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Method for Optimizing the Parameters of Mechanical Processing of Holes to Ensure Cutting Tool Stability and Cost-Effective Machining

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Abstract. This article describes a new approach to optimizing the parameters of mechanical hole machining, which solves the problem of compromise between various criteria, such as machining time, tool durability, and surface quality. Traditional optimization methods, as shown in the study, usually focus on a single parameter, which inevitably leads to deterioration in others. For example, increasing the cutting speed to reduce machining time causes rapid tool wear, while reducing parameters to improve surface quality significantly increases time and production costs. To overcome these shortcomings, a methodology based on weighted multi-criteria analysis was developed. The methodology includes several stages: data collection, formation of objective functions, definition of constraints, normalization of criteria, and selection of an optimization method. A key element is the use of weighting coefficients, which allow the methodology to be adapted to specific production priorities. The study was conducted using a specific example of optimizing hole drilling in 45 steel. Weighting coefficients were set, with the greatest weight given to processing time (0.5), followed by roughness (0.3) and tool resistance (0.2). As a result, the following parameters were recognized as optimal: cutting speed v_c = 22 m/min and feed f_z = 0.2 mm/rev. With these values, the processing time was reduced from 37.9 to 28.7 seconds, while tool durability decreased from 275.2 to 176.4 μm. This clearly demonstrates that the method has found a compromise solution that allows reducing the time without critically compromising tool durability.

Keywords: optimization, cutting speed, feed rate, tool resistance, processing time

Introduction

Modern mechanical engineering faces the need to reduce costs, increase productivity, and improve product quality [1]. In the context of hole machining, which is one of the most common and important operations in mechanical engineering, this task is particularly relevant [2]. The technological process of hole machining is a complex operation that can include several stages: drilling, boring, countersinking, and reaming [3]. Each of these stages has its own characteristics and requires a careful approach to the selection of machining parameters. Traditional methods based on optimizing a single parameter (e.g., minimizing machining time) often lead to deterioration in others, such as tool durability or surface roughness [4]. This makes it relevant to use a multi-criteria approach that allows finding a compromise solution that takes into account all important aspects of the technological process.

Traditional optimization methods have typically focused on maximizing a single specific criterion. For example, in drilling, the goal was often to reduce processing time, as this directly affects productivity [5]. To achieve this, the cutting speed (vc) and feed rate (fz) were typically increased. However, as studies [6] show, this approach leads to rapid drill wear and deterioration in the surface quality of the hole. This trade-off between high productivity and tool durability is one of the key problems with the traditional approach.

Boring is an operation used to increase the diameter and improve the accuracy of an existing hole [7]. In traditional boring optimization, the focus can be either on minimizing time or on achieving high accuracy. Time optimization, as with drilling, involves the use of high speeds and feeds, which in turn can cause vibrations, lead to poor surface quality, and premature wear of the boring tool [8]. If accuracy is the priority, then the machining parameters are reduced, which leads to a significant increase in machining time and, as a result, to an increase in production costs [9].

Countersinking is an intermediate stage used to increase the diameter of a hole and prepare it for subsequent reaming or thread cutting. In the traditional approach, countersinking optimization often boiled down to selecting parameters that would ensure minimum surface roughness [10]. This was achieved by reducing the cutting speed and feed rate, which in turn led to an increase in the operation time. Such a unidirectional approach does not take into account economic aspects and may be ineffective in mass production conditions.

Reaming is the final operation used to produce holes with high precision and low roughness. Here, traditional optimization methods are almost always aimed at achieving the highest possible surface quality. This is achieved by very low feed rates and cutting speeds, making reaming one of the slowest operations in the hole machining process [11]. While surface quality is a key criterion for reaming, completely ignoring machining time can lead to significant delays in the production cycle.

Particular attention should be paid to the drilling operation, as it is one of the first in the technological process and the success of subsequent stages largely depends on it. With traditional drilling optimization methods, parameters such as cutting speed (vc), feed rate (fz), and cutting depth (ap) vary [12]. These parameters directly affect the machining time (Tpro), tool life (Tc), and surface quality (Ra) [13]. For example, increasing the cutting speed and feed rate to reduce machining time leads to faster tool wear and potential deterioration of surface quality [14]. On the other hand, reducing these parameters to increase tool life or improve surface quality leads to a significant increase in machining time [15]. Thus, the traditional approach, focused on a single criterion, does not allow finding the optimal balance between all important indicators, which creates a contradiction between them.

Thus, traditional optimization methods based on improving one parameter lead to deterioration of others, creating a trade-off between processing time, tool life, and surface quality. This problem is exacerbated by the fact that at each stage of hole machining (drilling, boring, countersinking, reaming), parameters such as cutting speed (vc), feed rate (fz), and cutting depth (ap) can be varied, which directly affect all three criteria [16]. This contradiction makes it relevant to use a multi-criteria approach, which allows finding a compromise solution that takes into account all important aspects of the technological process.

The application of a multi-criteria approach in technological processes is not only desirable but also vital for achieving competitive advantages. Unlike traditional methods, multi-criteria optimization allows several objectives to be taken into account simultaneously, such as minimizing processing time, maximizing tool durability, and achieving the required surface quality. The use of methods such as hierarchy analysis, weighted sum methods, or genetic algorithms allows for the construction of a mathematical model that reflects the relationship between processing parameters and key performance indicators. This enables engineers to make informed decisions based not only on production factors, but also on economic factors. Ultimately, comprehensive analysis allows not only to find the best compromise, but also to predict how a change in one parameter will affect the entire system, which significantly reduces risks and increases the stability of the production process. Multi-criteria analysis is becoming a key tool for improving production efficiency in a highly competitive market. This approach allows us to move from empirical parameter selection to scientifically based design of technological processes, ensuring sustainable development and innovative leadership.

The purpose of this study is to develop a methodology for improving the efficiency of the production process by optimizing key parameters such as processing time, surface quality, and tool wear based on multi-criteria analysis. The subject of this study is the development of a methodology for optimizing material flow parameters in mechanical engineering production.

A specific example is the technological operation of hole machining, which is one of the most common and important in mechanical engineering. As part of this work, an analysis of existing approaches to the optimization of technological processes was carried out, their shortcomings were identified, and a new methodology based on weighted multi-criteria analysis was proposed.

2. Research methodology

2.1 Selection of criteria

To solve this problem, a method based on multi-criteria analysis was developed. The essence of the method is to find the optimal solution that will be the best in terms of several criteria simultaneously.

The following criteria were selected for this study:

1. Minimizing processing time (Tpro):

$$Tpro = n \cdot f_z \cdot L \cdot i \tag{1}$$

where L - length of the surface being processed;
i - number of passes;
n - spindle rotation speed;
f_z - feed.

2. Minimizing surface roughness (Ra):

$$Ra = C \cdot f_{zx} \cdot v_{cy} \tag{2}$$

where C,x,y - empirical coefficients;
v_c – cutting speed.

3. Maximizing tool resistance (Tc):

$$Tc = v_{cm} \cdot f_{zn} \cdot Cv \tag{3}$$

where Cv,m,n - коэффициенты, зависящие от материала инструмента и заготовки.

The goal is to find a combination of parameters (vc, fz, ap) that will be optimal according to all three criteria.

2.2 Stages of the parameter optimization methodology

The methodology includes the following stages, as shown in Figure 1.

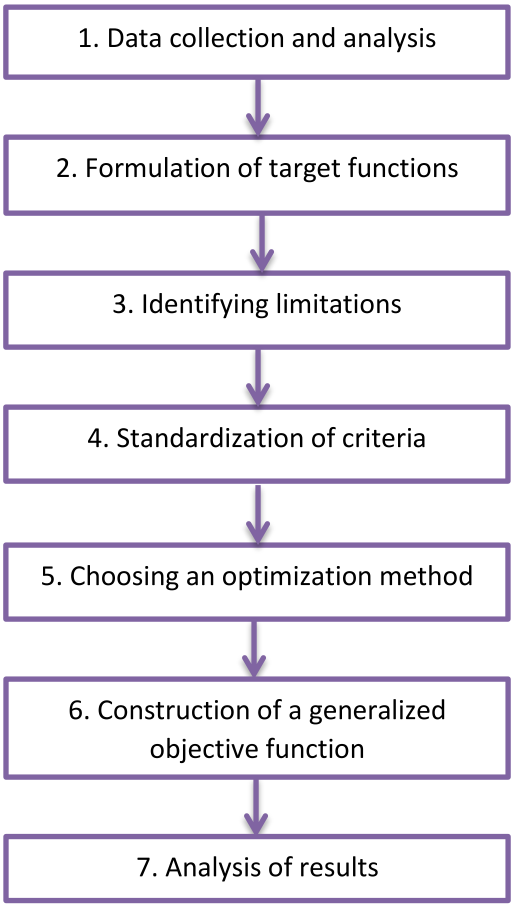

Fig. 1. – Stages of the methodology for optimizing mechanical processing parameters

During the data collection and analysis stage, information is gathered on materials, tools, equipment, and quality requirements. When forming target functions, mathematical models are created for each of the three criteria. It is also important to impose restrictions on variable parameters (vc, fz, ap) based on the technical characteristics of the equipment and tools [17]. For example, maximum spindle speed, maximum feed rate, etc. At the criterion normalization stage, all criteria must be converted to a dimensionless form, since they have different dimensions and ranges of values [18]. This allows them to be compared with each other. After standardizing the criteria, it is necessary to select an optimization method. To solve the problem of multi-criteria optimization of hole processing, the weight coefficient method was chosen [19]. This method allows each criterion to be assigned a certain weight (significance) depending on production priorities. For example, if speed is most important, the weight coefficient for processing time (Tpro) will be higher.

When constructing the generalized objective function, the normalized criteria were combined into a single function, taking into account the weighting coefficients:

$$F_{gen} = w_1 \cdot \frac{T_{pro}}{pro} + w_2 \cdot \frac{Ra}{Ra_{min}} + w_3 \cdot \left(1 - \frac{T_c}{T_{cmax}}\right) \quad (4)$$

where w_1, w_2, w_3 - weight coefficients, the sum of which equals 1;

T_{pro} – processing time;

T_{promin} – minimum processing time;

Ra – roughness;

Ra_{min} – minimum roughness.

At the stage of solving the optimization problem, the minimum of the generalized objective function was sought using the gradient descent method [20].

3. Results and discussion

A specific example was chosen to demonstrate how the method works: drilling a hole with a diameter of 10 mm and a length of 65 mm in a 45 steel part. P6M5 high-speed steel drill bit was used for mechanical processing of the holes. The resulting roughness of the machined surface was Ra 1.6.

The initial data for the calculation are given in Table 1.

Table 1. Initial data for optimizing the mechanical processing of holes

Parametr	Value
Cutting speed, v_c	from 10 to 30 m/min
Feed rate, f_z	from 0.1 to 0.3 mm/rev
Cutting depth, a_p	from 1 to 5 mm
Weight coefficients: w_1 (time) w_2 (roughness) w_3 (resistance)	 0.5 0.3 0.2

Based on empirical formulas and constraints, dependency graphs were constructed and an optimal solution was found that minimizes the generalized objective function. The optimization process for the mechanical processing of holes by drilling is shown in Figure 2.

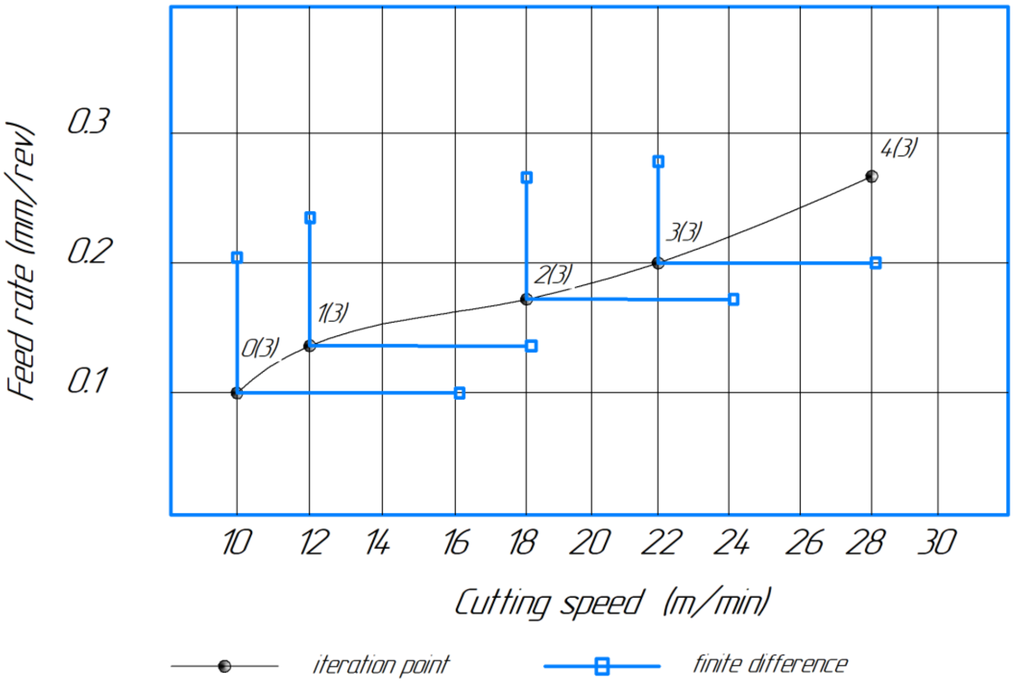

Fig. 2. Optimization of cutting parameters during mechanical processing of a hole

Based on the graph presented, which illustrates the optimization of drilling parameters, it is possible to trace the relationship between cutting speed (vc) and feed rate (fz) at each iteration.

The graph shows how the system searches for the best combination of parameters during the optimization process. The starting point, designated as iteration 0, corresponds to a cutting speed of 10 m/min and a feed rate of 0.1 mm/rev. Then, at each subsequent iteration (1, 2, 3, and 4), the parameters gradually change.

As a result, the optimal parameters were achieved in the fourth iteration, since the final difference between the parameters under consideration is minimal. This point corresponds to the following values: the cutting speed (vc) is 22 m/min, and the feed rate (fz) is 0.2 mm/rev.

The graph (Figure 3) shows that with each iteration, the processing time (green line) decreases. For example, at iteration 0, the time was 37.9 seconds, and at iteration 4, it was 28.7 seconds. This confirms that the optimization process succeeded in reducing the time, which is one of the goals of the methodology.

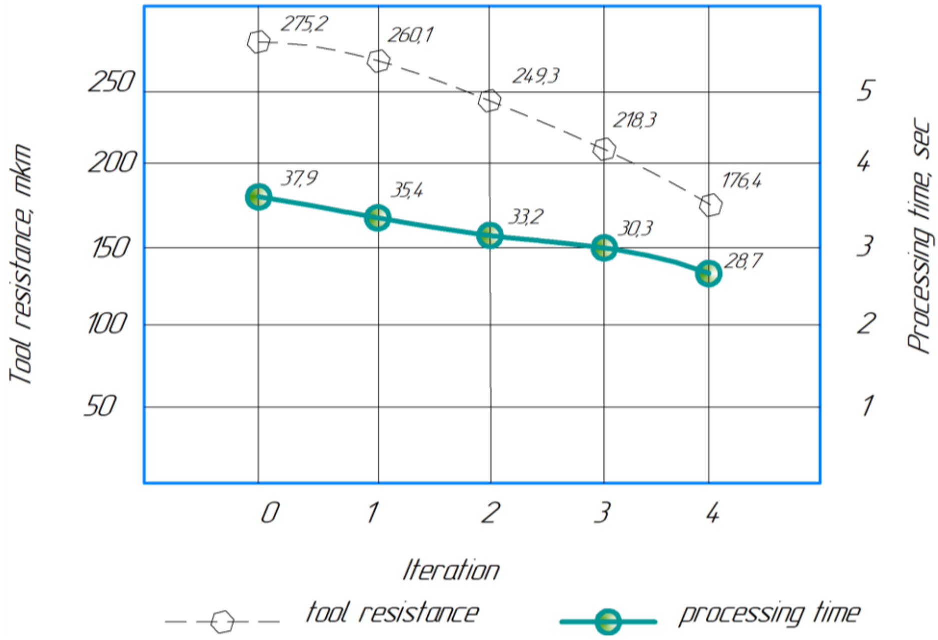

Fig. 3. Dependence of tool resistance and processing time in each iteration

At the same time, the tool's durability (dashed line) also decreases, but not as much as if the optimization had been performed only in terms of time. At iteration 0, the durability was 275.2 μm, and at iteration 4, it was 176.4 μm. This result demonstrates that the methodology has found a compromise solution that reduces processing time without completely sacrificing tool durability.

The following parameters were recognized as optimal:

- v_c = 22 m/min;
- f_z = 0.2 mm/rev;
- a_p = 4 mm.

These parameters achieve a compromise between processing time, tool durability, and surface quality, which is the best solution for these conditions.

The results showed that the proposed method allows finding optimal cutting parameters that differ significantly from those that would be selected when optimizing according to a single criterion. For example, when optimizing only for time, the cutting speed would be maximum, which would lead to rapid tool wear. When optimizing only for quality, the speed would be minimum, which would lead to a significant increase in processing time. Thus, a multi-criteria approach allows finding a balanced and effective solution.

Conclusions

The study showed that traditional optimization methods focused on a single criterion lead to compromises that worsen other important indicators. For example, increasing the cutting speed to reduce processing time leads to rapid tool wear. Conversely, lowering parameters to improve surface quality significantly increases processing time and production costs. The proposed approach solves this problem by finding a balanced and effective solution.

The developed method for optimizing material flow parameters based on multi-criteria analysis has proven its effectiveness in the example of a technological operation for machining holes. It allows finding the optimal cutting parameters that take into account not only the processing time, but also the surface quality and tool durability.

Main conclusions:

- multi-criteria analysis is an effective tool for solving complex optimization problems in mechanical engineering;
- the use of weighting coefficients allows adapting the methodology to specific production priorities;
- The methodology can be scaled to optimize more complex technological processes, including turning, milling, and grinding.

The next step in the research will be to develop software to automate calculations and implement the methodology in real production.

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