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# OPTIMIZATION OF THE NUMBER OF MACHINING STAGES WORKPIECES FOR MECHANICAL ENGINEERING PARTS

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**Abstract:** The productivity of machining in the production of machine parts is determined by the time spent on shaping surfaces according to the drawing and the number of machining stages required to achieve the specified accuracy of the part from workpieces of varying accuracy. Due to the well-known property of the technological system related to the technological inheritance of errors from the workpiece to the part, the refinement of the workpiece dimensions is carried out in several stages. The required number of machining (refining) stages for the workpiece depends both on the characteristics of the technological system itself and on the degree of variation in the workpiece's input parameters and its machining conditions. In addition, since the process of reducing the workpiece error depends on the dispersion of its dimensions, the required number of machining stages to achieve the specified accuracy is primarily determined by the change in the dimension of the dynamic setup at each stage. At the same time, the dimension itself is typically adjusted by changing the static setup. The dimension of the dynamic setup arises due to the elastic displacements of the elements of the technological system under the influence of cutting forces. The greater the difference between the dynamic setup dimension and the setup dimension (static setup dimension), the larger the error in the resulting dimension. Errors caused by fluctuations in the dynamic setup dimensions are difficult to compensate for, as they depend on many parameters: the strength properties of the material being machined, cutting conditions, cutting tool parameters and its wear, the rigidity of the technological system, and others. The article presents an approach to finding combinations of technological process parameters that ensure the shortest production time for parts and the specified accuracy. For parametric optimization, the identified patterns of the influence of the main technological process parameters on the refinement coefficient of the workpiece dimensions at each machining stage are discussed.

***Keywords:*** *machining stages, cutting conditions, turning, properties of the material being machined*

## Introduction.

Considering the technological inheritance of workpiece errors, it is customary to process the workpiece in several stages (phases) [1]. At each stage, the dimension of the workpiece is refined by a certain amount – the refinement coefficient. For example, in turning operations, four stages are typically used: roughing, semi-finishing, finishing, and polishing [2]. The required number of machining stages depends on the dimensional accuracy of the workpiece and part, the rigidity of the technological system, the cutting conditions, and other factors. Each machining stage may be performed in one or several passes. The number of machining stages collectively determines the total time for completing the technological transition and the technological operation as a whole. This requires finding the optimal number of machining stages when designing the technological process [3–14].

To solve this problem, it is necessary to analyze the influence of individual technological process parameters on the refinement coefficient of the workpiece at each stage.

The refinement coefficient of the workpiece at each machining stage largely depends on the load-bearing capacity of the technological system. It determines the magnitude of the error in the dynamic setup dimension. The greater the cutting force and the lower the rigidity of the technological system, the smaller the refinement coefficient of the dimensions at that machining stage. In turn, the components of the cutting force are largely determined by the cutting conditions, and many researchers suggest finding the optimal values for feed rate and cutting speed [15–17, 18, 19–26]. At the same time, decisions regarding the number of stages and the refinement coefficient of dimensions at each stage are made by the machining engineer, guided by their experience.

The task of determining the optimal values of the refinement coefficients at each machining stage is reduced to finding the conditions that ensure the shortest total machining time while achieving the specified dimensional accuracy. To optimize the magnitude of the refinement coefficient and determine the required number of machining stages, it is necessary to identify the degree of influence of the main parameters of the technological system on them.

The influence of the feed rate on the refinement coefficient in turning operations. Technological limitations that must be considered during turning operations include restrictions on the power of the machine's main drive, the strength of the feed drive mechanism, the maximum torque, and the strength of the tool holder and cutting insert. Technological limitations also include restrictions on the required accuracy and surface roughness of the machined surface. Additionally, there are limitations related to the design features of the machines, such as the ranges of feed values and spindle speed.

The search for the optimal option can be illustrated by an example of machining a cylindrical surface with a diameter of Ø60h10, length L = 40 mm, and a required surface roughness of Ra = 2.5 μm for a "Bushing" part made of steel 45 ($\sigma_i$ = 1380 MPa) on a 16K20T1 machine using a cutting tool with a T15K6 insert, 2101-0637, according to GOST 18883-73.

The required 10th grade from a 16th grade workpiece with a surface diameter of 60 mm can be achieved in 4 machining stages, with a refinement coefficient of 1 grade at each stage. The refinement route for this case can be represented as a sequence of grades: 16 → 14 → 13 → 12 → 10. The task of selecting the optimal number of machining stages and corresponding cutting conditions is reduced to a discrete problem of determining the shortest time path for refinement between the specified accuracy of the part and the workpiece.

The time required for each machining stage depends on the feed rate and the length of the working stroke. For feed rate values chosen in consideration of all restrictions, the main time for the corresponding stages is provided in Table 1.

*Table 1. Main time spent on machining stages*

| No | Machining stages, grade | Main time, min |
|---|---|---|
| 1 | 16→14 | 0,073 |
| 2 | 16→ 13 | 0,2 |
| 3 | 16→ 12 | 0,44 |
| 4 | 16→ 10 | 1,3 |
| 5 | 14 →13 | 0,093 |
| 6 | 14 →12 | 0,11 |
| 7 | 14 →10 | 0,8 |
| 8 | 13 →12 | 0,105 |
| 9 | 13 →10 | 0,5 |
| 10 | 12 →10 | 0,27 |

From Table 2, it can be seen that it is not always advantageous to work with the maximum permissible feed rate, as in this case, the accuracy requirements for the workpiece at each machining stage increase, leading to a higher number of stages. For example, if all machining stages are performed with the maximum feed rate allowed by the limitations, four machining stages will be required (refinement route 16→14→13→12→10), and the cycle time for automatic operation (Tca) increases to 0.708 minutes (see Table 2). However, choosing the minimum possible feed rate values, although it reduces the number of refinement stages, increases the time of each technological transition. For example, the refinement sequence 16→14→10 results in a cycle time ($T_{ca}$) of 0.953 minutes, although the number of stages is only two. In this example, the shortest cycle time ($T_{ca}$ = 0.573 minutes) is achieved with the refinement option over three stages – 16→14→12→10.

*Table 2. Options for forming machining stages*

| No | Refinement route, grade | Cycle time, min |
|---|---|---|
| 1 | 16→ 14→ 13→ 12→10 | 0,708 |
| 2 | 16 →13 →12 →10 | 0,695 |
| 3 | 16 →14 →12 →10 | 0,573 |
| 4 | 16 →12 →10 | 0,79 |
| 5 | 16 →14 →13 →10 | 0,786 |
| 6 | 16 →13 →10 | 0,78 |
| 7 | 16 →14 →10 | 0,953 |
| 8 | 16→ 10 | 1,3 |

Options with the intermediate 11th grade precision were excluded because the stage 11→10 requires a feed rate of 0.19 mm/rev, which exceeds the permissible limit for surface roughness.

Thus, determining the optimal number of machining stages should be accompanied by the optimization of cutting conditions (feed rate and cutting speed).

**The influence of tool wear on the refinement coefficient of the workpiece.** Tool wear leads to an increase in cutting force, which in turn changes (increases) the dynamic setup dimension of the specified part dimension. This change in the dynamic setup dimension causes an additional dispersion field of the performed dimension and deteriorates the machining accuracy.

To determine the extent of the influence of tool wear on the flank surface on the number of required machining stages, let us refer to the previous example of machining the part "Bushing," which has a surface Ø60h10. We will calculate the automatic machine cycle time according to the program ($T_{ca}$) for different refinement sequence options, assuming a wear value ($l_з$) of 0.8 mm, which is the criterion for the standard tool life.

The schemes of machining options with the indication of the time required for each stage are provided in Tables 1 and 2. Calculations using the direct enumeration method show that, in this case, the optimal option is machining in four refinement stages (refinement route: 16→14→13→12→10). This option results in a cycle time of **$T_{ca}$ = 0.708 minutes**.

If the calculations assume a minimum wear value of 0.05 mm, the time will increase by **24%**.

**The influence of the principal cutting edge angle on the optimal number of machining stages.** The cutting (cutting edge) angles determine the directions of the components of the cutting force. Consequently, changes in these angles alter the load on the feed drive mechanism and the carriage-part assembly. This can lead to additional elastic deformations in the machine elements and influence the refinement coefficient of the workpiece at different machining stages.

Figure 1 shows graphs of the changes in main time required to perform a single machining stage of a hypothetical surface, depending on the angle φ. The graphs indicate that changing the cutting angle from 30° to 90° increases the main time by a factor of 1.3 to 1.6. This confirms the practical recommendations of using tools with small principal cutting edge angles for rough machining. Figure 2 illustrates the dependence of the required number of machining stages on changes in the cutting angle. The graph confirms the appropriateness of using tools with cutting angles of 30°–45° for rough stages and angles close to 90° for finishing stages.

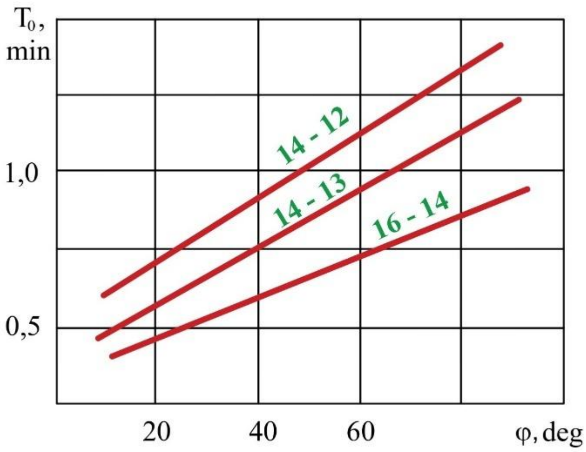


*Fig. 1. Dependence of the main time of execution of the rough stage of machining on the cutting angle of the tool*

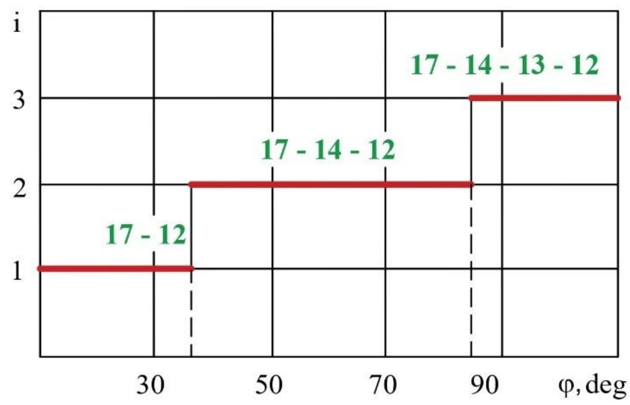


*Fig. 2. Influence of the principal cutting angle on the refinement route of the workpiece under the condition L/D ≤ 1*

As the rigidity of the technological system decreases, the nature of the influence of the cutting angle on the target function changes. This is because, with low rigidity of the technological system, the active limitation on the feed rate is determined by the accuracy of the dynamic setup dimensions. Figure 3 shows the dependence of the main time on the cutting angle during the machining of a part with an **L/D ratio of 10**, while Figure 4 presents the corresponding dependence of the number of machining stages on this angle. From these graphs, it can be observed that in the case of a low-rigidity technological system, using a tool with a cutting angle close to 90° results in shorter machining times, and the required accuracy is achieved in fewer refinement stages. These findings confirm the existing experience in machining parts, providing indirect validation of the proposed method for determining the necessary number of machining stages.

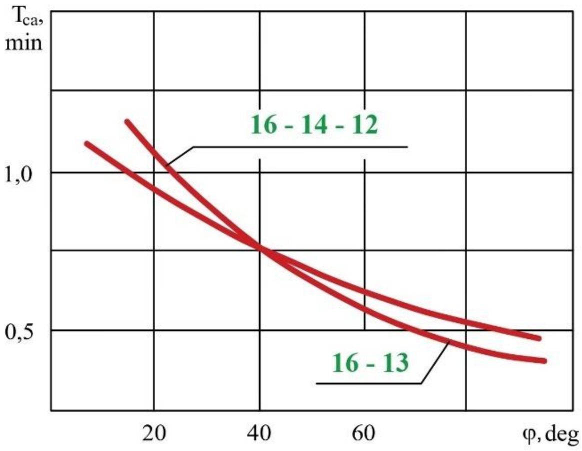


*Fig. 3. Effect of cutting edge angle on machining cycle time at L/D = 10*

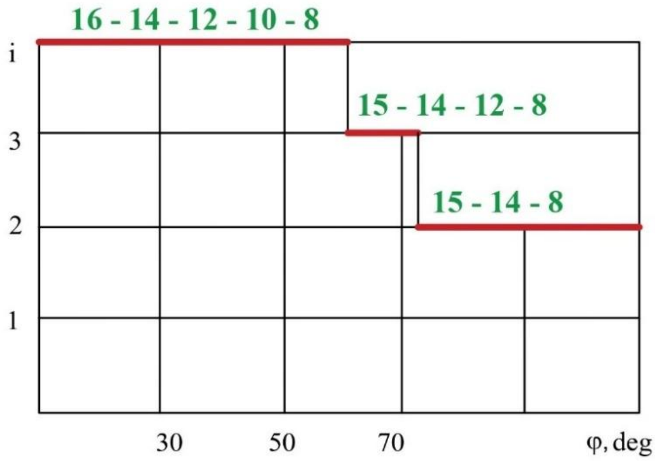


*Fig. 4. Influence of the cutting edge angle on the refinement route of the workpiece under the condition L/D = 10*

The influence of the strength properties of the workpiece material on the refinement coefficient at all machining stages. The intensity of stresses in the cutting zone, $\sigma_i$, most accurately characterizes the material's ability to resist the cutting process. This value is part of the formula for determining the cutting force and, consequently, directly influences the dimensional accuracy errors of the dynamic setup.

Figure 5 presents graphs showing the dependence of the main time required to complete a single machining stage on the stress intensity in the cutting zone ($\sigma_i$), obtained through calculations. The graphs indicate that the influence of $\sigma_i$ on machining efficiency varies across different refinement stages.

This is due to the fact that when determining the feed rate at different stages, different constraints may be active. For instance, at the finishing stages, the feed rate is limited by surface roughness requirements. In such cases, higher values of σi allow for the selection of larger feed rates, which consequently reduces the main transition time. This occurs because, at higher σi values, surface roughness decreases (at cutting speeds exceeding 100 m/min).

Figure 6 illustrates the influence of stress intensity on the refinement route of the workpiece.

Calculations show that as the rigidity of the technological system (j) increases, the refinement coefficient for all machining stages rises, while the number of stages decreases.

Since the values of $\sigma_i$ and the rigidity of the technological system are most often uncontrollable parameters, these dependencies can be used to determine the boundary values of σi and j for specific conditions.

Industrial Verification of the Methodology for Determining the Optimal Number of Machining Stages. The methodology was tested at sixteen enterprises. The verification involved assigning the calculated number of machining stages and their corresponding cutting conditions in the control program, followed by machining a batch of parts with these parameters according to the program. After each machining stage, the resulting dimension was measured. Based on the measurement results, distribution curves of the dimensions were constructed, and conclusions were drawn about the accuracy of the machining stage performed. The randomness of the sample parts was verified using the Pearson criterion.

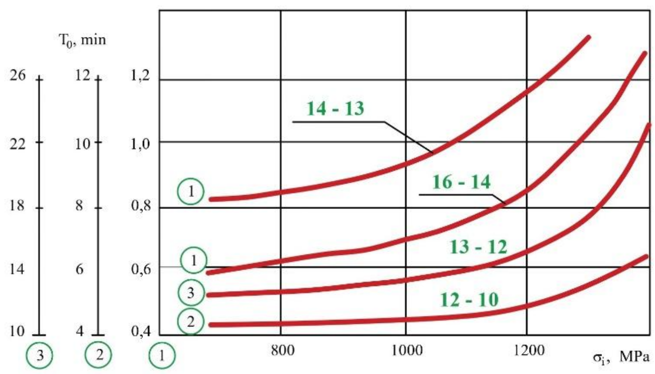


*Figure 5. Influence of the properties of the machined material on the main time*

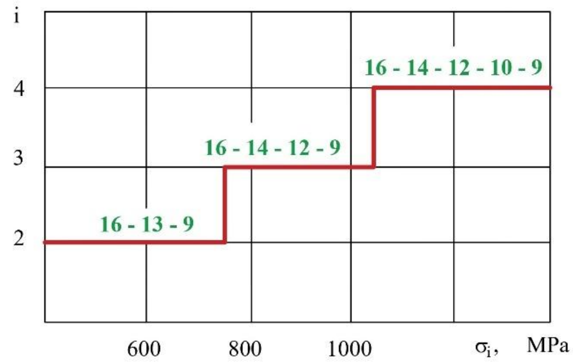


*Figure 6. The refinement route of the workpiece depending on the properties of the machined material*

Let us examine the data from the methodology testing on specific parts. Table 3 provides the machining parameters for the part "Bushing". Workpiece material: Steel 20. Machine tool: ATPr-2M12SN (АТПр-2М12СН). Cutting tool: T15K6 2102-0307 in accordance with GOST 6743-61 (Т15К6 2102-0307 ГОСТ 6743-61).

From Table 3, it is evident that the machining option with the optimal refinement route for the workpiece reduces the labor intensity of the technological transition by 24%.

To verify compliance with the specified grade at each intermediate machining stage, statistical control of the intermediate dimensions $Ø55_{-0,74}$ and $Ø52,4_{-0,3}$ was performed.

Figures 7 and 8 show the graphs of the empirical and theoretical distribution curves of the part dimensions after the roughing and semi-finishing stages, respectively.

*Table 3. Machining parameters of the "Bushing" part*

| Parameters | Refinement route, grades | Feed rate, mm/rev | Main time, minutes | Time for the complex, min. |
|---|---|---|---|---|
| Old parameters of machining | 16 ↓ 13 ↓ 11 ↓ 8 | 0,246<br>0,18<br>0,143 | 0,24<br>0,33<br>0,21 | 0,78 |
| New parameters of machining | 16 ↓ 14 ↓ 12 ↓ 8 | 0,45<br>0,34<br>0,10 | 0,13<br>0,174<br>0,29 | 0,59 |
| Labor intensity of the new option as a percentage of the current option. | 76,3% | | | |

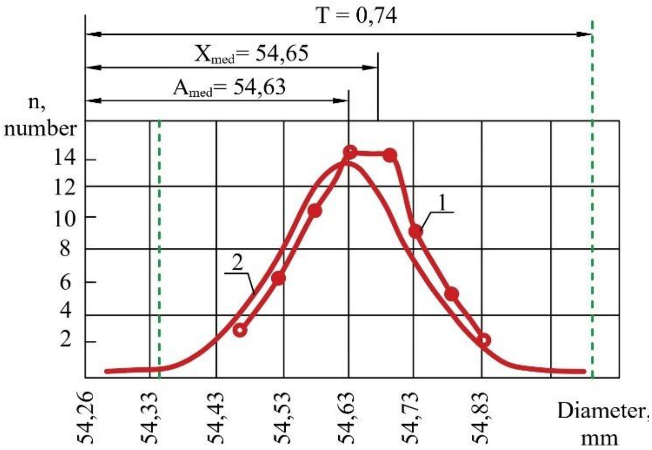


*Fig. 7. Graphs of the density of the dimension distribution after the roughing stage of machining dimension Ø55$_{-0,74}$: 1-empirical curve; 2-theoretical curve*

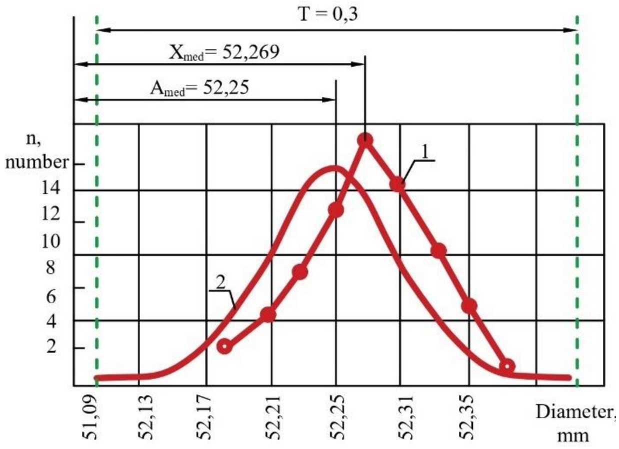


*Fig. 8. Graphs of the density of the dimension distribution after the semi-finishing stage of dimension Ø52,4$_{-0,3}$: 1-empirical curve; 2-theoretical curve*

An analysis of these statistical data shows that for the roughing stage, the standard deviation of dimensions (σ) is 0.103, and the operation accuracy coefficient ($\mu_o$) is calculated as: $\mu_o = 6\sigma / T = 0.835$, indicating sufficient process accuracy. The adjustment accuracy coefficient (l) is 0.027, while the allowable value of this coefficient under these conditions ($l_a$) is 0.0825.

For the semi-finishing stage (achieving the dimension Ø52.4-0.3), statistical control of dimensions revealed the following accuracy data: the standard deviation of dimensions is 0.0374, the operation accuracy coefficient is 0.748, the adjustment accuracy coefficient is 0.019, with its allowable value being 0.0378. These data confirm conditions for defect-free work: $\mu_o \leq 1$, $l \leq l_a$.

The achievement of the final part dimension Ø51.964-0.054 after the finishing stage was studied by the enterprise during a control operation, and the results showed positive outcomes.

Thus, it can be concluded that the new refinement route for the workpiece and the corresponding cutting conditions ensure the required machining accuracy and improve its productivity.

Table 4 provides the machining parameters for the part "Support" made of brass LS-59 (ЛС-59) on a 16K20T1 machine tool. The transitions considered include external turning of diameter

Ø23,93-0,14 from a stamped workpiece of Ø27(-0,5)^(+0,8), as well as boring transitions from diameter Ø17_(-0,8)^(+0,5) to Ø20+0,21 and from diameter Ø15_(-0,8)^(+0,5) to Ø18-0,18.

*Table 4. Parameters for machining the "Support" part*

| External turning $Ø23{,}93_{-0{,}14}$ | | | | |
|---|---|---|---|---|
| Parameters | Refinement route, grades | Feed rate, mm/rev | Main time, minutes | Time for the complex, min. |
| Old parameters of machining | 16 ↓ 13 ↓ 11 | 0,15<br>0,10 | 0.118<br>0,18 | 0,298 |
| New parameters of machining | 16 ↓ 11 | 0,16 | 0,11 | 0,11 |
| Labor intensity of the new option as a percentage of the current option. | 37% | | | |
| Boring $Ø18_{-0{,}18}$ | | | | |
| Old parameters of machining | 16 ↓ 12 | 0,10 | 0,10 | 0,10 |
| New parameters of machining | 16 ↓ 12 | 0,12 | 0,083 | 0,083 |
| Labor intensity of the new option as a percentage of the current option. | 83% | | | |

The results of the statistical control of dimensions are presented in Figures 9 and 10 as a comparison of empirical and theoretical distribution curves.

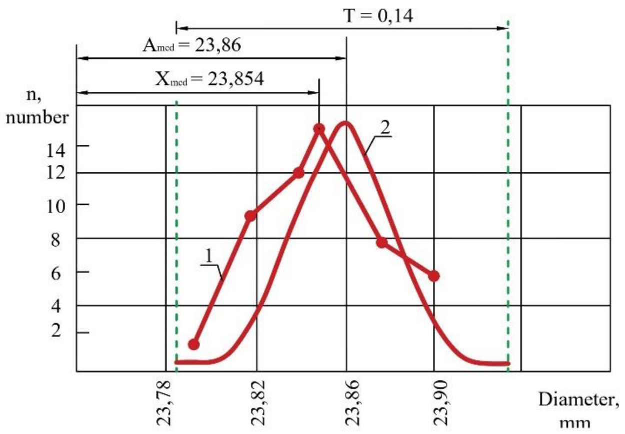


*Fig. 9. Graphs of the density of the dimension distribution after the semi-finishing stage $Ø23{,}93_{0{,}14}$: 1-empirical curve; 2-theoretical curve*

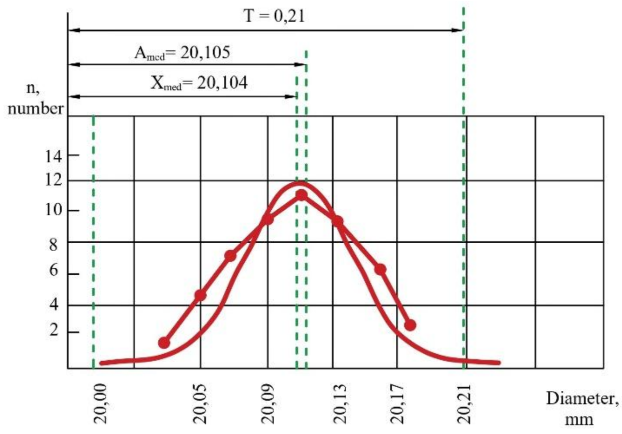


*Fig. 10. Graphs of the density of the dimension distribution after the semi-finishing stage $Ø20^{+0{,}21}$ 1-empirical curve; 2-theoretical curve*

For the external turning transition to $Ø23.93_{-0.14}$, the standard deviation was 0.0254, the technological transition accuracy coefficient was 1.0, and the adjustment accuracy coefficient was 0.043, with an allowable value of 0.045. An analysis of this transition shows that the feed rate in the new technological process variant can be reduced (since the labor intensity of the transition in the new variant is 37% of that in the old variant), providing an opportunity to increase the reliability margin for dimensional accuracy in this transition.

For the boring transition to $Ø20^{+0.21}$, the standard deviation is 0.039, the process accuracy coefficient $\mu_0$ is 0.97, and the adjustment accuracy coefficient l is 0.005, with an allowable value $l_a$ of 0.015. Similar results were obtained for thirty other parts from nine different enterprises.

**Conclusion.** The application of the optimal design methodology allows for a 15-18% increase in the productivity of operations performed in mass production and a 60-70% increase in small-batch and single-item production.

Thus, optimizing the number of machining stages, taking into account rational cutting conditions, enhances machining productivity and reduces the cost of the operation.

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