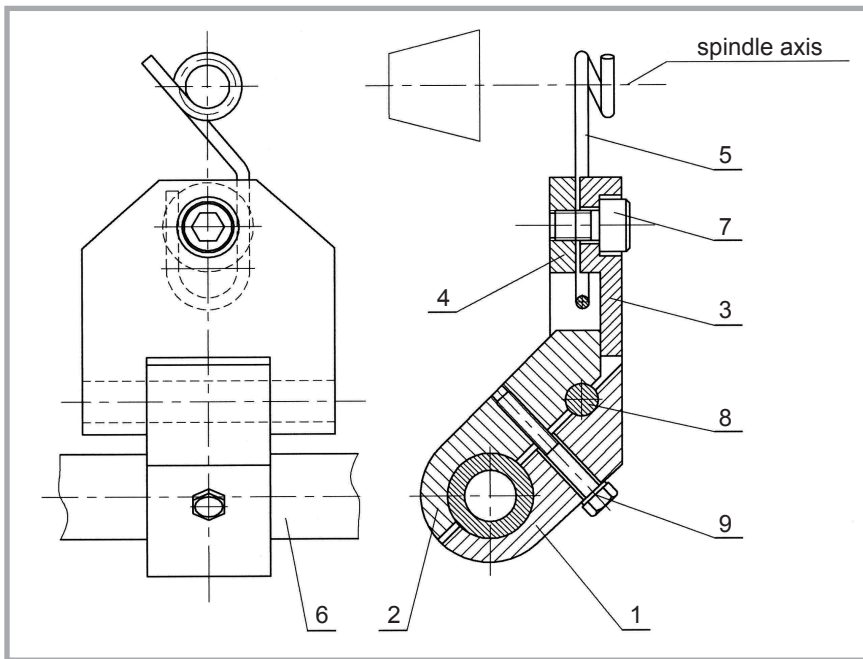
Figure 1. *Attachment of the yarn guide on the ring spinning frame: 1 – upper part of the fixture, 2 – lower part of the fixture, 3 – small flap, 4 – nut, 5 – guide, 6 – supporting pipe, 7 – screw, 8 – pink, 9 – clamping screw.*

iants of the process (in our case it is a set of thermochemical treatment types) for the object analysed, assessed according to the criteria determined, is a starting point for the assessment and selection of the best solution.

In the most general case, except criteria having a deterministic character (stated precisely, sharp) or probabilistic-statistic one, criteria with a fuzzy (subjective) character can be present [14]. Optimisation criteria are often treated in conventional models as deterministic criteria – e.g. cost, and during the development stage of the manufacturing process, they should be repeatedly treated as non-deterministic ones, for instance, as subjective pointwise assessments [10, 13], or fuzzy assessments [14]. In general, however, in the majority of cases, when optimising the manufacturing processes of similar products, to simplify the procedure, optimisation criteria of a probabilistic-statistic character are treated as deterministic criteria, e.g. surface roughness parameters.

The objective of this study is to present a method of assessment of thermochemical treatment types with respect to many criteria, whose values were evaluated from calculations and measurements, with consideration of their importance when selecting the best variant of thermochemical treatment of a steel guide of yarn for a ring spinning frame.

Method of assessment due to many criteria with consideration of their importance

To select optimal thermochemical treatment of steel guides of yarn for ring spinning frames, a method of optimisation was implemented taking into account the many criteria and their importance. The unit manufacturing cost and six criteria of manufacturing quality were taken as criteria for the assessment. Values of the criteria obtained from calculations and measurements were normalised. The knowledge of experts was implemented for evaluation of the importance of the criteria taken for assessment. Using the Saaty method, each of the experts built their own matrix of criteria for the assessment, comparable in pairs [17]. On the basis of the matrixes obtained, called partial ones, a collective matrix was created with its elements above the diagonal, being the arithmetic mean from corresponding elements of individual partial matrixes. Whereas elements of the matrix located under the main diagonal are the converses of corresponding elements located above the main diagonal. Based on the collective matrix B and using the Power method, eigenvalues λ of this matrix were found. In the next step, coordinates y_t of the eigenvector were calculated for the highest eigen values $\lambda = \lambda_{max}$, which are simultaneously the weights w_t of the corresponding criteria. Normalised

decisions were created in the successive step, raising each assessment to a power equal to the appropriate weight. In the last step of the procedure, it a single optimal lining-up was created, with its elements being the lowest s-th elements of the individual decisions $d_1, d_2, ..., d_m$. The best variant is that which corresponds the biggest component of the optimal lining-up. A detailed discussion of this method, together with the mathematical notation, is included in paper [16].

Example of the selection of an optimal variant of the thermochemical treatment of a guide of yarn made of steel for a ring spinning frame

A lot of information on the requirements to be fulfilled by the components of machinery serving as a guide of yarn or thread and on guidelines concerning the selection of materials for the guide, in dependence on the brand of the yarn, can be found in study [5], among others. The relation between the coefficient of kinetic friction μ_k and the surface roughness parameter Ra of the steel guide for wool or cotton staple yarn, as well as for viscose rayon, is presented in publications [5, 10]. The relation between the coefficient of kinetic friction μ_k and the surface roughness parameter Ra of the steel guide obtained as a result of various methods of surface treatment is presented in study [10].

Set of allowable variants of thermochemical treatment of the yarn guide

Due to the lack of consent of the ring spinning frame manufacturer to reconstruct only the guides as well as their attachment on the spinning frame (*Figure 1*), the study was restricted to the guides produced from 50SiCr4, 41CrAlMo7 and C45 steels only (omitting guides made of glazed porcelain, sintered carbides and Al_2O_3ceramal).

To increase the durability of the yarn guides, 12 variants of the manufacturing process were elaborated and analysed, differing mainly in the brand of the material and, most of all in the type of thermochemical treatment The guides from 50SiCr4 steel were subjected to the following type of thermochemical treatment: chrome hardening, diffusion boronising, and titanising, the guides from 41CrAlMo7 steel – nitrosulfiding and nitrogen case hardening, while those from C45
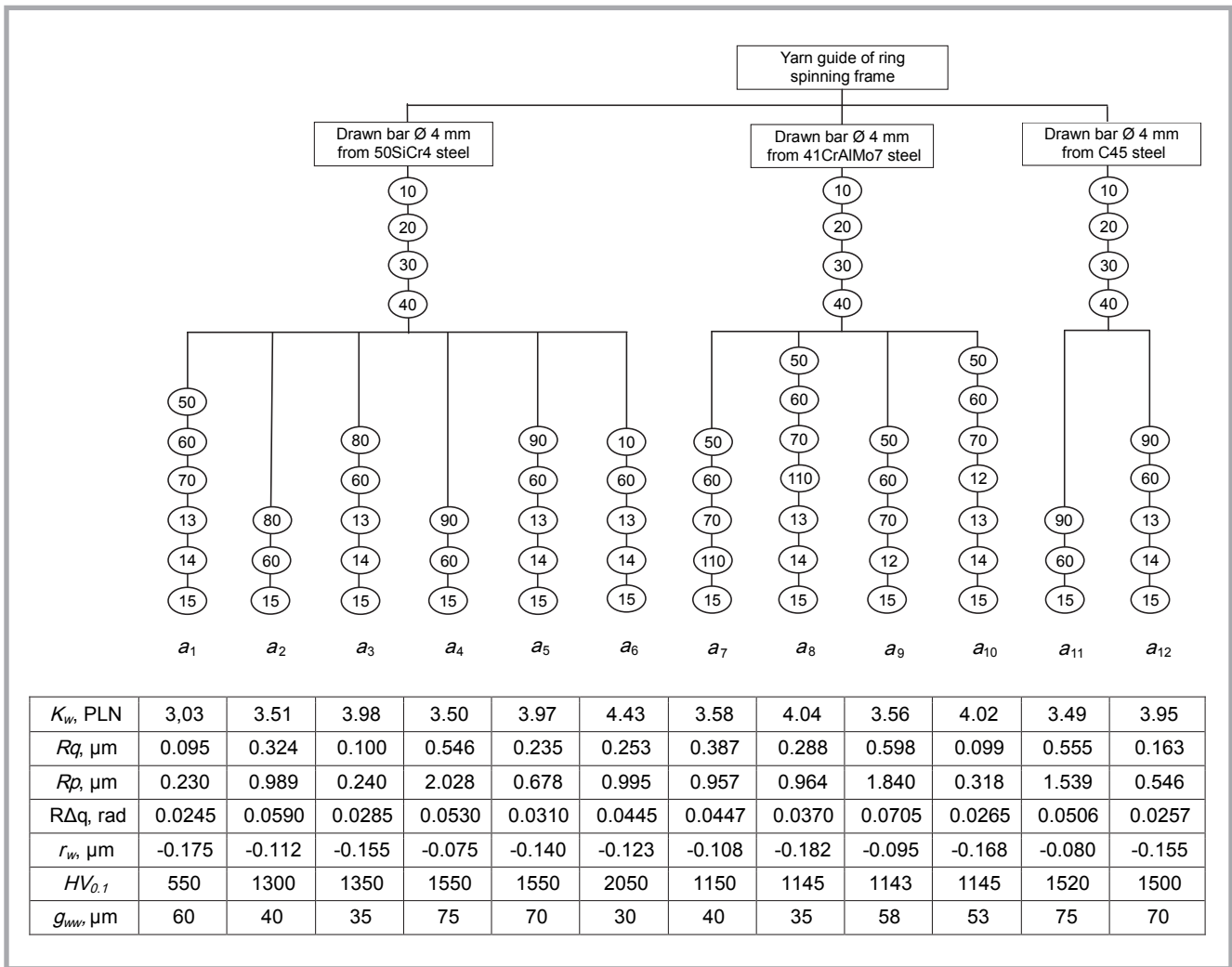
Figure 2. *Graph-tree with variants of manufacturing process of the yarn guide with consideration of different types of thermochemical treatment.*

steel − diffusion boronising only [3, 4]. Variants of the manufacturing process of the yarn guides with the use of the above-mentioned types of thermochemical treatment are presented in the form of a graph – tree (***Figure 2***), while a description of the operations is given ***Table 1***.

Set of criteria for assessment of a yarn guide subjected to various types of thermochemical treatment

The unit manufacturing cost and six criteria of manufacturing quality were taken to assess variants of the manufacturing process, in particular, the thermochemical treatment of a yarn guide for a ring spinning frame:

- unit manufacturing cost K_w, PLN,
- root mean square height of the profile Rq, μm,
- maximum peak height of the profile Rp, μm,
- mean square gradient of the profile roughness $R\Delta q$, rad,

Table 1. *List of variants of the operations in the manufacturing process of yarn guide with consideration of thermochemical treatment types.*

No of oper.	Name of operation	Machine
10	Cutting of the drawn bar ø4 mm to length 145 mm	Press, PHS-160 type
20	Chamfering of two ends of the bar ø4 mm to size 0.5 mm x 45°	Special type of grinder, typeTSZ-06
30	Soft annealing	Electric furnace, typePEC-90
40	Straightening/ bending of attachment according to drawing	Fitter's bench + special attachment
50	Quench hardening of guides	Electric furnace, type PEC-90
60	Tempering of guides from 50SiCr4 steel to 400HB hardness, and from 41CrAlMo7 and C45 steel to 350HB hardness	Electric furnace, type PEC-90
70	Vibrational removal of scale	'Bolton' vibration container
80	Chrome hardening and quench hardening	Furnace, VFC type
90	Diffusion boronising and quench hardening	Furnace, VFC type
100	Diffusion titanising and quench hardening	Furnace, VFC type
110	Diffusion nitrosulfiding	Retort furnace
120	Diffusion nitriding	Retort furnace
130	Grinding with PS20 abrasive paper of 600 grain size	Special purpose grinder
140	Blacking	Tank: bath NaOH 1000 g/l + NaNO₃ 130 g/l
150	Final control	Control station

Table 2. *Values of the criteria after normalization and transformation in dependence on the method of optimisation.*

	a_1	a_2	a_3	a_4	a_5	a_6
k_1	0.9000	0.6257	0.3571	0.6314	0.3629	0.1000
k_2	0.9000	0.5358	0.8920	0.1827	0.6773	0.6487
k_3	0.9000	0.5623	0.8956	0.1000	0.7007	0.5596
k_4	09000	0.3000	0.8304	0.4043	0.7870	0.5522
k_5	0.1523	0.6234	0.3019	0.9000	0.4140	0.5411
k_6	0.1000	0.5000	0.5267	0.6333	0.6333	0.9000
k_7	0.6333	0.2778	01889	0.9000	0.8111	0.1000
	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
k_1	0.5857	0.3229	0.5971	0.3343	0.6371	0.3743
k_2	0.4356	0.5930	0.1000	0.8936	0.1684	0.7918
k_3	0.5765	0.5734	0.1836	0.8608	0.3176	0.7594
k_4	0.5487	0.6826	0.1000	0.8652	0.4461	0.8791
k_5	0.6533	0.1000	0.7505	0.2047	0.8626	0.3019
k_6	0.4200	0.4173	0.4163	0.4173	0.6173	0.6067
k_7	0.2778	0.1889	0.5978	0.5089	0.9000	0.8111

- average curvature radius of profile peaks r_w, μm,
- maximal hardness on the face of the surface layer $HV_{0,1}$,
- hardening depth of the surface layer g_{ww}, μm.

Calculations of the unit manufacturing cost for different types of materials and thermochemical treatments of the yarn guides were based on an algorithm of multistage additive calculation according to the costs of the workplace, as published in studies [18, 19].

Surface roughness parameters: *Rq, Rp, RΔq* and r_w were used for the assessment of the SGP [7-9], because values of the calculated coefficient of the linear correlation *R* between these parameters and the coefficient of kinetic friction μ_k of the yarn against the surface was the highest [10].

Recording and measurements of the geometrical structure of the surface were made with the use of a Talysurf 6 profile measurement gauge, produced by Rank Taylor Hobson, with a conical measuring probe with an imaging nose radius of $r_{os} = 2$ μm. The measurements were made on the surfaces of the guides under a measuring pressure of 0.75 mN, feed rate of the measuring probe of 0.5 mm/s, sampling step of 0.20 μm, sampling length of 0.4 mm and measuring length of 5×0.4 mm = 2.0 mm. On each yarn guide at least three measurements spaced every 120° were performed. Whereas the average curvature radius of the profile peaks r_w was evaluated on the basis of a parabolic approximation of selected, representative 10 peaks of the profile. To

test the possibility of graphical evaluation of the quality of the chosen sectors of the profile, were ten profiles from all local peaks were selected for evaluation, being of typical shape for a given profile.

To evaluate physical properties of the surface layer, the following parameters were taken: maximal hardness on the face of the surface layer $HV_{0,1}$ and the hardening depth of the surface layer g_{ww}. As a result of many years' observations and investigations within the industrial environment, it has been ascertained that the wear of components of ring spinning and anti-balloon spinning frames, being in direct contact with yarn, decreases together with an increase in the hardness of the surface and surface layer [10]. Measurements of the Vickers hardness distribution over the depth of the surface layer $HV = f(g_{ww})$ of the guides were performed on skewed microsections, cut at an angle of 1°30' (0.026 rad), under an intender's load of 0.98 N, using a microhardness tester made by Leitz Wetzlar. During the measurements of the hardness performed at least triple repeatability was used. Using Grubbs test, all measurement results were verified for statistical homogeneity to eliminate all gross errors. The critical value of the test function T_{kr} was read from Table 51 [20] as a function of the number of tests $n_p = 5$ (only in the case of the average curvature radius of profile peaks $r_w - n_p = 10$), the number of repetitions $n_p = 3$, and as a function of the assumed level of importance $\alpha = 0.05$ (5%). Average values for individual criteria of the assessment were calculated and are presented in **Figure 2** after elimination of all gross errors.

Selection of an optimal variant of the thermochemical treatment in terms of the unit manufacturing cost and criteria of manufacturing quality

Values of criteria of the the assessment obtained as a result of calculations and measurements for the variants of thermochemical treatments of a yarn guide analysed are presented in **Figure 2**. Normalisation of the values of the criteria obtained from the calculations and measurements for the interval of $\leq 0,1; 0,9 \geq$ was performed in the next stage of the procedure. The first step of normalisation enables a direct reduction of the assessments to the normalized value c_{st}^*, made with the use of **Equation (1)**.

$$c_{st}^* = 0,1 + \frac{c_{st} - \min_{1 \leq s \leq n}(c_{st})}{\left[\max_{1 \leq s \leq n}(c_{st}) - \min_{1 \leq s \leq n}(c_{st})\right] \cdot 1,25} \quad (1)$$

where: c_{st} – values of criteria of variants analysed in respect of individual criteria, $s = 1, ..., n$; $t = 1, ..., m$. n – number of variants; m – number of criteria.

The normalised assessments c_{st}^* obtained according to formula (1) are the fractions from interval $\leq 0.1; 0.9 \geq$. Such a method of normalisation eliminates extreme assessments equal to 0 and 1.

In the second step of the normalisation, consideration was taken whether a given criterion in the optimisation task needs to be maximised or minimised. To perform this step, **Equation (2)** was used.

$$c_{st}^o = (1 - k_{rt}) \cdot (1 - c_{st}^*) + k_{rt} \cdot c_{st}^* \quad s = 1, ..., n; t = 1, ..., m \quad (2)$$

where: k_{rt} for $t = 1, ..., m$ is a scalar with coordinates 0 or 1.

If $k_{rt} = 1$ – the best variant is that with the highest value of the assessment according to the *t-th* criterion, and $k_{rt} = 0$ – the best variant is that with the lowest value of the assessment according to the *t-th* criterion.

In the case of the example analysed, the minimised criteria (for which $k_{rt} = 0$) include the manufacturing cost of a single workpiece of the yarn guide K_w, the root mean square height of the profile *Rq*, the maximum peak height of the profile *Rp*, and the mean square gradient of the profile roughness *RΔq*, while the average curvature radius of the profile peaks r_w, the maximal hardness on the face of the

surface layer $HV_{0.1}$, and the hardening depth of the surface layer g_{ww} are the maximised criteria ($k_{rt} = 1$).

Values of the assessments after normalisation and transformation, depending on the method of optimisation, for individual criteria and each of the variants of thermochemical treatment, are presented in the **Table 2**.

Determination of the eigenvector **Y**, which fulfills the following matrix **Equation (3)**, is performed in the successive step of the proper phase of searching for the optimal variant of thermochemical treatment of the yarn guide.

$$\mathbf{B} \cdot \mathbf{Y} = \lambda_{max} \cdot \mathbf{Y} \qquad (3)$$

where: B – collective matrix of importance of the criteria,
Y – eigenvector, which in the equation above is a column matrix (comprises as many coordinates as there are criteria, which are simultaneously the weights of the criteria),
λ_{max} – scalar value denoting the maximal eigenvalue of matrix B.

To create a collective matrix of the importance of criteria B, the knowledge of five experts were used. The xpert marked E1 was a specialist from the field of textile machinery, the expert marked E2 – a specialist from the field of spinning technology, the expert marked E3 – a specialist from the field of the design and optimisation of production processes, the expert marked E4 – a specialist from the field of materials technology, heat treatment and thermochemical treatment, and the expert marked E5 was a specialist from the field of production costs and economic analyses. To evaluate the importance of the given criteria using the Saaty method, each of the experts built his own importance matrix of criteria for the assessment; comparable in pairs [17] (**Tables 3÷7**).

Table 7. *Partial importance matrix of the criteria for expert E5.*

	k_1	k_2	k_3	k_4	k_5	k_6	k_7
k_1	1	3	6	8	9	4	5
k_2	1/3	1	4	6	7	2	3
k_3	1/6	1/4	1	3	4	1/3	1/2
k_4	1/8	1/6	1/3	1	2	1/5	1/4
k_5	1/9	1/7	1/4	1/2	1	1/6	1/5
k_6	1/4	1/2	3	5	6	1	2
k_7	1/5	1/3	2	4	5	1/2	1

Table 3 and **4.** *Partial importance matrixes of the criteria for experts E1 and E2.*

	k_1	k_2	k_3	k_4	k_5	k_6	k_7		k_1	k_2	k_3	k_4	k_5	k_6	k_7
k_1	1	5	1/5	4	1/4	1/5	2	k_1	1	1/4	1/5	1/7	1/9	1/10	1/10
k_2	1/5	1	1/9	1/2	1/8	1/9	1/4	k_2	4	1	1/2	1/4	1/6	1/7	1/7
k_3	5	9	1	8	2	1	6	k_3	5	2	1	1/3	1/5	1/6	1/6
k_4	1/4	2	1/8	1	1/7	1/8	1/3	k_4	7	4	3	1	1/3	1/4	1/4
k_5	4	8	1/2	7	1	1/2	5	k_5	9	6	5	3	1	1/2	1/2
k_6	5	9	1	8	2	1	6	k_6	10	7	6	4	2	1	1
k_7	1/2	4	1/6	3	1/5	1/6	1	k_7	10	7	6	4	2	1	1

Table 5 and 6. *Partial importance matrixes of the criteria for experts E3 and E4.*

	k_1	k_2	k_3	k_4	k_5	k_6	k_7		k_1	k_2	k_3	k_4	k_5	k_6	k_7
k_1	1	1/4	1/10	1/6	1/10	1/11	1/8	k_1	1	1/2	1/6	1/3	1/5	1/10	1/7
k_2	4	1	1/7	1/3	1/7	1/8	1/5	k_2	2	1	1/5	1/2	1/4	1/9	1/6
k_3	10	7	1	5	1	1/2	1/3	k_3	6	5	1	4	2	1/5	1/2
k_4	6	3	1/5	1	1/5	1/5	1/3	k_4	3	2	1/4	1	1/3	1/8	1/5
k_5	10	7	1	5	1	1/2	3	k_5	5	4	1/2	3	1	1/6	1/3
k_6	11	8	2	5	2	1	4	k_6	10	9	5	8	6	1	4
k_7	8	5	1/3	3	1/3	1/4	1	k_7	7	6	2	5	3	1/4	1

Table 8. *Collective importance matrix of the criteria.*

	k_1	k_2	k_3	k_4	k_5	k_6	k_7
k_1	1	1.8000	1.3333	2.5286	1.9322	0.8982	1.4736
k_2	0.5556	1	0.9908	1.5167	1.5369	0.4980	0.7519
k_3	0.7500	1.0093	1	4.0667	1.8400	0.4400	2.0333
k_4	0.3955	0.6593	0.2459	1	0.6019	0.1800	0.2733
k_5	0.5175	0.6507	0.5435	1.6614	1	0.3667	1.8067
k_6	1.1134	2.0080	2.2727	5.5556	2.7273	1	3.4000
k_7	0.6786	1.3300	0.4918	3.6585	0.5535	0.2941	1

On the basis of the matrixes made by the experts, called partial matrixes, a collective matrix B was created (**Table 8**), with its elements above the main diagonal, being the arithmetic means of relevant elements of individual partial matrixes. Whereas the elements of the matrix under the main diagonal are the converses of values corresponding to the elements located above the main diagonal.

The collective matrix is the basis for evaluation of the importance (weights) of individual criteria taken for assessment of the variants of the thermochemical treatment of a yarn guide analysed.

In the next step, using the Power method [21], eigenvalues of the importance matrix of criteria B were calculated, comparing its determinant to zero, and solving the seventh degree equation, $n = 7$, with respect to λ **Equation (4)**.

The eigenvalues λ of matrix B: 7.2753, $0.0328 + 1{,}3058i$, $-0{,}0328 - 1{,}3058i$, $-0{,}0684 + 0{,}5190i$, $-0{,}0684 - 0{,}5190i$, and $-0{,}0875\ 0{,}0147$ are the solution of **Equation (4)**.

Therefore the maximal eigenvalue of matrix B sought amounts to: $\lambda_{max} = 7{,}2753$. Verification of the consistence condition of matrix B:

$$\begin{vmatrix} 1.0000 - \lambda & 1.8000 & 1.3333 & 2.5286 & 1.9322 & 0.8982 & 1.4736 \\ 0.5556 & 1.0000 - \lambda & 0.9908 & 1.5167 & 1.5369 & 0.4980 & 0.7519 \\ 0.7500 & 1.0093 & 1.0000 - \lambda & 4.0667 & 1.8400 & 0.4400 & 2.0333 \\ 0.3955 & 0.6593 & 0.2459 & 1.0000 - \lambda & 0.6019 & 0.1800 & 0.2733 \\ 0.5175 & 0.6507 & 0.5435 & 1.6614 & 1.0000 - \lambda & 0.3667 & 1.8067 \\ 1.1134 & 2.0080 & 2.2727 & 5.5556 & 2.7273 & 1.0000 - \lambda & 3.4000 \\ 0.6786 & 1.3333 & 0.4918 & 3.6585 & 0.5535 & 0.2941 & 1.0000 - \lambda \end{vmatrix} = 0$$

(4)

Equation (4).

Table 9. *Values of normalised decisions.*

	a_1	a_2	a_3	a_4	a_5	a_6
d_1	0.8726	0.5454	0.2641	0.5518	0.2696	0.0509
d_2	0.9191	0.6067	0.9126	0.2564	0.7320	0.7071
d_3	0.8891	0.5261	0.8842	0.0766	0.6724	0.5233
d_4	0.9621	0.6427	0.9341	0.7172	0.9158	0.8041
d_5	0.2594	0.7125	0.4236	0.9272	0.5313	0.6437
d_6	0.0115	0.2604	0.2881	0.4121	0.4121	0.8150
d_7	0.7050	0.3752	0.2793	0.9225	0.8520	0.1717
	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
d_1	0.5007	0.2318	0.5134	0.2425	0.5583	0.2806
d_2	0.5140	0.6518	0.1582	0.9139	0.2401	0.8295
d_3	0.5410	0.5377	0.1510	0.8461	0.2781	0.7356
d_4	0.8022	0.8692	0.4294	0.9482	0.7435	0.9538
d_5	0.7369	0.1918	0.8139	0.3205	0.8994	0.4236
d_6	0.1857	0.1834	0.1825	0.1834	0.3921	0.3790
d_7	0.3752	0.2793	0.6745	0.5963	0.9225	0.8520

Table 10. *Optimal lining-up of the variants of the thermochemical treatment according to the criteria taken for assessment*

	a_1	a_2	a_3	a_4	a_5	a_6
D_S	0.0115	0.2604	0.2641	0.0766	0.2696	0.0509
	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
D_S	0.1857	0.1834	0.1510	0.1834	0.2401	0.2806

$$CI = \frac{\lambda_{max} - m}{m - 1} = \frac{7.2753 - 1}{7 - 1} = 0.0459 \le 0.1 \quad (5)$$

And hence, the condition of consistence is approximately fulfilled, because $CI = 0.0439 < 0.1$.

In the next step, coordinates of eigenvector Y are established for the maximal eigenvalue $\lambda_{max} = 7,2753$ of collective matrix **B**, and for the condition stating that the sum of coordinates of this vector should be equal to the number of the criteria, simultaneously with fulfillment of equation $B \cdot Y = \lambda_{max} \cdot Y$. The vector we are looking for has as many coordinates as there are criteria *Equation (6)*.

$$\sum_{t=1}^{m} y_t = m \quad (6)$$

where: y_t – *t-th* coordinate of eigenvector Y. Values of these coordinates, $y_t (t = 1, ..., m)$

were evaluated by solving the system of *Equations (7)*.

The solutions of the system of *Equations (7)* are the following values: $y_1 = 1.2931$, $y_2 = 0.8008$, $y_3 = 1.1156$, $y_4 = 0.3671$, $y_5 = 0.7172$, $y_6 = 1.9410$, and $y_7 = 0,7653$, satisfying *Equation (8)*:

$$1.2931 + 0.8008 + 1.1156 + 0.3671 + \\ + 0.717\,2 + 1.9410 + 0.7652 = 7.0000 \quad (8)$$

Coordinates of eigenvector y_t are simultaneously the weights of individual criteria, and are marked with letters $w_1, w_2, ..., w_m$. Each of these weights expresses the importance of corresponding criterion, where the higher the value of the *t-th* weight, the higher the importance of the *t-th* criterion.

$$d_t = \sum_{s=1}^{n} \left(c_{st}^o\right)^{w_t} \quad (9)$$

The next step of the method consists in creating normalised decisions by raising each component of successive decisions to a power equal to the appropriate weight, according to *Equation (9)*.

Values of the normalised decisions for each of the variants with respect to individual criteria are presented in *Table 9*.

The last stage of the method developed consists in the creation of a single optimal lining-up, which is used in the selection of the best variant of thermochemical treatment of the yarn guide, i.e. a variant which best fulfils all criteria taken for the assessment. Optimal lining-up in this method is considered as the decision minimum. The *s-th* element of the optimal lining-up, i.e. an element corresponding to the *s-th* variant of thermochemical treatment, is the smallest *s-th* element of individual decisions d_1, d_2, ..., d_m *Equation (10)*.

$$D_s = \min_t \left(c_{st}^o\right)^{w_t} \quad (10)$$

The value of the optimal lining-up for individual variants is shown in *Table 10*.

The best variant (the optimal one) of the thermochemical treatment is that which corresponds to the highest element of the optimal lining-up *Equation (11)*:

$$a_{(opt)} = \max D_s \quad (11)$$

Thus, the optimal variant is variant a_{12}, because the maximal value of the optimal lining-up, equal to 0.2806, corresponds to its variant. In this variant the yarn guide is made of C45 steel, which is next subjected to the process of diffusion boronising, quenching from the temperature of the boronising, and tempering. Next, the eyelet of the guide is ground with the use of PS 20 corundum abrasive paper with a grain size of 600. Variant a_5 is a little bit wors, because the value of 0.2696 corresponds to this variant, i.e. the yarn guide made of spring steel of the 50SiCr4 type is also subjected to the process of diffusion boronising.

In the case of the optimal variant of thermochemical treatment of the yarn guide, values of the criteria for the assessment are as follows: $Kw = 3.95$ PLN/pcs, $Rq = 0.163$ µm, $Rp = 0.546$ µm, $R\Delta q = 0.0257$ rad, $r_w = -0.155$ µm, $HV_{0.1} = 1500$, and $g_{ww} = 70$ µm.

$$
\begin{aligned}
&(1 - 7.2753)y_1 + 1.8000y_2 + 1.3333y_3 + 2.5286y_4 + 1.9322y_5 + 0.8982y_6 + 1.4736y_7 = 0 \\
&0.5556y_1 + (1 - 7.2753)y_2 + 0.9908y_3 + 1.5167y_4 + 1.5369y_5 + 0.4980y_6 + 0.7519y_7 = 0 \\
&0.7500y_1 + 1.0093y_2 + (1 - 7.2753)y_3 + 4.0667y_4 + 1.8400y_5 + 0.4400y_6 + 2.0333y_7 = 0 \\
&0.3955y_1 + 0.6593y_2 + 0.2459y_3 + (1 - 7.2753)y_4 + 0.6019y_5 + 0.1800y_6 + 0.2733y_7 = 0 \\
&0.5175y_1 + 0.6507y_2 + 0.5435y_3 + 1.6614y_4 + (1 - 7.2753)y_5 + 0.3667y_6 + 1.8067y_7 = 0 \\
&1.1134y_1 + 2.0080y_2 + 2.2727y_3 + 5.5556y_4 + 2.7273y_5 + (1 - 7.2753)y_6 + 3.4000y_7 = 0 \\
&0.6786y_1 + 1.3300y_2 + 0.4918y_3 + 3.6585y_4 + 0.5535y_5 + 0.2941y_6 + (1 - 7.2753)y_7 = 0
\end{aligned}
\quad (7)
$$

Equation (7).

■ Summary

The modified Yager method provides good results in terms of the best variant selection during the design of manufacturing processes of products similar to those already in production, as well as in the design of heat treatment and thermochemical treatment operations, where generally it is possible to determine, with sufficient accuracy, values of criteria taken for assessment. Presented In this paper an original method of optimisation according to criteria of a deterministic character, with consideration of their importance, is presented that can be implemented for selection of the best (optimal) variant for the production of machinery components, both for general application and with special properties. Assessment of the importance of the criteria should be made by at least three experts, while for successive calculations the collective importance matrix of the criteria is taken, with its elements above the diagonal being the arithmetic mean from corresponding elements of individual partial matrixes.

As a result of the investigations, measurements and calculations performed, it can be stated that diffusion boronising is the best variant of thermochemical treatment of yarn guides made of steel (in general, components of spinning mills in contact with movable yarn or thread). Such a type of thermochemical treatment ensures high surface hardness $HV_{0.1} = 1500 \div 1550$ (lower than surface hardness after titanising only), the biggest thickness of the surface layer, and a favourable geometrical structure of the surface with respect to the coefficient of kinetic friction of the yarn $- \mu_k = 0.190 \div 0.195$ [10], at a unit manufacturing cost equal to $K_w = 3.95 \div 3.97$ PLN.

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