Application of the Modified Genetic Algorithm for Optimization of Plasma Coatings Grinding Process

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Abstract. The problem of defining optimal conditions for grinding plasma coatings may be considered as multi-objective optimization problem with a system of bounding inequalities that contain surface roughness, temperature, local and residual stresses as well as intrinsic defects size. This approach contributes to applying evolutionary algorithms such as genetic algorithm to solve the stated problem. Taking into account special characteristics of technological process, modification of the classical genetic algorithm has been carried out in the presented research. The combined method of selection based on the mitosis and meiosis operators makes it possible to increase fitness of a population ensuring its diversity during the following iterations. It is particularly important to maintain population diversity in genetic algorithm. The reason for that is preventing premature convergence which causes the obtained solution to be far from optimal. Another way to ensure population diversity is applying the developed mutation domain model that allows to alter random genes in chromosomes with the lowest value of the fitness function. The presented algorithm is based on both the combined method of selection and the mutation domain model. In order to compare the results of solving the problem of optimization of plasma coatings grinding process using modified genetic algorithm with other evolutionary algorithms, solutions performed by the classical genetic algorithm, ant colony optimization, particle swarm optimization and scatter search algorithm are presented. It was found that applying modified genetic algorithm provides high efficiency of solving process and reliability of the obtained results.

Keywords: Genetic algorithm · Multi-objective optimization · Selection operator · Mutation operator · Surface grinding · Plasma coatings

1 Introduction

Spraying plasma coatings onto working surfaces of tools is becoming progressively widespread in modern mechanical engineering, automobile, aerospace and other branches of industry. Beyond additional opportunities provided by surface engineering to increase functionality of the finished products, economic usefulness of spraying

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plasma coatings plays an important role in industry. Physical and chemical properties of tools during their service are largely determined by the surface layer, which makes it possible to avoid production of the solid tool from expensive and scarce materials.

In the process of grinding plasma coatings, different properties of a substrate and a coating layer cause the risk of their debonding due to the destruction of adhesive contacts between them. Furthermore, there is still a possibility of surface and intrinsic defects occurrence, typical for grinding workpieces with solid structure − such as grinding cracks, burns, scratches etc. These defects make the processed tools inappropriate for further application, which, in turn, causes economic losses. Along with the conditions preventing defects generation and propagation, ensuring quality of the processed surface includes requirements for needed precision and roughness of the finished workpieces. Therefore, setting technological parameters while grinding plasma coatings depends on the complexity of factors.

Applying evolutionary algorithms is an advanced approach to solve complex optimization problems with a large number of parameters and processing constraints. With the help of evolutionary methods it is possible to determine optimal operating modes for each grinding regime, size and abrasive material of the grinding wheel and other conditions. An advantage of these methods, such as genetic algorithm, is that the result obtained at the beginning of the solving process is eventually improved on the basis of the analysis of further solutions. This scheme of optimization problem solving provides an opportunity to find multiple sets of possible solutions contained in an established database of designing technological regimes.

Evolutionary algorithm modifications carried out by setting new methods of selection, crossover principles and mutation strategy allow to increase efficiency of solving process and reliability of the solution. The genetic algorithm for grinding operations CAD system is developed in this report in order to determine optimal grinding parameters during plasma coatings processing.

2 Literature Review

The problem of grinding process optimization is generally based on the conditions of cost minimizing, achieving maximum productivity and best quality of the processed surface. Attempts to define optimal grinding parameters using linear and geometric programming, gradient method and the method of Lagrange multipliers are described in the works [1–4]. However, these methods appeared to be inefficient for defining optimal processing regimes because of non-linearity of the objective functions and large number of constraints regarding the process of grinding.

Various innovative metaheuristic algorithms have advanced and become increasingly popular recently for solving complex multi-objective problems of optimization technological system parameters. In the work [5] grinding parameters selection problem is stated and solved in terms of quadratic programming. Grinding wheel speed, workpiece speed and dressing parameters are considered variables, and total production cost, production rate and roughness of the processed surface are selected as objective functions of the created model.

To find a set of Pareto optimal solutions of the grinding parameters search problem authors of [6] use multi-objective evolutionary algorithm. Obtained results appear to be much better in comparison to the previously applied methods.

An attempt of adapting genetic algorithm to grinding process optimization is made in paper [7] on the basis of mathematical model presented in paper [5]. Despite a number of advantages, this method has a high probability of convergence to the local extremum, which impedes solving the stated problem.

Authors of [8] carried out optimal grinding parameters search using ant colony optimization algorithm based on modeling the behavior of simulated ants located in the vertices of the imaginary graph and moving with some probability of one or the other route selection. Results of the algorithm application are rather effective.

In the researches [9–11] authors propose algorithms based on Taguchi method to analyze the relationship between the grinding parameters and the quality of the processed surface. Taguchi method is a robust statistical method of technological process optimization which is often used to design manufacturing systems and to control the resulting products quality.

Since the grinding process optimization is based on nonlinear objective functions of several variables, some authors [12, 13] prefer to apply differential evolution algorithm and its modifications. Differential evolution algorithm has much in common with the genetic algorithm strategy, but it does not require to represent the variables in binary code.

Modification of the scatter search method for grinding process optimization problem is presented in the work [14]. The main feature of scatter search algorithm is that the solutions from initial population should be sufficiently scattered over the feasible set region.

When reviewing advanced evolutionary methods, particle swarm optimization should also be mentioned as it can be used to search for the global extremum if calculating the gradient of an objective function raise some difficulties. Particle swarm optimization algorithm is based on the collective animal behavior model and characterized by speed adjustment which is defining for the convergence of an algorithm. An example of applying particle swarm optimization method to solve the problem of grinding process parameters optimization is presented in paper [15]. Authors of [16] suggest an enhanced particle swarm optimization algorithm to improve the results of solving the stated problem. Paper [17] is focused on the development of hybrid particle swarm optimization method which combines the dynamic neighborhood topology for particle swarm optimization with the mutation approach based on the conditions of surface grinding process. In paper [18] chosen regression model of the surface roughness in finishing turning of hardened steel with mixed ceramic cutting tools.

Analysis of the scientific literature referred to in this review has revealed a number of unresolved problems regarding optimization of the parameters of plasma coatings grinding process and the algorithm of the stated problem solving:

– previous research of the grinding regime parameters was carried out for the workpieces that have the solid structure. Structural steel was typically used as a material of the processed tool. Taking into account that structural steel is not very expensive, loss of the material during the process of grinding has no effect on the

finished products cost. However, plasma coatings materials are often characterized by the high price and low availability, so they are important factors of price formation that will influence on the optimality criterion formulating;
- while grinding plasma coatings, different properties of the coating layer and the substrate material should be taken into account as well as possibility of destruction of adhesive contacts and debonding of a coating layer from a substrate;
- genetic algorithm is one of the main evolutionary methods for solving optimal technological parameters search problem. An advantage of the classical genetic algorithm is its fast convergence. But the fast convergence may become an important disadvantage in case of convergence to the local extremum, because then it would not be possible to find optimal parameters values for the global extremum;
- the mutation probability remains almost the same for all of the solutions in the population with very little reference to the fitness function value. But the results of the mutation of chromosomes within the neighbourhood of the global maximum might be less fit than their parents. It has negative consequences for problem solving process. Hence, the mutation mechanism should particularly contribute to altering among the solutions with the least value of the fitness function.

3 The Aim and Objectives of the Research

The aim of the presented research is to develop modified genetic algorithm in order to find optimal parameters for grinding plasma coatings.

To achieve this objective, the following tasks should be accomplished:

- to define special aspects of grinding parameters selection problem statement for processing workpieces with plasma coatings, taking into account additional conditions and constraints imposed on mathematical model of grinding workpieces with solid structure;
- to develop method of selection that would allow to avoid decreasing fitness of the solutions from the global maximum neighbourhood as a result of recombination with less fit chromosomes, to maintain the highest population diversity and to prevent premature convergence of the algorithm;
- to propose mutation mechanism that would allow the solutions with the least fitness value to alter faster without decreasing population size of the system.

4 Formalization of the Optimal Technological Parameters Search Problem for Plasma Coatings Grinding Process

Optimal technological parameters search problem for the process of grinding plasma coatings studied in the work [19] is presented as multi-objective optimization problem. Productivity of the coated workpieces processing and allowance loss of coating material are considered optimum criteria which can be expressed as:

$$P = \frac{1000 \cdot a \cdot b}{L \cdot k \cdot (B + b + \Delta)} \cdot v_l^j \cdot v_{tr}^s \cdot \sum_{i=1}^{N} h_i\ , \quad j = \overline{1, M}; \quad s = \overline{1, Q} \tag{1}$$

$$\delta = \sum_{i=1}^{N} h_i \cdot n_i \tag{2}$$

where a is the length of the workpiece; b is its width; L is table length; k is precision coefficient; B is width of the grinding wheel; Δ is empty width of the table; v_l^j is longitudinal feed; v_{tr}^s is transverse feed; h_i is depth of cut for the i^{th} pass; n_i is number of passes with the set depth of cut.

Thus, problem statement consists in searching technological parameters of plasma coatings grinding process that provide maximum grinding productivity [20] and minimum loss of coating material on allowance with the required surface quality [21]:

$$P \to \max; \tag{3}$$

$$\delta \to \min; \tag{4}$$

$$\begin{cases} R_a \le R_a^*; \\ T(x) \le T_{\max}; \\ \sigma_{\max}(x, \tau) \le \sigma_{\lim}; \\ \sigma_y < \theta_{adh}; \\ \ell_0 < \ell_0^*, \end{cases} \tag{5}$$

where R_a and R_a^* − obtained and required roughness of the processed surface; T and $T_{\max}$ − grinding temperature and maximum temperature that allows to avoid grinding burns on the surface of plasma coating; $\sigma_{\max}$ − local stresses maximum value; $\sigma_{\lim}$ − stresses that trigger grinding cracks generation; θ_{adh} − adhesive strength between the coating layer and the substrate; σ_y − tangent stresses that destroy adhesion; ℓ_0 and ℓ_0^* − linear dimension of the structural defect and size of the defect that causes local fracture.

In order to solve multi-objective optimization problem, an additive function is built as a sum of the criteria $Z_1 = P$ and $Z_2 = \delta$, weighted according to their importance. Hence, complex optimality criterion can be expressed as:

$$Z = w_1 \cdot Z_1 - w_2 \cdot Z_2\ . \tag{6}$$

Depending on the priority of one or another criterion during the process of spraying and grinding plasma coatings, weight coefficients are selected so that their values are within [0; 1] and their sum is $w_1 + w_2 = 1$.

Vector of technological parameters which can be set at the grinding process design stage includes wheel speed, longitudinal and transverse feed, grinding depth and number of passes of the grinding wheel. Other parameters are constant for each case of circumstances for the stated problem. Therefore, searching for Pareto optimal solutions is carried out within the set of possible values of the vector $x = \left(v_w, v_l^j, v_{tr}^s, h_1, n_1, \ldots, h_i, n_i\right)$.

5 Strategy of the Optimization Problem Solving

5.1 Genetic Algorithm Application

General idea of the genetic algorithm consists in following methods of optimization that are usual for living organisms: genetic inheritance and natural selection. In this case biological terminology is used to explain operations of the algorithm. The main principle of natural selection is based on a statement, that it is the fittest individuals who survive and reproduce during the process of evolution. According to the law of genetic inheritance, their offsprings inherit the main characteristics of parents. Besides, being exposed to the random mutations gain them a number of new features. If the changes contribute to organism adaptation, they are inherited in the next generations. Therefore, average fitness of the population is eventually increasing.

Genetic algorithm relies on fundamental operators common to all evolutionary algorithms of optimization: phenotype building, selection, crossover, mutation etc. Genetic algorithm running consists in systematic performing operations presented in Fig. 1.

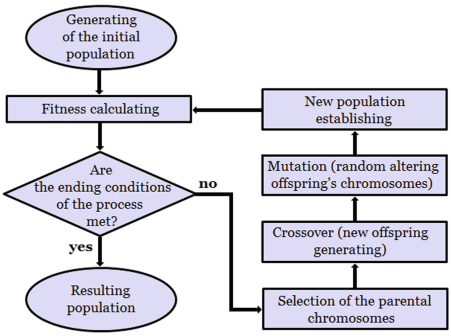

Fig. 1. General scheme of the classical genetic algorithm

5.2 Development of the Modified Genetic Algorithm for Solving Grinding Parameters Search Problem

Sufficient size of the population and maintaining its diversity are necessary conditions for genetic algorithm running. Premature stopping of an algorithm before the global extremum is reached may obstruct its reliability meaning the obtained result is not Pareto optimal. The reason of premature convergence is natural selection principle that forms the basis of the genetic algorithm. Selection of the parental solutions is carried out with regard to their fitness: the higher it is the greater is the probability that the chromosome will take part in further crossover. Hence, fitter solutions have an advantage and begin to replace other variants of the code from the population. In case the population size is insufficient for diversity maintaining and the solution with the highest value of the fitness function is far from the global extremum, algorithm prematurely converge to the local maximum or minimum. And even if after a certain number of iterations a much fitter solution is generated, it has no influence on the final result, as it remains in the minority among the large number of former leaders' off-springs. Probability of reaching the global or the local extremum of the fitness function also greatly depends on its type. Premature convergence is more likely to occur if local extremums of the function are far from one another within its definition domain [22].

In Fig. 2 distribution of chromosomes within the population during the process of solving optimal grinding parameters search problem using the classical genetic algorithm is presented.

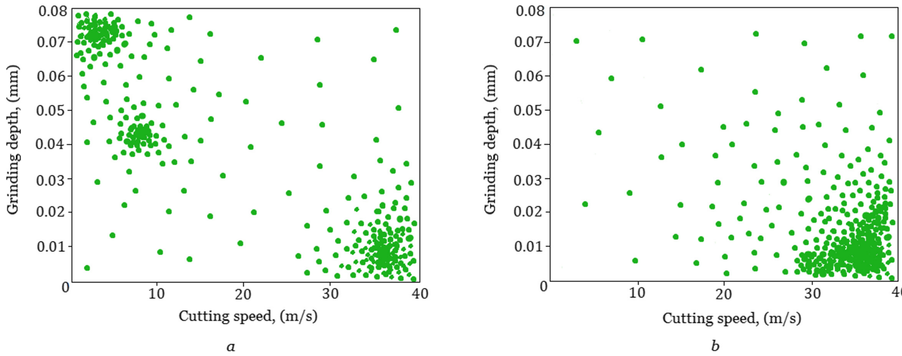

Fig. 2. Distribution of chromosomes for the classical genetic algorithm: a – grouping around several extremums; b – dominating of one of the extremums and driving out other solutions from the population

At the early stages of the genetic algorithm running fitness of the solutions vary significantly from the global extremum. During the further crossover sets of the solutions eventually group around the local and the global extremums (Fig. 2a). After that solutions concentrate in one of the areas which randomly started to dominate by the number of solutions (Fig. 2b). Chromosomes concentrated in other areas within the problem solution space are gradually driven out from the population. Therefore, in order to prevent premature convergence and avoid the loss of the useful genetic material, it is necessary to concentrate the set of the problem solutions step by step towards the global extremum area.

The fundamental idea of the classical genetic algorithm reflects the reproductive division mechanism which is called meiosis in the natural sciences. Along with meiosis, there is one more reproduction method typical for living organisms – mitosis. When applying the mitosis operator, chromosomes are exposed to replication of their genetic code. It means that the considered solution at some stage is rewritten and moved to the next iteration unchanged. Applying the mitosis operator to the best solutions in the population enables to increase its general fitness and maintain population diversity. If chromosomes with the highest values of the fitness function at the current stage of problem solving reproduced with the help of mitosis operator, it would be possible to prevent decreasing their values as a result of recombination with less fit solutions and to avoid driving out other variants of the genetic code. Proportion of elite solutions within the ith population may be defined by relative fitness function values:

$$\xi = \frac{f_k^i}{\max Z(x^i)}, \tag{7}$$

where f_k^i is fitness function value for the kth solution of the ith population; $\max Z(x^i)$ is the highest value of the fitness function within the ith population.

Hence, having determined relative fitness ξ, lower limit $\underline{\xi}$ of fitness for solutions that are moved to the next generation unchanged can be found out. Solutions whose relative fitness is within $\xi \in [\underline{\xi};\ 1]$ characterize dispersion of the elite chromosomes to the highest value of the fitness function at each stage of the algorithm running. If the elite solutions loosed their leading positions afterwards, they would be involved in crossover and new generation establishing. Thus, at the beginning of the problem solving process convergence would be slowed down, whereas there would be increasing fitness of the population with wide diversity of possible solutions. In that case, the size of the population remains the same during the whole problem solving process.

Chromosomes with less values of the fitness function form a set of solutions for further selection and crossover. Selecting chromosomes is carried out on the basis of the tournament selection. Crossover is taking place until there is the required number of solutions in the next generation.

For the least fit solutions in the population it would be useful to provide a mechanism that would allow them to alter faster under the conditions of the stated problem. For this purpose the mutation operator should be applied, which makes it possible to turn parts of the binary code into the opposite values. Knowing relative fitness of the solutions and value $\overline{\xi}$ defining upper limit of the solutions with the least fitness, chromosomes for the further mutation are easily found. Relative fitness function of these solutions lies within $(0\,;\ \overline{\xi}\,]$ values. Principle of generating each new population in the modified genetic algorithm is shown in Fig. 3.

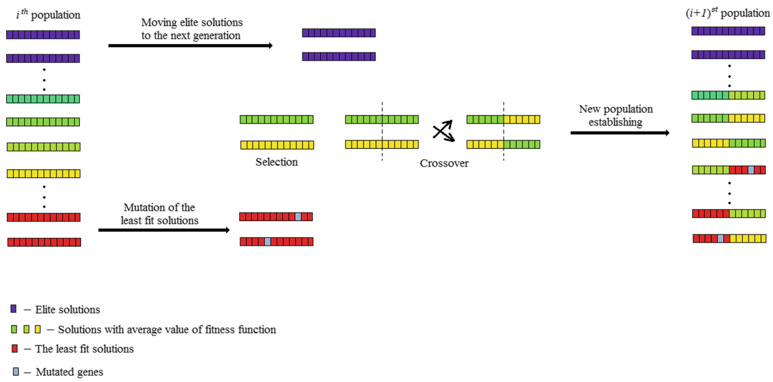

Fig. 3. Scheme of the new population establishment for the modified genetic algorithm

While solving the problem of optimization of plasma coatings grinding process, along with the conditions of diversity maintaining and premature convergence preventing, constraints ensuring quality of the processed surface (5) have a particular importance. These constraints are determined by characteristics of the processed coating, grinding wheel parameters and the workpiece geometry. Besides, grinding machine characteristics play an important role in generating the initial population and the set of possible solutions, as they define limitations of the processing speed and other key parameters of surface grinding. Information required for calculations during the stated problem solving is stored in corresponding databases of the plasma coatings grinding CAD system.

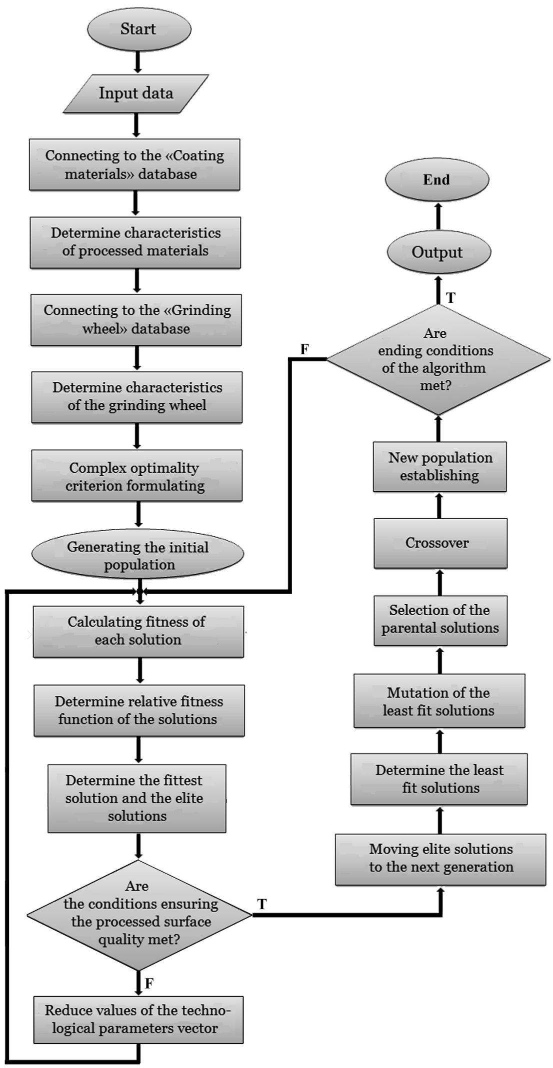

Fig. 4. Modified genetic algorithm for optimization of plasma coatings grinding process

In case the conditions ensuring surface quality are not met at some stage of the solving process, values of the technological parameters vector $x_k = \left(v_w, v_l^j, v_{tr}^s, h_1, n_1, \ldots, h_i, n_i\right)$ should be reduced by the minimum value Δ possible for the grinding machine. Therefore, reduction of values $\left(v_w - \Delta v_w,\ v_l^j - \Delta v_l^j, v_{tr}^s - \Delta v_{tr}^s, h_1 - \Delta h_1, n_1, \ldots, h_i - \Delta h_i, n_i\right)$ will take place until the conditions that ensure surface quality are met. The modified genetic algorithm for optimization of plasma coatings grinding process within the CAD system is presented in Fig. 4. An ending condition of the algorithm is achieving such level of convergence when there is no better result for several iterations.

6 Discussion of the Results of the Modified Genetic Algorithm Performance Analysis

In order to compare the efficiency of the modified genetic algorithm with the results of the classical genetic algorithm, the corresponding graphics are plotted in Fig. 5. Objective function values for each iteration are determined regarding the maximum value obtained as a result of solving optimization problem. Presented graphics demonstrate that applying the mitosis and meiosis operators as well as mutation domain model makes it possible to increase the efficiency of the optimization process for grinding plasma coatings.

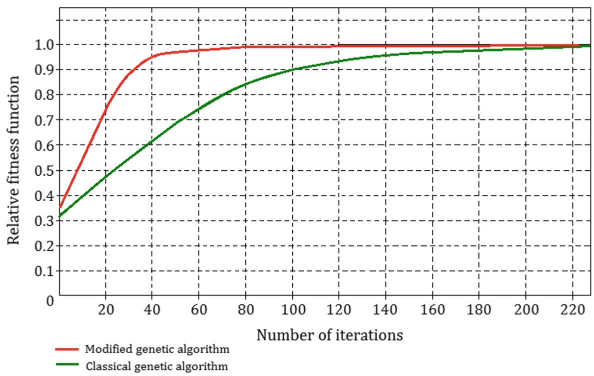

Fig. 5. Objective function value dependence on the number of iterations during the process of optimization for the modified and the classical genetic algorithm

Figure 6 shows the results of technological process optimization for grinding plasma coatings applying other evolutionary methods such as ant colony optimization algorithm, particle swarm optimization algorithm and scatter search method.

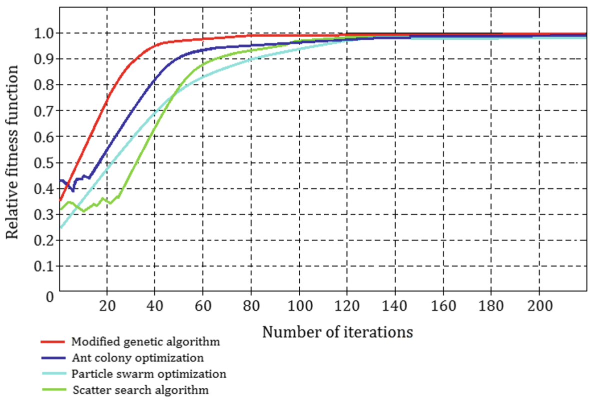

Fig. 6. Comparison of convergence of the modified genetic algorithm, ant colony optimization algorithm, particle swarm optimization method and scatter search method for the process of optimization of grinding plasma coatings

7 Conclusion

Analysis of the conditions and constraints that ensure required quality of the processed surface is carried out in the presented research. Mathematical model of the optimal technological parameters search problem is developed for the process of grinding plasma coatings. In this case, the porosity of coating layer as well as an adhesive strength between the coating layer and the substrate are considered for the first time. The resulting system of constraints provide zero-defect grinding of a workpiece and the required surface roughness, while optimality criteria include key factors of price formation for the finished products.

On the basis of the mitosis operator the combined method of selection is developed. It assumes replication of the elite chromosomes into the next generation and allows to prevent driving out less fit solutions from the population, to increase general fitness of the population and ensure its maximum diversity. This approach helps to slow down convergence of the algorithm at the beginning of problem solving process and makes it possible to avoid premature convergence to the local extrema.

Mutation operator that allows the least fit chromosomes in the population to alter faster is presented and investigated. Thus it becomes possible to maintain size of the population system and to involve the solutions with the least fitness value in the next generation establishing that has a positive effect on population diversity.

The results of the modified genetic algorithm performance are compared with other evolutionary methods of optimization. This comparison has proved an advantage of the modified genetic algorithm for the optimal technological parameters search during the process of grinding plasma coatings.

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