MULTICRITERIA OPTIMIZATION OF MANUFACTURING PROCESSES OF THE ROTORS TO OPEN END SPINNING MACHINE

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Summary

The paper presents Pareto-optimum method and POLOPT computer program enabling, with the use of principle of conversation with computer, assessment of solutions (variants) in the view of two or more criteria (up to 10). The Pareto-optimal set is univariate in a few cases only, and therefore, in remaining cases to selection of the best solution from this set one proposed the distance function. The chosen procedure of the multicriteria optimization was tested on the example of selection of the best variant of the manufacturing process of rotors to the open end spinning machine.

Keywords: manufacturing processes, optimization, manufacturing cost, product quality

Wielokryterialna optymalizacja procesów wytwarzania wirnika przędzarki bezwrzecionowej

Streszczenie

W artykule przedstawiono metodę optimum w sensie Pareto oraz program POLOPT umożliwiający, na zasadzie konwersacji z komputerem, ocenę rozwiązań (wariantów) z uwzględnieniem liczby 2 i większej kryteriów (do 10). Zbiór Pareto-optymalny tylko dla kilku przypadków jest jednowariantowy. Dlatego w pozostałych przypadkach do wyboru rozwiązania najlepszego z tego zbioru zapropo-nowano funkcję dystansową. Opracowaną procedurę optymalizacji wielokryterialnej poddano weryfikacji w procesie doboru najlepszego wariantu wytwarzania wirnika przędzarki bezwrzecionowej.

Słowa kluczowe: procesy wytwarzania, optymalizacja, koszt wytwarzania, jakość wyrobu

1. Introduction

Optimization of manufacturing processes occupies a special position in course of optimization of manufacturing activities. The concept of optimization of manufacturing processes should be understood both as optimization of processing conditions (parametric optimization) and optimization of process structure (structural optimization). Optimization of processing conditions fulfils the task complementary to optimization of a structure. These two issues

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are interrelated: optimization of a structure requires prior assignment of values, close to optimal, to parameters of individual treatments comprising the operations, and these, in turn, comprising the process. Optimization of parameters requires prior optimization of process structure and its individual operations. Solution to the emerging conflict is iteration proceeding, in which usually at the beginning one solves a task of selection of a process structure, and next of the operation close to the optimal (taking typical values of parameters – recommended by producers of cutting tools), and in the next step one performs optimization of the parameters. Then one can go again to more precise selection of the structure, etc. [1, 2].

Objective for the purpose of parametric optimization is selection of (among possible to implementation in a given conditions – in an area of feasible solutions, determined by limitations) such values of cutting parameters like: cutting speed v_c, feed rate f and depth of cut a_p, which assure the extreme value of assumed criterion of the optimization [3].

Issue of optimization of manufacturing operations parameters has lived to see a rich bibliography, which was discussed in detail in works [3-5]. Whereas, issue of optimization and polyoptimization of manufacturing processes structures was presented so far in a few works only [6-18]. The starting point to the optimization of the structure is determination of a set of solutions (variants) of the process of the analyzed workpiece, assessed in the light of specified criteria.

The objective of this work is to present a procedure of multicriteria optimization of processes structures and its verification on the example of selection of the best variant, with respect to adopted criteria. of the manufacturing process of the rotors to the open end spinning machine.

2. Method of selection of the optimal variant

2.1. Pareto-optimal methods

Problems of multicriteria optimization of manufacturing processes structure are generally solved in two phases: determining a set of Pareto-optimal solutions and next, selecting the best (optimal) solution from this set [1, 19-21].

To select an optimal variant (solution) one has chosen the Pareto-optimal method, which consists of determination of a set of non-dominated variants (set of compromises) or set of Pareto-optimal variants [1, 19]. Let A denote a feasible set of manufacturing process variants:

$$A = \left\{ a_1, a_2, ..., a_n \right\} \tag{1}$$

and $K^{(d)}$ – set of criteria with deterministic character from 1 to m:

$$K^{(d)} = \left\{ k_1^{(d)}, k_2^{(d)}, ..., k_m^{(d)} \right\} \qquad (2)$$

The table with assessments of the variants with respect to individual criteria has a form of:

$$
\begin{bmatrix}
k_{11}^{(d)}, k_{12}^{(d)}, ..., k_{1i}^{(d)}, ..., k_{1s}^{(d)} \\
k_{21}^{(d)}, k_{22}^{(d)}, ..., k_{2i}^{(d)}, ..., k_{2s}^{(d)} \\
.... \\
k_{j1}^{(d)}, k_{j2}^{(d)}, ..., k_{ji}^{(d)}, ..., k_{js}^{(d)} \\
.... \\
k_{m1}^{(d)}, k_{m2}^{(d)}, ..., k_{mi}^{(d)}, ..., k_{ms}^{(d)}
\end{bmatrix}
\qquad (3)
$$

where: $k_{ji}{}^{(d)} = k_j^{(d)}(a_i)$ – assessment of *i-th* variant according to *j*-th criterion, $j = 1, ..., m$.

Such a variant, which simultaneously extremizes each criterion, is taken as the ideal variant of the manufacturing process.

In a case of minimization, $a_i^{(id)}$ is taken as the ideal variant if:

$$\bigwedge_{a_i \in A} \bigvee_{a_i^{(id)} \in A} \mathbf{k}^{(d)}(a_i^{(id)}) \le \mathbf{k}^{(d)}(a_i) \qquad (4)$$

where: $\mathbf{k}^{(d)}(a_i)$ – a vector of assessments of *i*-th variant with respect to each from the criteria.

Because these criteria are usually in conflict, the ideal variant does not exist in such a case.

As non-dominated variant is taken such a variant, for which none criterion can be improved without simultaneous worsening of at least one criterion from the remaining ones.

In a case of minimization, $a_i^{(nd)}$ is a non-dominated variant, if:

$$\bigwedge_j \rceil \bigvee_{\mathbf{k}^{(d)}(a_i) \in K^{(d)}} k_j^{(d)}(a_i) \le k_j^{(d)}(a_i^{(nd)}) \quad \wedge \quad \bigvee_j k_j^{(d)}(a_i^{(nd)}) < k_j^{(d)}(a_i) \qquad (5)$$

A set of non-dominated variants *ZA* is also called a set of compromise variants or a set of Pareto-optimal variants. To the set *ZA* is assigned a set of criteria – compromise criteria $ZK \in K^{(d)}$.

A set of Pareto-optimal variants usually contains many variants, and among them, generally the best (optimal) variant $a_i^{(opt)} \in ZA$ is chosen on the basis of the additional criterion.

A task of multicriteria Pareto optimization of manufacturing process variants can be formulated as follows-determine a set of compromise assessments:

$$ZK = \left\{ \mathbf{k}^{(d)}(a_i^{(nd)}): \bigwedge_j \neg \bigvee_{\mathbf{k}^{(d)}(a_i)\in K^{(d)}} k_j^{(d)}(a_i) \leq k_j^{(d)}(a_i^{(nd)}) \quad \wedge \quad \bigvee_j k_j^{(d)}(a_i^{(nd)}) < k_j^{(d)}(a_i) \right\} \quad (6)$$

and assigned to it set of Pareto-optimal variants:

$$ZA = \left\{ a_i^{(nd)}: \mathbf{k}^{(d)}(a_i^{(nd)}) \in ZK \wedge a_i^{(nd)} \in A \right\} \quad (7)$$

Variant $a_i^{(nd)}$ constitutes solution of multicriteria Pareto optimization task if the corresponding vector of the criteria $\mathbf{k}^{(d)}(a_i^{(nd)})$ is the smallest vector in sense of the partial ordering.

In this formulation one adopted that all the criteria should be minimized. If in the task of multicriteria optimization one should maximize the criterion $k_j^{(d)}(a_i)$, such task can be reduced to the task of minimization, changing sign of the criterion.

$$\max_j k_{ji}^{(d)} = -\min_j(-k_{ji}^{(d)}) \quad (8)$$

To identify the set of Pareto-optimal variants one made use of specially written in Pascal code computer program called POLOPT. The program enables, on the base of conversation with computer, determination of a set of Pareto-optimal variants, from a set of feasible variants consisting of maximally 100 variants, assessed maximally with respect to 10 criteria each. Developed in such way program enables determination of the Pareto-optimal set of variants with respect to any number of criteria from the interval between 2 and 10.

The program consist of the following modules: generation of the criteria set, reading of criteria set, selection of criteria to determination of Pareto set, determination of Pareto set, sorting, reviewing and printing of the Pareto set.

2.2. Selection of the best solution with use of distance function

Methods of distance function, in their classic approach, enable determination of a single compromise assessment, what usually leads to determination of a single compromise variant. The obtained result depends on the implemented norm and preference of criteria specified by experts. Big

number of different criteria of the assessment, which characterize variants, makes one have to deal with vector indicators of quality. In situation when some of these indicators are minimized and other maximized, and having in mind that majority of these indicators is expressed in various units, the problem of correct selection of the best variant (solution) is difficult [21]. For independence from influence of different units of individual criteria, and taking into account that the set of criteria comprises assessments both to minimization and to maximization, one has developed a distance function $f_{d(i)}$ having the following form:

$$f_{d(i)} = \sqrt{\sum_{j=1}^{m} [d_{i(j)} - d_{id(j)}]^2} \rightarrow \min \qquad (9)$$

where: $d_{i(j)}$ – normalized value of j criterion for individual variants (solutions), $d_{id(j)}$ – normalized value of j criterion for ideal point.

The best variant from Pareto-optimal set of solutions is such a variant, for which the distance function $f_{d(i)}$ achieves the minimum.

3. Example of selection of optimal variant of manufacturing process of the rotor to open end spinning frame

3.1. Preparation of optimization proceeding

In the PW12 open end spinning machine as a raw material to production of rotors was used *AlCu4Mg* aluminum alloy in form of extruded bars in condition of natural precipitation hardening, which resulted in large waste (about 60%). Rotors in the spinning machine operate with rotational speed from 300 to 400 revs/s (18 000 to 24 000 rpm) and should fulfill predetermined requirements concerning quality of manufacturing, i.e.: low roughness of internal surfaces Ra = 0.08-0.16 μm, very low value of axial and radial run-out on all end faces and diameters above 40 mm – $\Delta B \leq 0,050$ mm and high durability. Moreover, they should undergo dynamic balancing, when assembled with elastic bearing and race, at rotational speed of n = 200 revs/s, while value of unbalance should not exceed $e_r \leq 0,05$ μm [2]. The shape of the single-piece rotor and consisting of a few components is presented in the Fig. 1.

On base of observations of spinning machine in operational conditions it is evident that the rotor belongs to the most often replaced elements of defibering-twisting heads, and simultaneously to the most expensive. Big wear of the rotors is result of production process of yarn [2].

To increase durability of rotors at specific costs of production, one made selection of material and form of a semi-finished product, as well as a type of surface and finish treatments, with respect to fulfillment of high quality

requirements at the lowest manufacturing costs. Taking into account design and geometry of rotors (Fig. 1), seven types of aluminum alloys in nine different forms of semi-products were taken into considerations.
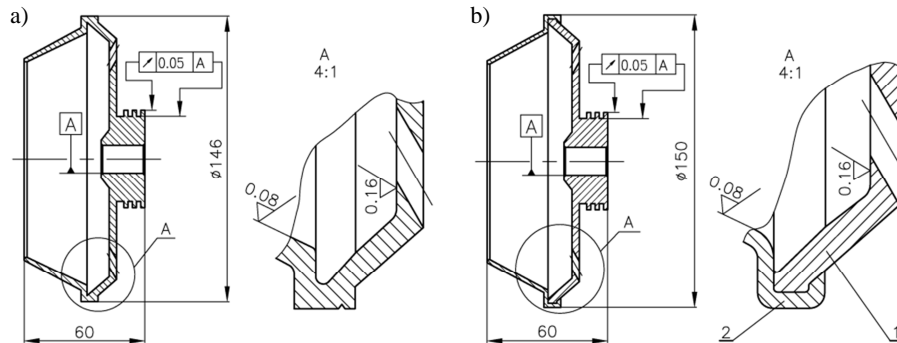

Fig. 1. Rotor: a) single-piece rotor, b) rotor composed of two components: disc (1), cone (2) from *AlMg2.5* plate plastic formed by spinning, connected together in clenching operation

Within the set of feasible variants of manufacturing process of rotors to the open end spinning machine one isolated nine sub-groups: *A1*, *A2*, *A3*, *A4*, *A5*, *A6*, *A7*, *A8*, *A9*, differing in form of semi-product, which are presented in Tables 1 and 2 [17].

For sub-groups *A1*; *A2*; *A3*; *A4*; *A5*; *A6*; *A7*; *A8*; *A9*, of the variants of manufacturing process of the rotor one anticipated three combinations of surface and finishing treatment:

1 – grinding with corundum abrasive cloth of HTJ-13-3 type with grain size of 150, and next with grain size of 220 and polishing with felt buffing wheel impregnated with abrasive compound of Z-50 type,

2 – grinding with corundum abrasive cloth of HTJ-13-3 type with grain size of 150, and next with grain size of 220, and electrolytic oxidation,

3 – grinding with corundum abrasive cloth of HTJ-13-3 type with grain size of 150, and next grain size of 220, electrolytic oxidation, grinding with abrasive cloth having grain size of 240, grinding with abrasive cloth having grain size of 360, and grinding with corundum abrasive paper of PS20 type having grain size of 600.

In the sub-group *A8* and *A9* of manufacturing variants of the rotor, due to high surface roughness after electrolytic oxidation, one implemented additional operation of grinding with abrasive cloth having grain size of 120, prior operations of grinding with abrasive cloth having grain size 240 and 360, as well as corundum abrasive paper of PS20 type with grain size of 600.

Table 1. Characteristics of semi-products for rotors

Alphanumeric denomination	Variants	Marking with chemical symbols	Shape of the semi-product
EN AW-2024	I II III	*AlCu4Mg1*	Extruded rod φ150×64.5 mm
EN AW-6082	IV V VI	*AlSi1MgMn*	Extruded rod φ150×64.5 mm
EN AW-2618A	VII VIII IX	*AlCu2Mg1.5Ni*	Die hammer forging φ155×70 mm
EN AW-2014	X XI XII	*AlCu4SiMg*	Die hammer forging φ155×70 mm
EN AW-6082	XIII XIV XV	*AlSi1MgMn*	Die hammer forging φ155×70 mm
EN AW-45000	XVI XVII XVIII	*AlSi6Cu4*	Casting from sand mould φ153×91 mm
EN AW 45000	XIX XX XXI	*AlZn9Si7*	Casting from sand mould φ153×91 mm
EN AW-2024 EN AW-5052	XXII XXII XXIV	*AlCu4Mg1* *AlMg2.5*	Disc made from extruded rod φ155×33 mm, while the cone plastic formed by spinning from metal plate with dimensions of 195×195×2 mm
EN AW-2618A EN AA-5052	XXV XXVI XXVII	*AlCu2Mg1.5Ni* *AlMg2.5*	Disc made from die forging φ155×38 mm, while the cone plastic formed by spinning from metal plate with dimensions of 195×195×2 mm

Table 2. Characteristic of semi-product's form for rotors

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Sub-group A1, A2	Rotors from these sub-groups were made from semi-product in form of an extruded bar from *AlCu4Mg1* alloy; i.e. in condition of natural precipitation hardening (ta) and from a extruded bar from *AlSi1MgMn* alloy in condition of artificial precipitation hardening (tb).
Sub-group A3, A4, A5	Rotors from these sub-groups were made from semi-product in form of die forgings, made from *AlCu2Mg1.5Ni; AlCu4SiMg; AlSi1MgMn,* aluminum alloys, hammer forged, and next artificially precipitation hardened (tb).
Sub-group A6, A7	Rotors from these sub-groups were made from semi-product in form of a sand mould castings, from *AlSi6Cu4; AlZn9Si7* aluminum castings.
Sub-group A8, A9	Rotors from these sub-group were made as assembled from two elements: disc and cone, while the disc was turned from an extruded bar from *AlCu4Mg1* aluminum alloy (sub-group *A8*) and from a die forging from *AlCu2Mg1.5Ni* aluminium alloy, hammer forged (sub-group *A9*), whereas the cone in a both sub-groups was plastic formed by spinning on mandrel, material of the cone: metal plate from *AlMg2.5* alloy, thickness 2 mm.
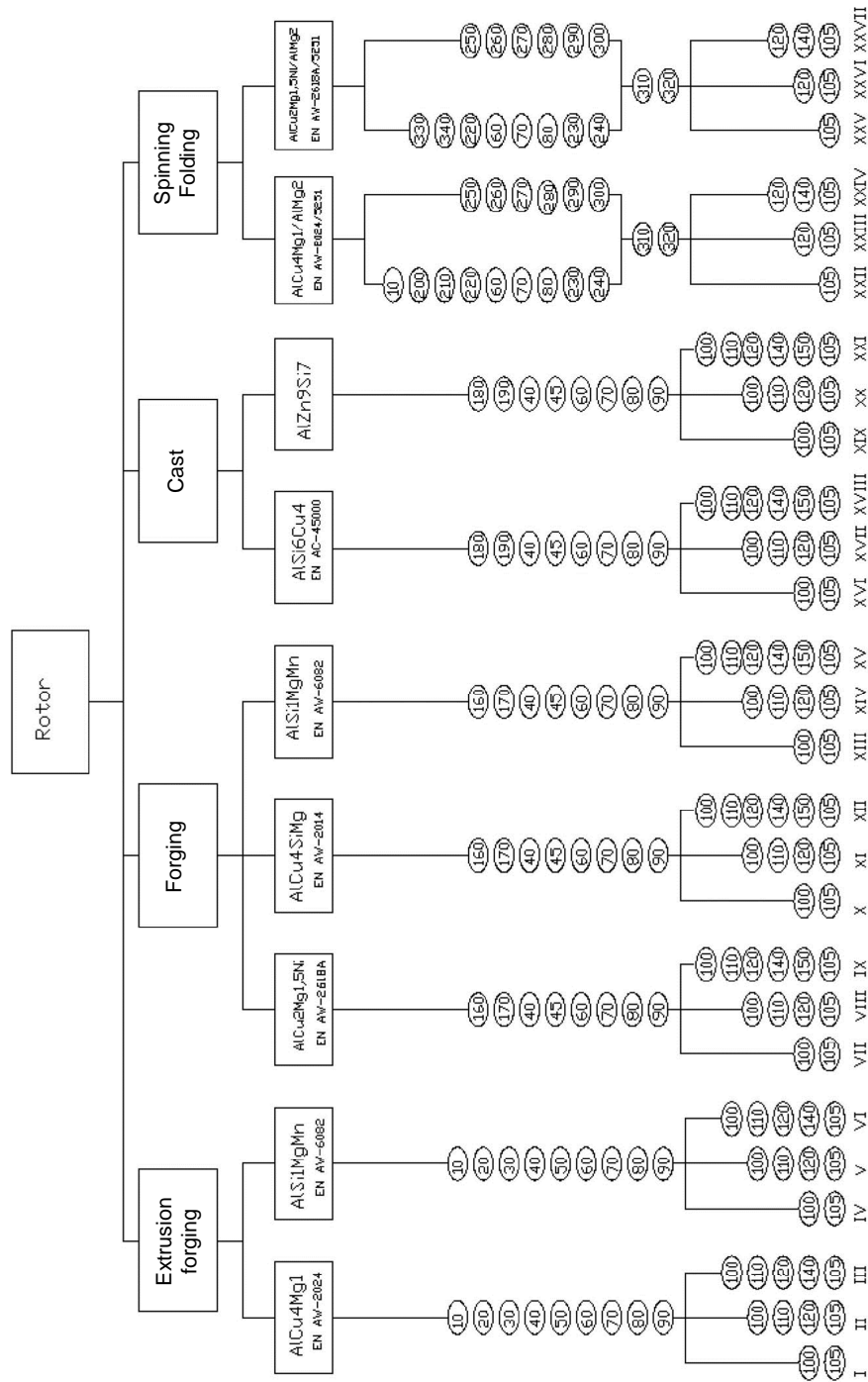
Fig. 2. Graph-tree with variants of manufacturing process of rotor to open end spinning frame

To improve durability of rotors at a given manufacturing costs, while maintaining performance characteristics, one developed and analyzed 27 variants of the manufacturing process of the rotor to open end spinning frame, which are presented with use of the graph-tree (Fig. 2) and described in Table 3.

Table 3. Description of the graph-tree with variants of the manufacturing process of the rotor

No. of oper.	Name of operation	Workstation
10	Cutting material to dimension „x"	Band-saw SBA421/S
20	Turning external surfaces and drilling hole φ11	Turning lathe TZC-32N1
30	Drilling hole φ50, turning external surfaces, turning internal surfaces, boring recess and collector groove. Boring hole φ12 and reaming the hole to φ12.2 U7	Turning lathe TZC-32N1
40	Turning hub to φ47 and grooves on width of 2.5 mm	Turning lathe TZC-32N1
45	Finish turning external surfaces, boring internal surfaces, and deepening the collector groove	Turning lathe TZC-32N1
50	Finish turning external surfaces, and boring internal conical surface together with the collector groove	Turning lathe TZC-32N1
60	Inter-operational control	Bench testing centres and sensing element
70	Drilling twelve holes φ6	Drilling machine 2H-125
80	Rounding off sharp edges	Grinding station
90	Grinding with abrasive cloth having grain size 150 and 220	Special grinder
100	Polishing with the felt disc impregnated with an abrasive compound	Special polisher
105	Dynamic balancing	Dynamic balancer
110	Final inspection	Inspection-Measuring station
120	Electrolytic oxidation	Anodizing station
130	Final inspection	Inspection-Measuring station
140	Grinding with an abrasive cloth having grain size of 240 and 360	Special grinder
150	Grinding with an abrasive paper having grain size of 600	Special grinder
160	Turning end face and external diameter of hub and face of disc, drilling hole φ11	Turning lathe TZC-32N1
170	Rough and shape turning external surface, facing end face, rough and shape boring internal surface of a hole, turning collector groove, reboring a collector groove and other internal surfaces, boring a hole φ102, finish boring internal cone with collector groove, chamfering a hole and reboring the hole φ12.2 U7	Turning lathe TZC-32N1
180	Cutting off skinhead, drilling hole φ11, reaming hole to φ12.2 U7, turning external diameter of a hub and facing the end face of hub.	Turning lathe TZC-32N1
190	Boring internal surface with collector groove, turning external surface, finish boring internal surfaces and the collector groove	Turning lathe TZC-32N1

Table 3. (contd) Description of the graph-tree with variants of the manufacturing process
of the rotor

No. of oper.	Name of operation	Workstation
200	Initial turning hub, turning cone, spot drilling with rigid drill $\phi20$, drilling hole $\phi11$, turning hub	Turning lathe TZC-32N1
210	Facing end face, turning internal surface with recess, turning collector groove, reaming hole $\phi12.2$ U7, chamfering hole	Turning lathe TZC-32N1
220	Turning external surface of hub and disc, turning grooves	Turning lathe TZC-32N1
230	Grinding with abrasive cloth having grain size of 150 and 220	Special grinder
240	Polishing internal surface of disc with felt disc impregnated with abrasive compound Z-50	Special polisher
250	Cutting plate from AlMg2.5 alloy having thickness of 2 mm to size 195x195mm	Mechanic guillotine Q11 2x2000
260	Marking-off hole, drilling hole $\phi6$ blunting sharp edges, turning disc to dimension $\phi188$, blunting edges	Drilling machine 2H-125
270	Grinding disc with abrasive paper having grain size of 220	Special grinder
280	Polishing cut-off disc $\phi188x2$ mm with abrasive compound Z-50	Special grinder
290	Attaching on core and plastic forming by spinning	Turning lathe TUG-56MN
300	Attaching on mandrel, cutting-off flange and bottom of cone	Turning lathe TUG-56MN
310	Clenching disc with cone	Turning lathe TUG-56MN
320	Facing end face of cone, boring hole $\phi102\pm0.2$	Turning lathe TUG-56MN
330	Facing end face of disc, turning face of disc, turning hub, spot drilling with rigid drill $\phi20$, drilling hole $\phi11$, chamfering hole	Turning lathe TZC-32N1
340	Facing end face, turning external surface, turning recesses, turning collector groove, reboring hole $\phi12.2$ U7	Turning lathe TZC-32N1

3.2. Determining Pareto-optimal set of variants

To determine the set of Pareto-optimal variants one made use of specially developed *POLOPT* computer program, written in the Pascal code. Assessment criteria in this algorithm are treated as equally important (on equal importance right). Using individual modules of the program one created the set of criteria for 27 variants of the manufacturing process of the rotor. Next, one assigned to the criteria the index *max,* if the criterion in the multicriteria optimization task should be maximized, or *min,* if a given criterion in the multicriteria optimization task should be minimized.

In the next step, one determined Pareto-optimal set for the analyzed set of feasible variants, consisting of 27 variants of the manufacturing process of the rotor. Pareto-optimal set with respect to the following six criteria: unit manufacturing cost K_w, surface roughness expressed with parameters S_p and S_q,

maximal micro-hardness μHV, hardening depth of a surface layer or depth of an oxide layer g_u, and the coefficient of break spinning efficiency W_{sz}, consisting of 16 variants.

To Pareto-optimal variants belong the following variants: I; IV; VIII; IX; X; XIII; XIV; XV, XVI; XVII, XVIII; XIX; XX; XXI; XXII; XXVII.

Value of the criteria for the Pareto-optimal set of variants is specified in Table 4.

Table 4. Pareto-optimal set for six criteria: K_w, S_p, S_q, μHV, g_u, W_{sz}

No.	Number of variant	K_w, PLN/piece	S_p, μm	S_q, μm	μHV, MPa	g_u, μm	W_{sz}
1	I	151.20	2.33	0.19	1.530	15	1.0
2	IV	137.50	0.79	0.19	1.010	15	1.0
3	VIII	223.70	5.67	1.35	3.870	110	0.7
4	IX	232.05	1.06	0.36	4.560	105	1.0
5	X	103.85	2.13	1.01	1.510	15	1.0
6	XIII	102.40	0.86	0.18	1080	15	1.0
7	XIV	222.40	5.68	1.49	7080	120	0.9
8	XV	229.90	1.61	0.80	7280	110	1.0
9	XVI	91.10	2.29	0.20	1140	10	1.0
10	XVII	210.10	17.01	5.37	3150	80	0.5
11	XVIII	271.65	4.20	1.35	3440	70	1.0
12	XIX	88.50	5.33	0.34	1360	20	1.0
13	XX	208.50	12.32	4.04	2940	80	0.6
14	XXI	216.30	6.90	2.05	3390	70	1.0
15	XXII	125.10	1.29	0.17	1480	15	1.0
16	XXVII	232.20	1.04	0.38	4420	105	0.9

3.3. Selection of the best variant with use of the distance function

In the next stage of the proceeding, deterministic values of criteria for assessments for the Pareto-optimal set were reduced to space of <0; 1>, making use of the following normalization function:

$$d_{i(j)} = \frac{k_{ij} - \min_{1 \le l \le n}\left(k_{lj}\right)}{\left[\max_{1 \le l \le n}\left(k_{lj}\right) - \min_{1 \le l \le n}\left(k_{lj}\right)\right]} \tag{10}$$

In result of the normalization one obtained the following values of the criteria from space <0; 1> for individual variants constituting the Pareto-optimal set (Table 5).

Table 5. Normalized values of criteria of Pareto optimal set

No.	Number of variant	K_w, PLN/piece	S_p, μm	S_q, μm	μHV, MPa	g_u, μm	W_{sz}
1	I	0.436326	0.094945	0.003846	0.082935	0.045455	1.000000
2	IV	0340988	0.000000	0.003846	0.000000	0.045455	1.000000
3	VIII	0.940849	0.300863	0.226923	0.0456140	0.909091	0.400000
4	IX	0.998956	0.016646	0.036538	0.566188	0.863636	1.000000
5	X	0.106820	0.082614	0.161538	0.078745	0.045455	1.000000
6	XIII	0.096729	0.004316	0.001923	0.011164	0.045455	1.000000
7	XIV	0.931802	0.301480	0.253846	0.968102	1.000000	0.800000
8	XV	0.983994	0.050555	0.132692	1.000000	0.909091	1.000000
9	XVI	0.018093	0.092478	0.005769	0.020734	0.000000	1.000000
10	XVII	0.846207	1.000000	1.000000	0.341308	0.636364	0.000000
11	XVIII	0.898747	0.210234	0.226923	0.387560	0.545455	1.000000
12	XIX	0.000000	0.279901	0.032692	0.055821	0.090909	1.000000
13	XX	0.832985	0.710850	0.744230	0.307814	0.636363	0.200000
14	XXI	0.889352	0.376695	0.361538	0.379585	0.545454	1.000000
15	XXII	0.254697	0.030826	0.000000	0.074960	0.045456	1.000000
16	XXVII	1.000000	0.015413	0.543860	0.543860	0.863636	0.800000

In the successive step, taking into consideration fact whether the criterion is to be maximized or minimized, one determined co-ordinates of the ideal point:

$$d_{id(j)} = (0; 0; 0; 1; 1; 1) \tag{11}$$

To select the best variant from Pareto-optimal set one used the distance function described by the formula (9). In case of the six criteria, shape of the function is as follows:

$$f_{d(i)} = \sqrt{[d_{i(1)} - d_{id(1)}]^2 + [d_{i(2)} - d_{id(2)}]^2 + ..., + [d_{i(6)} - d_{id(6)}]^2} \tag{12}$$

The value of the distance function $f_{d(i)}$ for sixteen Pareto-optimal variants is presented in Table 6.

As the best variant is taken such a variant for which the value of the distance function $f_{d(i)}$ is the lowest. In our case, the best variant is the variant *XV*, for which $f_{d(XV)} = 0.998335$.

For the best variant, values of the criteria are as follows: $K_w = 229,90$ PLN/piece; $S_p = 1.61$ mm; $S_q = 0.86$ mm; $mHV = 7280$ MPa; $g_u = 110$ mm; $W_{sz} = 1,0$.

Table 6. Value of the distance function $f_{d(i)}$ for sixteen Pareto-optimal variants

No.	Number of the variant	Distance from ideal variant	No.	Number of the variant	Distance from ideal variant
1	I	1.396988	9	XVI	1.402810
2	IV	1.423884	10	XVII	2.069341
3	VIII	1.300483	11	XVIII	1.218661
4	IX	1.098323	12	XIX	1.340647
5	X	1.3425519	13	XX	1.714706
6	XIII	1.377800	14	XXI	1.098885
7	XIV	1.031795	15	XXII	1.353764
8	XV	0.998335	16	XXVII	1.126289

4. Summary

In multicriteria designing of manufacturing processes of products similar to ones already being in production, where generally it is possible to determine with sufficient accuracy values of criteria taken to assessment, good results of selection of the best variant can be obtained in the two-stage procedure of multicriteria optimization. In the first stage, the procedure comprises determination of the set of non-dominated variants (the set of Pareto-optimal variants), while in the second stage – using the distance function, selection of the best variant from this set. The advantage of this procedure is that in both stages of optimization proceeding one uses the same criteria of assessment. Thus, it becomes unnecessary to define an additional (most often new) criterion, what greatly facilitates selection of the best solution.

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