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Review Article

SUBTRACTIVE MACHINING STRATEGIES FOR THE ESTIMATION AND SELECTION OF EFFICIENT

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ABSTRACT

The paper shows the acuteness of the efficient strategy selection for the subtractive machining of heterogeneous structures with the nanometre positioning accuracy. Definitely, the selection of the machining regimes can be carried out basing on the expert's experience. In this paper, we systematize the criteria for selecting the optimum regime of the heterogeneous structure subtractive machining. We offer using the decision support system (DSS) "Resheniye" for choosing the efficient subtractive machining strategies. Here we describe the special features of the used system, the stages of the optimum subtractive machining strategy determination processes with the demonstration of the obtained results. The hierarchy of the optimum surface machining method selection is built to let determine the priorities of the machining methods basing on the pair-wise comparison of solutions by experts. The possibility of using the proposed smart means for solving the set tasks is proved.

INTRODUCTION

At present, the share of various-shape parts with micro- and nano-size surfaces with stiff tolerance scopes is growing. These parts often have complicated multi-layer heterogeneous structures, e.g., based on fiberglass plastics comprising corundum-based glass fabric filler layers, bonding polymeric materials, and metal films. Nanoscale laminates are also qualified as such products. In many cases, the manufacturing error for such parts must not exceed 100 nm, and sometimes several tenths of nanometres.

Subtractive machining operations are often applied in the technological manufacturing processes of such products (Mahalik, 2006; Lei, 2014), in particular, in cutting. At that, multi-axial production equipment with the manufacturing error of the order of 10 μm can be used.

During the designing of the subtractive machining technology, the choice of the machining strategy is of great importance. A set of such parameters as the tooling standard size, its motion trajectory at the removing the tolerance, and the cutting regime (Pahk, *et al.*, 2001) are referred to as the subtractive machining strategies. Therefore, it is necessary to develop smart means allowing estimating and choosing efficient machining strategies and algorithms.

SYSTEMATIZATION OF THE EFFICIENT SUBTRACTIVE MACHINING STRATEGIES SELECTION CRITERIA

As the developed mock-up machining station for subtractive machining does not imply the presence of the automatic tool change system, the machining of each surface on it will be performed using one tool, and its selection will depend on the type of the item surface and material properties only. In view of this, its hardness and wear-resistance at the cutting temperatures (red hardness) shall be considered as the main parameters associated with the tool.

The supposed varieties of machined items do not

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have complicated shapes; therefore, out of the parameters associated with the motion trajectory, we should consider the cutting direction.

Very often the process of the cutting regime selection for hard-to-machine materials can be accomplished only basing on the accumulated operator's experience. This is most true for the case of elaboration of the machining strategy for heterogeneous structures with the nanometer accuracy. The reason for this is the insufficient amount of published data and no possibility to observe the results during the cutting process (Lomakin, *et al.,* 2015).

To reach the best result, multiple factors shall be taken into account, as follows: cutting speed, depth and direction, material hardness and viscosity, tool parameters, etc. At that, the operator follows multiple tasks: to increase the machining rate, to decrease the tool degradation, to decrease the effect of the cutting process on the material structure, to improve the quality of the machined surface, and to improve the accuracy (Kirichek, *et al.*, 2007).

Many parameters out of those specified above are mathematically interconnected; however, the creation of a model that takes into account all factors for each separate case is not justified, and sometimes impossible due to the lack of data on the cutting parameters.

The paper proposes the means that help the operator without significant experience to determine the optimum cutting regime with the minimum information on the work parameters of a certain process. Basing on the expert estimations of the machining criteria and their effect on the cutting process, the proposed smart means provide the operator with the recommended choice of the machining parameters. This allows taking into account the previous accumulated experience of the best decision making (Lomakin *et al.*, 2015).

At the expert estimation stage, the connection between the cutting parameters is determined, and their effect on the machining results is estimated over the nine-grade scale. The estimation results can be corrected in the course of acquiring new data on the material and tool behaviours in the course of cutting.

The user, basing on the available experience, performs the comparative estimation of the available variants and gets the machining parameters for the creation of the strategy with the maximum machining speed, minimum tool degradation, and maximum accuracy of the obtained part (Afonin, *et al.*, 2015).

Let us describe our approach to the determination of the optimum machining method. Table 1 shows 20 most frequently used machining methods, out of which the operator is to select the optimum one for the following machining.

Basing on the rough, preliminary estimation, with the results presented in Table 1, we can narrow the optimum solution search area. For this purpose, we reject the variants with the lowest estimates (methods No. 5, No. 7, No. 8, No. 12, No. 15, No. 16). Thus,

Table 1. Characteristics of the machining methods and their rough estimation

Method No.	Cutting velocity	Cutting depth	Cutting Direction	Tool hardness	Tool red hardness	Value
1	Low	low	climb cut	low	low	5
2	High	high	conventional	high	high	10
3	High	high	climb	high	high	9
4	High	low	conventional	medium	high	7
5	Low	high	climb	low	low	2
6	Medium	medium	conventional	high	medium	9
7	High	high	climb	low	low	1
8	Low	high	conventional	low	high	1
9	Medium	low	climb	high	medium	6
10	High	medium	conventional	medium	high	7
11	Low	medium	climb	high	low	6
12	Low	high	conventional	low	high	2
13	High	low	conventional	medium	high	8
14	medium	high	climb	low	low	4
15	low	high	climb	low	high	3
16	high	low	conventional	low	low	3
17	medium	medium	climb	medium	medium	6
18	medium	medium	conventional	medium	medium	7
19	high	medium	conventional	medium	high	8
20	low	medium	conventional	low	low	6

within the optimum solution search area 14 variants are left.

So, the following criteria are determined for the selection of the optimum variant: time of machining, material structure, machining accuracy, quality of the machined surface, tool degradation. These are the criteria that will be used for the determination of the optimum machining method with account for the mutual importance of the criteria.

SELECTION OF THE EFFICIENT SUBTRACTIVE MACHINING STRATEGIES

The hierarchy analysis technique (HAT) is chosen as the expert estimation method. An expert performs pair-wise comparisons of the machining methods over each criterion. Apart from this, he or she performs pair-wise comparisons of the criteria. For the selection of the best machining method we use the decision support system (DSS), "Resheniye" with the modified hierarchy analysis technique (HAT) at the base (Lomakin, *et al.*, 2014a). The steps of the expert operation process for obtaining the optimum variant in the DSS are shown in Fig. 1.

One of the key stages of the decision making process with the application of the pair-wise comparison methods, in particular, HAT, is the check of the pair-wise comparisons matrix conformity. It is recommended, that the matrix conformity relation (CR) shall not exceed 10% (Lei, 2014). In the cases when this recommendation is not taken into account, there is a risk that the obtained final estimations that characterize the predominance of one compared element over another in the considered properties, may significantly differ from the values obtained in the ideal experiment.

We have offered and realized the "Resheniye" algorithm in the DSS, which can help an expert

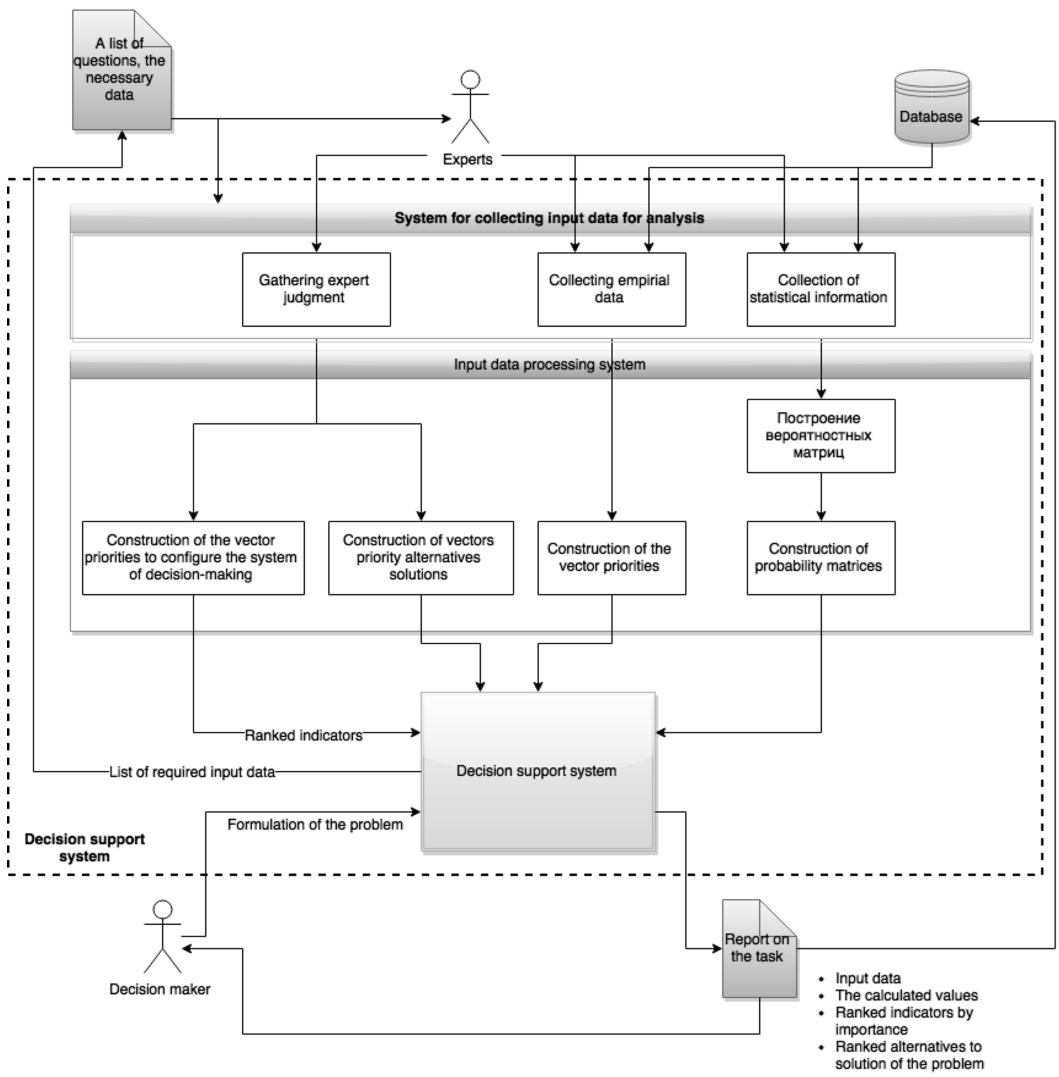


Fig. 1 The diagram of interaction of experts and modules of the Decision Support System.

determine separate elements of pair-wise comparisons that introduce the biggest errors in the results. The developed algorithm, basing on the filled pair-wise comparisons matrix, provides the possibility to prompt the expert in the form of recommendations to change the estimations into more preferable ones (Lomakin, *et al.*, 2013). The algorithm is based on the analysis of the pair-wise comparisons vectors, which in the case of high coherence, must have one-way direction. We have offered the functional (Lomakin, *et al.*, 2014b), the minimization of which leads to the obtaining of a more consistent pair-wise comparisons matrix.

$$F(\alpha)=1-\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij}}{n^2} \qquad (1)$$

where [alpha] is the matrix of calculated cosines of the angles between the pair-wise comparisons vectors for each pair-wise comparison in the source matrix.

The practical use of the offered functional significantly facilitates the process of the pair-wise comparison matrix correction to improve the degree of the logical certainty of the judgements.

Let us describe the sequence of obtaining the optimum decision for the selection of the justified machining regimes, using the "Resheniye" DSS. At the first step, an expert builds the hierarchy of the optimum machining method selection (Fig. 2). In the future, the expert can reuse his hierarchy for solving an analogous problem with changed conditions and requirements to the machining regime.

Then the expert moves to the stage of the pair-wise comparison of the methods over the 5 criteria indicated in the hierarchy. An example of one of such stages is shown in Fig. 3, for all other criteria the obtained results are similar. In view of the significantly large dimensionality of the pair-wise comparisons matrix, we do not present them here.

Then, the expert compares the criteria, but in this case all 5 criteria were equally important for the expert; therefore, the pair-wise comparisons matrix became the unity matrix (Fig. 4). However, this situation can change, and the importances of the criteria will be different, and the result will influence the global priorities of the alternatives.

COMPARISON RESULTS

At the next step, in the "Resheniye" DSS, the expert obtains the calculation results for the optimum variant basing on the performed estimation (Fig. 5 and Table 2).

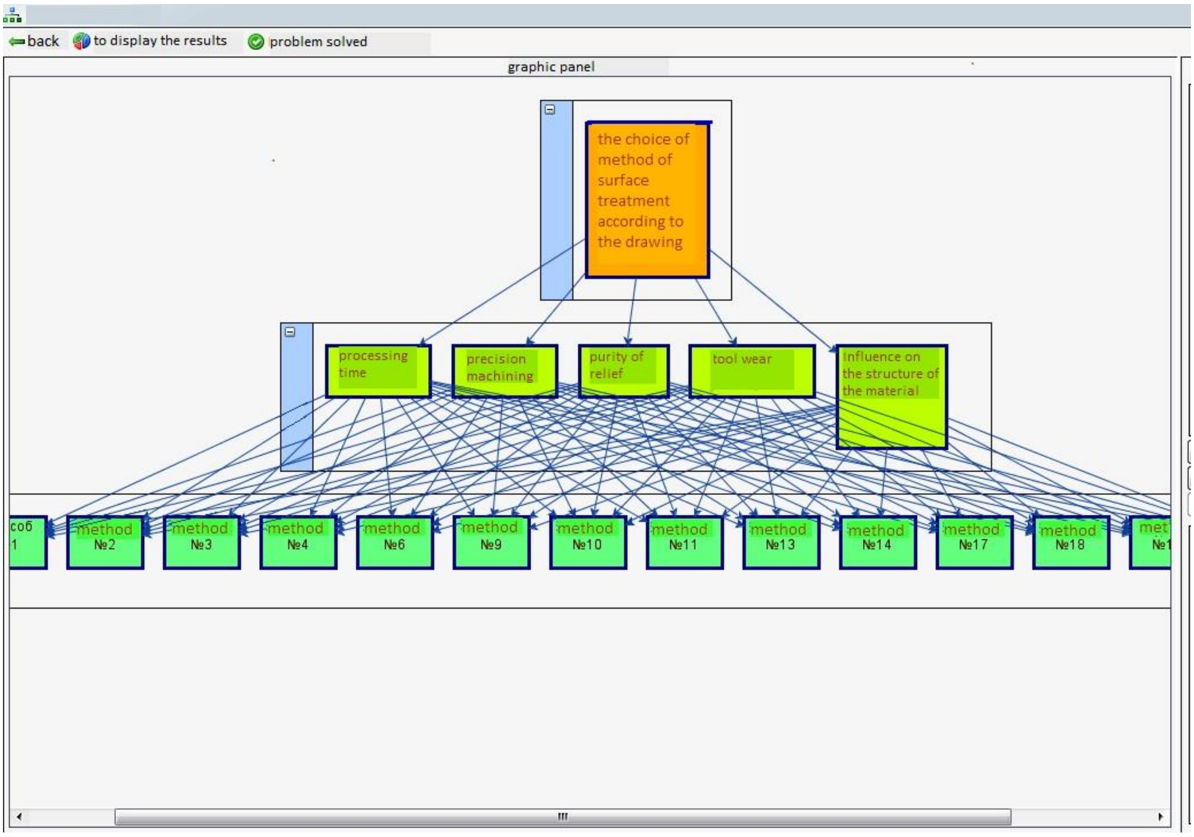
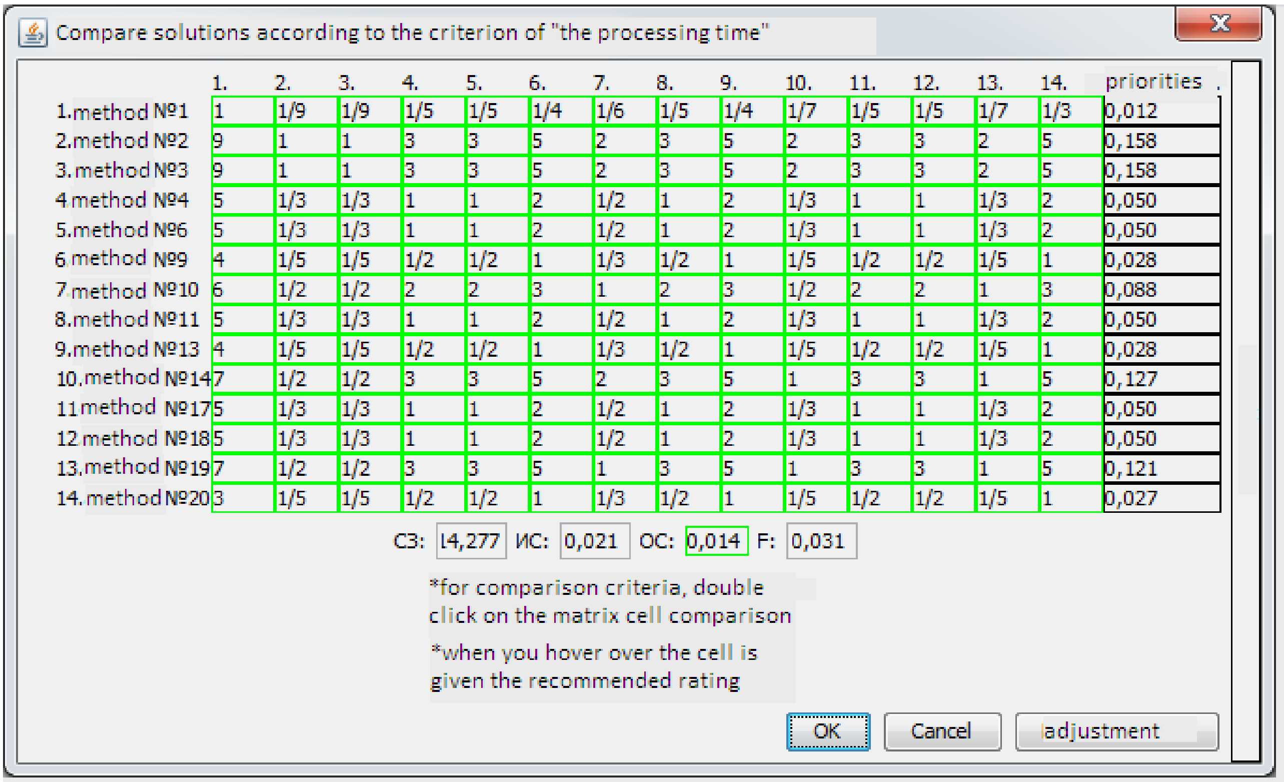
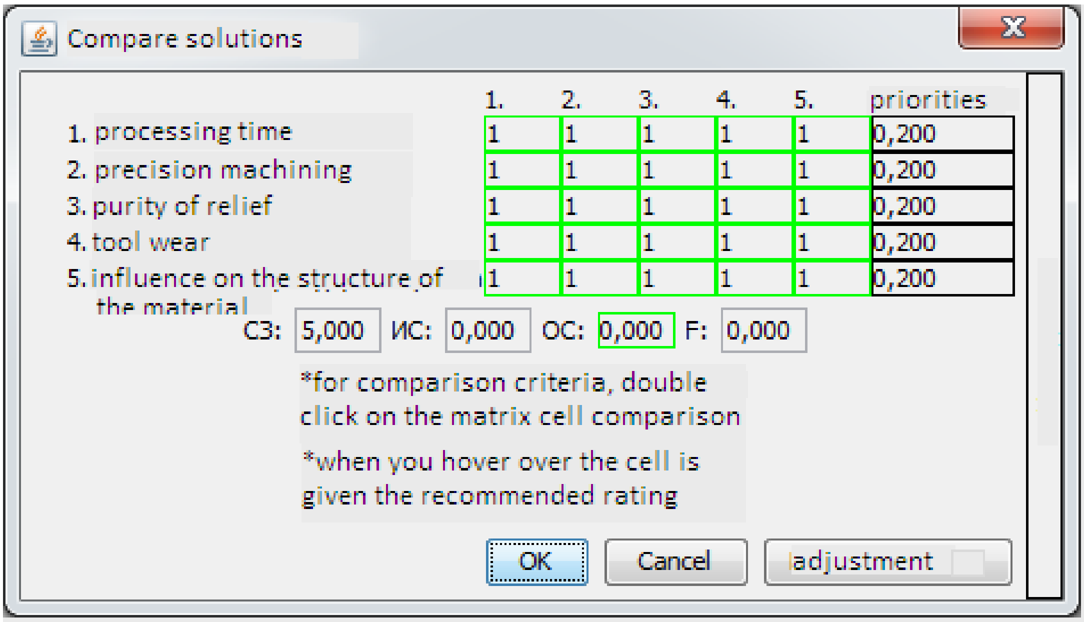


Fig. 2 Hierarchy of the optimum surface machining method selection.



	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	priorities
1.method №1	1	1/9	1/9	1/5	1/5	1/4	1/6	1/5	1/4	1/7	1/5	1/5	1/7	1/3	0,012
2.method №2	9	1	1	3	3	5	2	3	5	2	3	3	2	5	0,158
3.method №3	9	1	1	3	3	5	2	3	5	2	3	3	2	5	0,158
4.method №4	5	1/3	1/3	1	1	2	1/2	1	2	1/3	1	1	1/3	2	0,050
5.method №6	5	1/3	1/3	1	1	2	1/2	1	2	1/3	1	1	1/3	2	0,050
6.method №9	4	1/5	1/5	1/2	1/2	1	1/3	1/2	1	1/5	1/2	1/2	1/5	1	0,028
7.method №10	6	1/2	1/2	2	2	3	1	2	3	1/2	2	2	1	3	0,088
8.method №11	5	1/3	1/3	1	1	2	1/2	1	2	1/3	1	1	1/3	2	0,050
9.method №13	4	1/5	1/5	1/2	1/2	1	1/3	1/2	1	1/5	1/2	1/2	1/5	1	0,028
10.method №14	7	1/2	1/2	3	3	5	2	3	5	1	3	3	1	5	0,127
11.method №17	5	1/3	1/3	1	1	2	1/2	1	2	1/3	1	1	1/3	2	0,050
12.method №18	5	1/3	1/3	1	1	2	1/2	1	2	1/3	1	1	1/3	2	0,050
13.method №19	7	1/2	1/2	3	3	5	1	3	5	1	3	3	1	5	0,121
14.method №20	3	1/5	1/5	1/2	1/2	1	1/3	1/2	1	1/5	1/2	1/2	1/5	1	0,027

Fig. 3 Result of pair-wise comparisons of the results performed by the expert over the Machining Time criterion.



	1.	2.	3.	4.	5.	priorities
1. processing time	1	1	1	1	1	0,200
2. precision machining	1	1	1	1	1	0,200
3. purity of relief	1	1	1	1	1	0,200
4. tool wear	1	1	1	1	1	0,200
5. influence on the structure of the material	1	1	1	1	1	0,200

Fig. 4 Results of the mutual comparisons of the criteria performed by the expert.

Upon obtaining the results, we can make a conclusion that the machining methods that are most suitable for the expert are No. 4 (10%), and No. 19 (10.4%). As the expert considers, the best surface machining method is No. 19.

RESULTS DISCUSSION

As we can see, the results obtained using HAT in the Resheniye DSS differ from the rough expert estimation (Table 1); nevertheless, they do not contradict each other. This is due to the fact that the rough estimation seldom helps determine precisely the optimum variant if there is a large number of variants and multiple criteria with different importances for the expert, as a person tries to obtain independently the final priorities basing on his or her

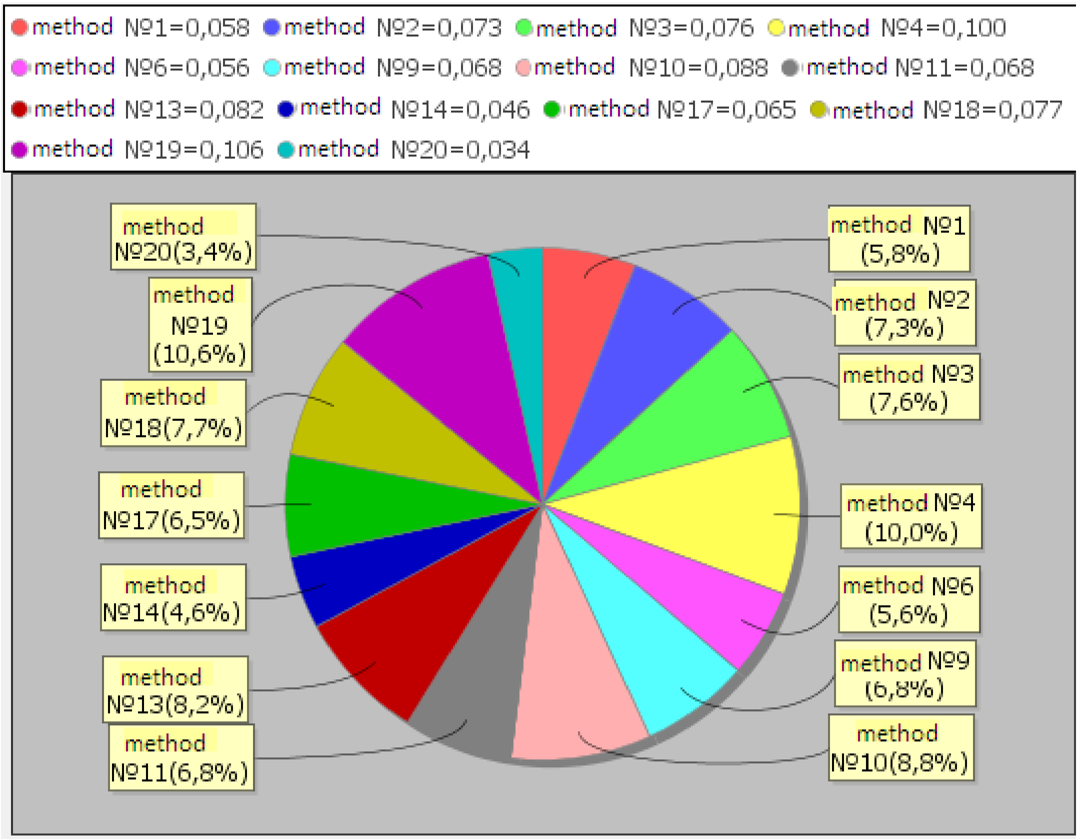


Fig. 5 Radial diagram showing the calculation results for the priorities of the surface machining methods.

Table 2. Obtained priorities of the surface machining methods

Variant of the problem solution	**Priority**
Method No. 1	0.058306353
Method No. 2	0.073173889
Method No. 3	0.075717601
Method No. 4	0.099927377
Method No. 6	0.05584166
Method No. 9	0.068327061
Method No. 10	0.088258411
Method No. 11	0.068247143
Method No. 13	0.082493703
Method No. 14	0.046454093
Method No. 17	0.065119015
Method No. 18	0.077296345
Method No. 19	0.106436395
Method No. 20	0.034400956

experience. This cannot be done precisely without using the means of multi-criteria estimation.

For the selected machining method, the programs were developed and tested on full contouring CNC. At the manufacturing of the samples used for the obtained programs testing, the Complex for material synthesis and study, based on the NIKA-2012 facility installed in the BelSU Shared Scientific Equipment Use Center, Diagnostics of the nanomaterial structure and properties, was used.

CONCLUSIONS

1. The heterogeneous structure machining methods were systematized, and basing on the rough expert estimation 14 variants of the method most suitable for the subtractive machining of heterogeneous structures were identified.

2. The hierarchy of the optimum surface machining method selection based on the identified 14 variants and 5 criteria (machining time, material structure, machining accuracy, quality of the machined surface, tool degradation) was built to enable determination of the surface machining methods priorities basing on the pair-wise comparisons of the solutions performed by the experts. We have discovered that according to the expert decision No. 19 (10.4%) is the best surface machining method. The special feature of the approach is the possibility of multiple use of the built hierarchy with further analysis of the accumulated solutions.

3. The proposed expert estimation method is suitable for the choice of the surface machining

method and in the future will allow improving the machining quality, at that the costs of the tools and consumables will be reduced.

FINDINGS

The developed smart means for estimation and selecting efficient heterogeneous structure subtractive machining strategies will allow determination of the optimum machining method basing on the expert poll, and secure the support of the multiple criteria-based production process for the operators with various levels of operation experiences.

Conflict of interest

The authors confirm that the data presented in this paper do not imply the conflict of interest.

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