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Improvement of Base Sets for Complex Configuration Parts when Assessing their Manufacturability within Industry 4.0

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Annotation. Assessment of the manufacturability of products is carried out at the early stages of production preparation. The quality of this assessment significantly affects the efficiency of subsequent actions, including the development of technological processes and equipment operation. Currently, there is no accurate and complete description of the assessment methodology, which makes it dependent on the subjective experience of the technologist and prevents the creation of a formalized model. The purpose of this paper is to improve the quality of machining of complex configuration parts and the efficiency of manufacturing systems by developing new quantitative indicators of manufacturability. The paper presents a sequence of steps to create and calculate these indicators using the example of the part "Cover 2522-4202051". This process includes the formation of graphs of interrelationships between the surfaces of the part, taking into account the design bases and requirements to their geometric characteristics. The obtained information is transformed and formalized in the form of a database, which serves as a basis for defining new quantitative indicators of manufacturability. The result is a set of new indicators that allow to evaluate the conformity of the part design to the possibilities of using a single base when designing its manufacturing process. The proposed indicators provide analysis of the use of rational technological bases in the manufacturing process of parts and complement the existing indicators, providing more complete information on the compliance of the part design with technological processing methods and the efficiency of manufacturing systems.

Key words: production automation, basing, basis set, graph, dimensional analysis, Industry 4.0

Introduction

In recent decades, the advent of Industry 4.0 has ushered in a new era in the industrial landscape, marked by a profound focus on novel technologies and automation, instigating significant global transformations. Industry 4.0 embodies the integration of cutting-edge technologies such as the Internet, artificial intelligence, automation, and cloud computing into industrial and economic operations. Given its aspirations for modernization, the Republic of Kazakhstan stands among the nations diligently embracing the principles of Industry 4.0 across various sectors of its economy [1].

The manufacturing industry stands out as a pivotal domain where Kazakhstan endeavors to implement the tenets of Industry 4.0. Advanced automation and robotics technologies hold the promise of substantially enhancing production efficiency, curbing labor expenses, and elevating product quality. Notably, in sectors like automotive manufacturing, automated assembly lines and robotic systems accelerate production timelines while concurrently minimizing the occurrence of errors.

At its core, Industry 4.0 represents a paradigm shift in industrial and economic progress, underscored by the integration of cutting-edge technologies into manufacturing processes. Central to this transformative journey are Computer Numerical Control (CNC) machines. These sophisticated devices, facilitating automation and adaptability in production, play a pivotal role in realizing the vision of Industry 4.0 [2].

The complex of issues related to the assessment of production manufacturability of manufactured parts is at the forefront of the development of machining production machine-building systems. At present, the evaluation of manufacturability of manufactured parts directly depends on the technologist's (designer's) experience and subjective knowledge, which does not guarantee correct decision-making based on the knowledge of data on actively developing capabilities and on the real state of production. The assessment of manufacturability is used to display the relationship between the costs at the time of manufacturing a part and its design features, it has a contradictory nature, and also does not have an accurate and complete description of the procedure of carrying out [3-6, 11].

The main approaches to resolving the currently existing problems are:

- finding the weight values of individual manufacturability indicators depending on the characteristics of real production and the nomenclature of manufactured parts;
- expansion of the nomenclature of quantitative indicators of production manufacturability assessment, which are aimed at taking into account the used approaches to production preparation and the peculiarities of certain production complexes [7-9, 11].

The main purpose of the study is to improve the methodology for assessing production manufacturability on the basis of the formation of additional indicators, which, in turn, are interrelated with the constantly updated requirements for improving product quality, the production process itself, as well as the rational use of available equipment. The works [10 - 11] reflect the indicators that provide an opportunity to orient the evaluation of manufacturability on the design features of multi-nomenclature complexes of mechanical processing and that take into account the requirements of a particular production system, the conditions of formation of links between production manufacturability and its impact on the technological aspects of processing. The composition of additional indicators for assessing manufacturability for their application in the planning system of multinomial technological processes is presented [11].

1. Methodology

In mechanical engineering technology as a science, one of the fundamental rules, which is applied when assigning technological bases for the creation of technological processes, is the principle of unity and constancy of bases. Known indicators of manufacturability assessment do not provide an open and complete possibility for predicting the conformity of the manufactured part design to the potential possibilities of compliance with these principles when designing technological processes of their manufacturing. In order to solve this problem, it is necessary to create absolutely new indicators of quantitative assessment of manufacturing manufacturability, which should allow to form a conclusion about the reality of compliance with the principle of unity and constancy of bases in the process of technological process design and to estimate the value of this compliance [11].

Let us consider the proposed sequence of determination of the developed new indicators of quantitative assessment of production manufacturability on the example of the part “Cover 2522-4202051”. The part “Cover 2522-420202051” (Figure 1) is a part of the rear PTO shaft of MTZ - 2522 tractors, belongs to the parts of the type of bodies of rotation and includes external and internal cylindrical surfaces, ends, chamfers, holes, internal grooves.

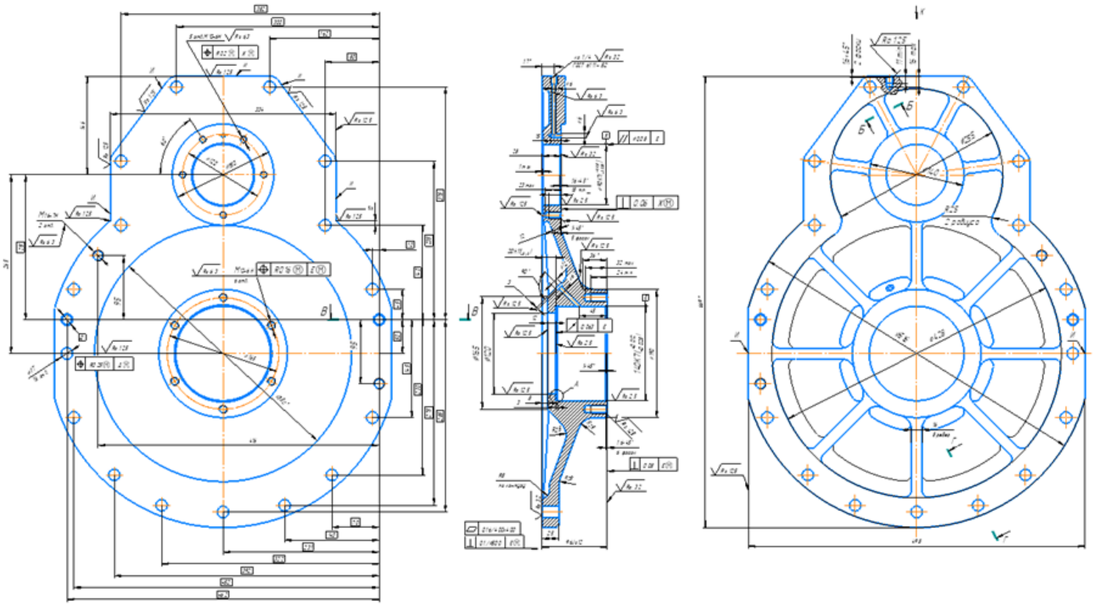


Fig. 1. - Drawing of the part "Cover 2522-4202051"

In order to fully analyze the structural properties of a manufactured part, first of all, it is necessary to determine the number of cross-sections in which dimensional relationships are formed, which open the possibility to reveal comprehensive data on the spatial and dimensional characteristics of various constituent elements of the manufactured part [11].

Modern manufacturing tends to apply advanced digital and intelligent technologies, including robotic systems. An important development trend in this area is the use of network-centric manufacturing networks. These networks allow efficient planning and execution of parallel manufacturing processes. Examples of such modern manufacturing sites include complexes of multifunctional CNC machines, 3D printers, and robots integrated into a network for optimal task execution [12, 13, 14-19].

Manufacturing process preparation (TPP) plays a key role in the part production process. It includes the solution of tasks to ensure manufacturability of the product design, design of technological processes, manufacturing of technological tooling and management of the production preparation process. In single and small batch production, standard automation methods such as element and process typing may be ineffective due to the high costs of preparatory work.

The construction of a simulation model of production processes and multi-criteria analysis on its basis are effective methods of selecting the optimal variant of technological process. The authors will use this model when evaluating the technological preparation of production.

Automation of production processes, including technological preparation, selection of sets of bases increases the efficiency of the enterprise and its competitiveness [12, 20]. Digitalization of processes reduces the time of production preparation and optimizes the total cost of manufacturing products. In addition, such automation allows adapting technological processes to changing conditions and promptly responding to them [12, 21].

When designing technological processes for manufacturing machine parts, dimensional calculations of the main output parameters of the technological process, as well as assessment of the accuracy of the technological process as a whole occupy a significant place in the whole set of works.

The dimensional analysis of technological processes is understood as a set of works on construction of special dimensional schemes, calculations of operational dimensional chains, determination of tolerances and allowances at operations, determination of blank sizes, evaluation of different variants of technological processes, etc.

Dimensional analysis is used for newly designed or existing technological process. In this case, the following tasks are solved:

a) to establish scientifically justified operational dimensions at all operations of the technological process;

b) to establish scientifically justified optimal dimensions of workpieces;

c) to ensure the design of technological processes with a minimum number of operations.

These tasks are solved with the help of dimensional chains. Dimensional chains, the links of which are operational dimensions and allowances, as well as the drawing dimensions of the processed part, are called technological [22].

Dimensional analysis of technological processes of part "Cover 2522-4202051" is presented in Figure 2.

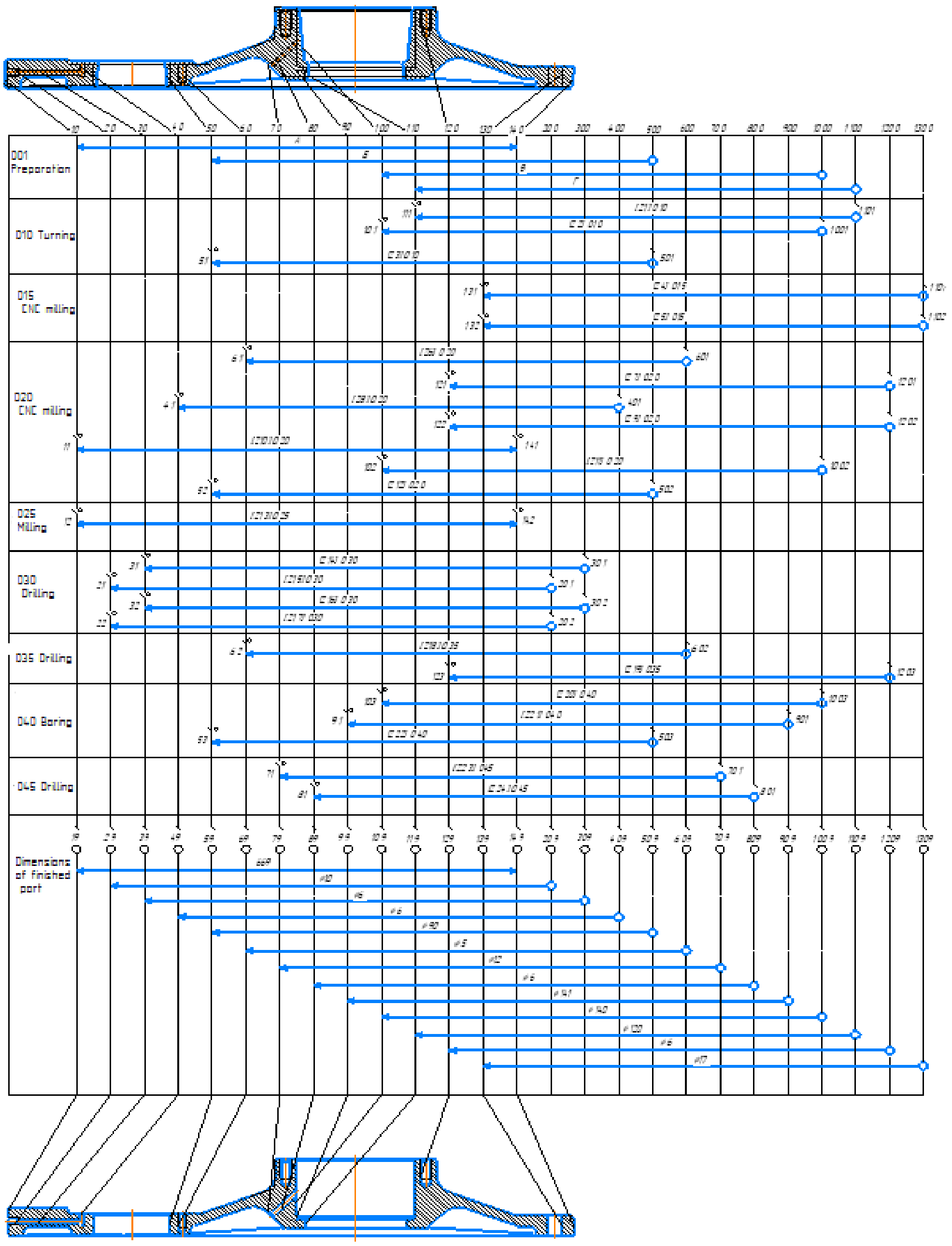
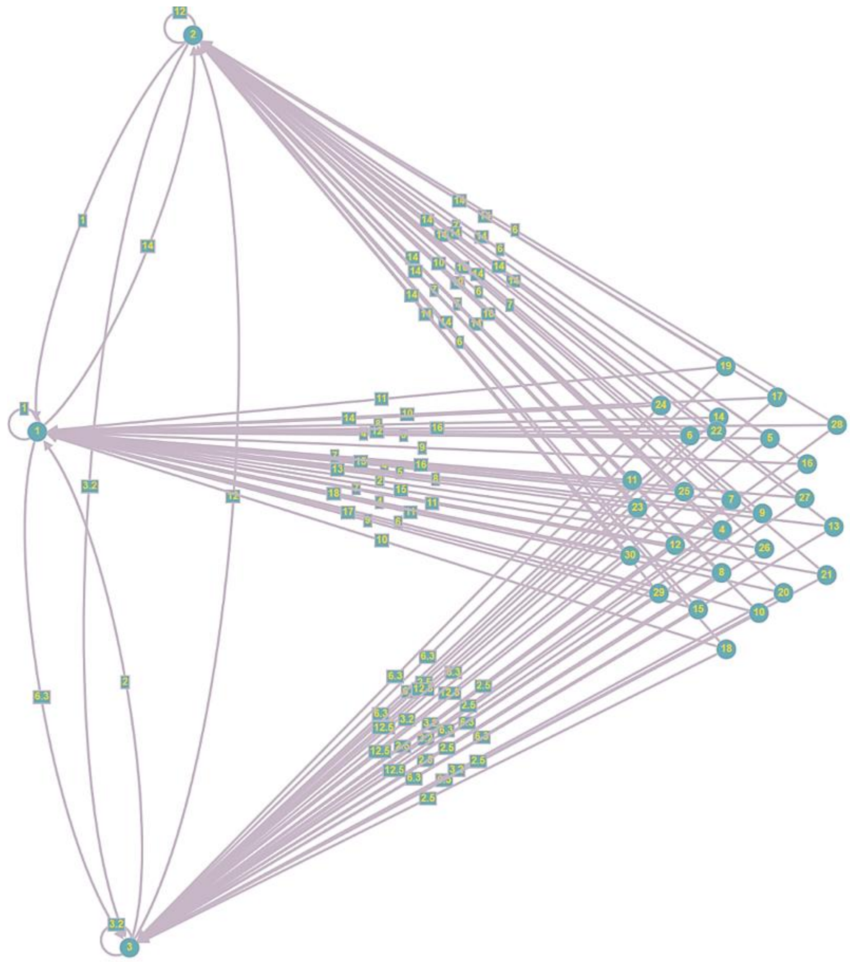


Fig. 2. Dimensional analysis of the technological process

The methodology for analyzing the similarity of design solutions within the framework of technological preparation of production relies on the formalization and comparison of design and technological solutions [12, 23-25]. The main concept in this methodology is a technological complex (hereinafter referred to as T-complex), which is a set of different typical surfaces. For these surfaces there is a common machining trajectory that allows them to be machined together. To each T-complex there correspond certain technological methods, which can be applied individually or in combination, depending on the production conditions and the required manufacturing quality.

T-complexes are characterized by the following features: types of incoming surfaces, production and operational quality indicators, as well as external attributes that determine the relationship of this complex with the others. These relations can be represented in the form of a graph model, where nodes are identifiers of selected T-complexes, and edges are corresponding links between them. The graph of links allows to estimate the constructive similarity in two ways: on the basis of the composition of T-complex models and on the basis of the structure of links between them [12, 26, 27].

From these positions, the part “Cover 2522-4202051” can be investigated using two views, respectively, one dimensional scheme, which is presented in the graph format in Figure 3 [22].



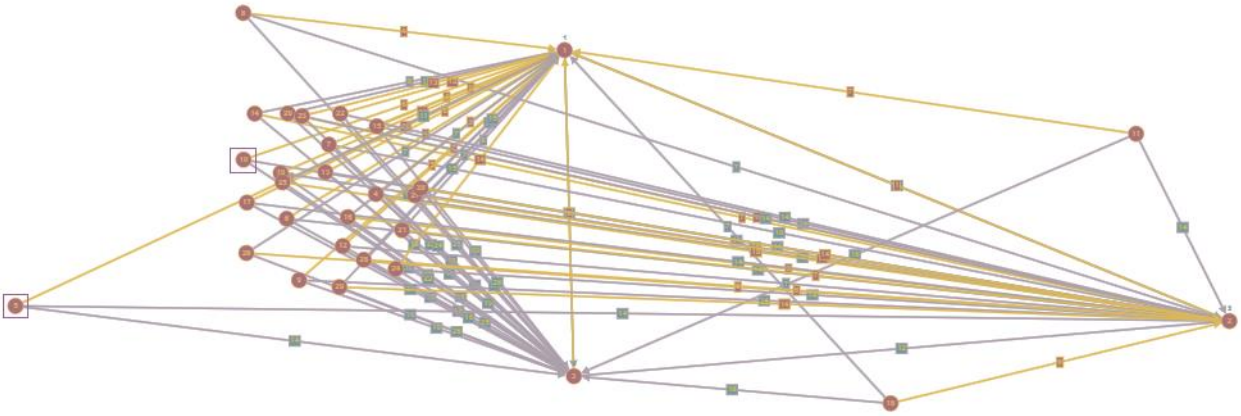
– symbolic designation on the graph, including: surface number on the design drawing, coding of elementary surface, regulated in the planning system of multi-nomenclature technological processes;

– accuracy characteristics of part surfaces

Fig. 3. Design graph for part “Cover 2522-4202051”

In order to assess the manufacturability of the manufactured part from the point of view of building predictive data on the level of meeting the requirement of unity of bases in the process of designing the manufacturing process, a necessary and obligatory condition is the study of information formed as a result of analyzing the operational design bases of parts during its operation directly in the assembly itself.

The part “Cover 2522-4202051” is a part of the rear power take-off shaft of MTZ-2522 tractors. These tractors are designed to perform a full range of agricultural work with mounted, semi-mounted, trailed machines and implements, loading and unloading equipment, with harvesting complexes, to drive various kinds of stationary special machines, as well as for transportation work in different climatic zones. The part is designed for connection with the body on one side and with the spacer on the other side. For the considered part the design bases are: surfaces 5 and 9 (Figure 4). To fix these data, additional designations for the surfaces of the part, which are the design bases and finding of the minimum spanning tree [11], are introduced into the constructed graphs.



☐ — basic design bases of the part "Cover 2522-4202051"

Fig. 4. A graph augmented with information about design bases and search for a minimal island tree

When selecting technological bases during the creation of technological processes, it is especially important to pay attention not only to dimensional characteristics, but also to the specified parameters that determine the requirements for the geometric shape of surfaces, for this purpose, the graph is saturated with this information. obtained from the design drawing of the part (Figure 5).

It is necessary to emphasize the requirement of the principle of unity and constancy of bases in the process of technological process development. For example, in addition to geometric and dimensional characteristics, it is necessary to take into account the constraints that are noted in the design documentation and set the limits of the mutual location of surfaces relative to each other. It is also important to consider the positional tolerance, which includes the mutual arrangement of the surfaces and the permissible deviation from the geometric shape. Based on the analysis of this information, the graph can be supplemented with the necessary data (Figure 5) [11].

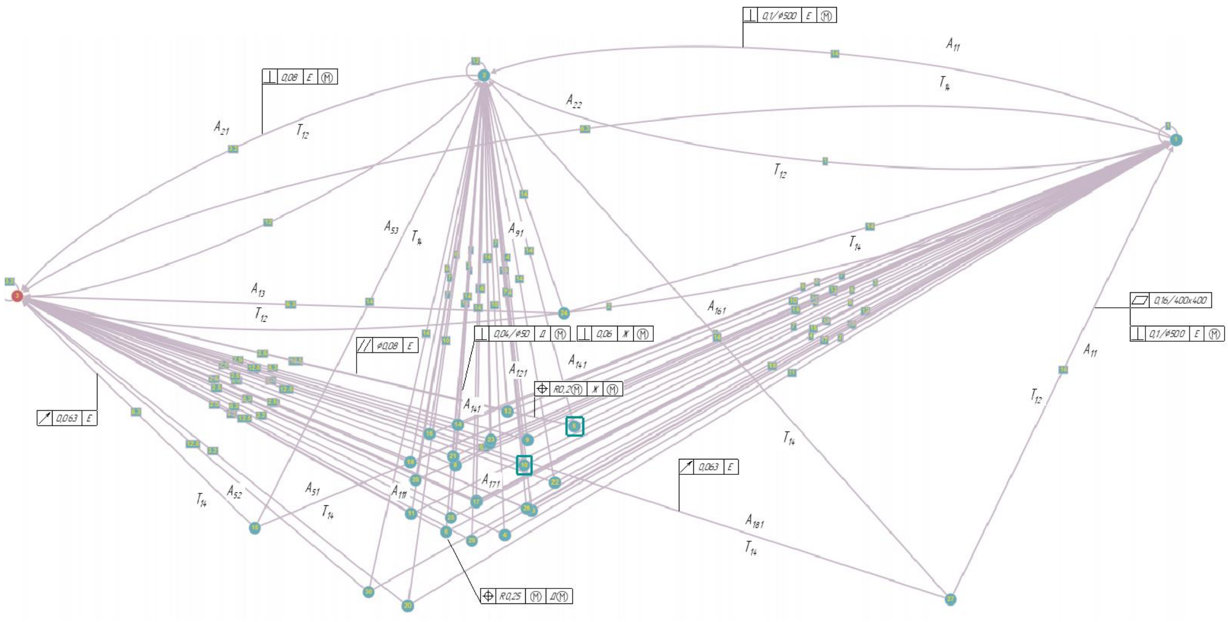


Fig. 5. Graph supplemented with information about the mutual arrangement of surfaces and positional tolerances of the part "Cover 2522-4202051"

The designed graph provides an opportunity for subsequent formalized processing of the generated information about the design characteristics of the manufactured part, without which it is impossible to perform the analysis of requirements satisfaction by the fact of assigning technological rational bases in the future development of the manufacturing process of the part. The obtained data are presented in the format of a relational database, which includes information about the relationships between all the elements of the manufactured part for each size and other norms presented in the design drawing [11].

The presented model of the sequence of data formation serves as a basis for the development of new quantitative indicators of production manufacturability, allowing to establish a relationship between the possibility of creating technological processes that meet the principle of unity and consistency of bases and design features of parts. It is used to propose an index of manufacturing manufacturability of a part, which reflects the possibility of compliance with the principle of unity of bases in the development of technological process in terms of evaluating the relationships between the surfaces of the part and the surface, which is the main design base:

$$K_{EO} = \frac{1}{M}\sum_{i=1}^{M} NO_i, \quad (1)$$

where M - total number of dimensions and requirements in the design drawing that define the relationship between the surfaces;

$NO_i \in \{0,1\}$ - presence or absence of relationship of each surface of the part with the main design basis established by the i-th dimension or requirement [11].

The index of manufacturing manufacturability of a part is proposed, which reflects the possibility of observing the principle of unity of bases in the development of technological process in terms of evaluating the relationships between the surfaces of the part and surfaces that are auxiliary design bases:

$$K_{EOB} = \frac{1}{M}\sum_{i=1}^{M} NOB_i, \quad (2)$$

where $NOB_i \in \{0,1\}$ indicates the presence or absence of interrelation of each surface of the part with auxiliary design bases established by i - size or requirement.

The calculation of the developed indicators of production manufacturability for the part "Cover 2522-4202051" has been performed: $K_{EO} = 0{,}95$, $K_{EOB} = 0{,}92$ [11].

2. Results and Discussions

The development of the technology for selecting a set of bases and basing technology is a solution to a complex complex problem. It is required to find the optimal variant of transition from semi-finished product to finished part that meets all the requirements of its service purpose [29].

Structural accuracy is justified by the conditions of workpiece operation in the assembly, machining capabilities and conditions for obtaining the initial workpiece. When machining on machine tools, the workpieces must be correctly oriented relative to the mechanisms and units of the machine, which determine the trajectories of movement of cutting tools. These include: guides; slides; milling and tool heads; copying devices and others. The tasks of mutual orientation of parts and assemblies in machines during their assembly and blanks on machines during the manufacture of parts are solved by basing. Basis is the provision of the required position of the product relative to the selected coordinate system. When applied to design or assembly, basing means giving the part or assembly unit the required position relative to other parts of the product. When machining workpieces on machine tools, basing is considered to be giving the workpiece the required position relative to the machine elements that determine the trajectories of the machining tool feed. Terms and definitions of the basic concepts of basing and bases are defined by the standard "Basing and bases in mechanical engineering".

The basis of the theory of basing is the concept of a non-free system studied in theoretical mechanics. According to these concepts, the required position or motion of a solid body relative to a selected coordinate system is achieved by imposing geometric or kinematic relationships. A free solid body has six degrees of freedom: displacements along the axes OX, OY, OZ and three rotations around the same axes. When geometric bonds are imposed, the body is deprived of a certain number of degrees of freedom and, if it is deprived of all six degrees of freedom, the body becomes stationary in the OXYZ system. Six connections, depriving the body of motion in six directions, are created by contact of connected bodies at six points. It is considered that the realization of necessary connections is achieved by contact of bodies on surfaces, and the existence of real connections is symbolized by reference points having theoretical character. To give a position to a body (using its planes of symmetry or axes of surfaces), the connections must be imposed directly on the planes of symmetry, axes, lines or points of their intersection. Reference point - a point symbolizing one of the workpiece or product relationships with the selected coordinate system.

To ensure the immobility of the workpiece or product in the chosen coordinate system, six bilateral geometric relationships must be imposed on them, which require a set of bases.

If the workpiece is to have a certain number of degrees of freedom, the corresponding number of degrees is removed. The theory of basing is general and applies to all bodies that can be regarded as solid, including mechanical engineering products in assembly and at all stages of the production process (machining, transportation, inspection, assembly, etc.) [28].

In order to solve the set tasks it is necessary to have the following initial data and materials:

1) assembly and working drawings of the product and the part;

2) specifications, accuracy standards and other data characterizing the service purpose of the part in the working machine, the requirements for the part, identified in the development of the technological process of assembly;

3) the number of parts to be manufactured per unit of time on the unchanged drawing;

4) the conditions in which the technological process should be carried out, the newly designed or operating plant, the composition of the equipment, the equipment of the plant, the equipment of the new plant, the equipment of the new plant. Information of this kind is very extensive and capacious, changing in time in a very short time.

To do this, the technologist needs large amounts of predictive information information information, and various data monitoring systems to be able to update them promptly [29].

Having established the refinements that must be provided between the surfaces of the part as a result of their processing, i.e. knowing the task, it is possible to proceed to the establishment of the sequence of processing of individual surfaces of the part, to the selection of technological bases in accordance with this and to identify the possibility of combining the processing transitions of different surfaces in time.

The most important reason for the lack of workable formal methods of assigning the schemes of basing, installation schemes and processing route of the workpiece, is the imperfection of the provisions of GOST21495-77; until now in the CIS countries there are still complaints about this GOST and disputes, but in numerous works devoted to the theory of basing do not describe the problems that are solved in basing, there is no clear distinction between the concepts of design and real basing, the theoretical scheme of basing and installation in the design, machining, assembly and co-processing.

One of the difficulties in the development of technological processes is the need to take into account the errors [30, 31] that affect the accuracy of technological processes. In this case, the errors arise, first, from the side of the process of development of the technology itself, and second, from the side of the production process [32].

The main causes of static adjustment error of dimensional and kinematic circuits of the technological system are:

1) incorrect choice of technological bases of the object being processed;

2) wrong choice of measuring bases and measuring method;

3) incorrect choice of method and means of static adjustment of dimensional and kinematic chains;

4) incorrect installation of cutting edges of the tool relative to the executive surfaces of the machine that determine its position;

5) incorrect installation and fixing of fixtures used to determine the position of the processed object and the cutting tool;

6) insufficient static (geometric) accuracy of the equipment, fixtures and cutting tools (manufacturing errors, condition, etc.);

7) insufficient qualification and errors of the equipment, fixtures and cutting tools.

The main reasons generating the error of dynamic adjustment of dimensional and kinematic chains of the technological system are:

1) heterogeneity of the material of machined objects;

2) fluctuations of machining allowances;

3) insufficient and variable rigidity of the technological system on the coordinate of relative movement of the cutting tool and the object being machined;

4) changes in the direction and magnitude of forces acting in the machining process;

5) quality and condition of the cutting tool;

6) condition of the equipment and fixtures;

7) temperature of the machined object, equipment, fixtures, cutting and measuring tools and medium, and especially its fluctuations;

8) properties, method of application and amount of lubricating and cooling fluid;

9) incorrect choice of methods and means for measuring the error of dynamic adjustment;

10) vibrations of the technological system;

11) insufficient qualification and errors of the worker or adjuster and a number of other reasons.

Let's consider the influence of installation error on the course of process design. In most cases, the causes of installation error of a machined object are: 1) incorrect selection of technological bases; 2) errors of technological bases (distances, dimensions, relative turns of geometric shape and roughness); 3) errors of the executive surfaces of the machine, fixture or workplace used to determine the position of the machined object; 4) incorrect use of the six-point rule in determining the position of the machined object; 5) incorrect force closure (creating insufficient magnitude, points and sequence of application); 6) incorrect choice of measuring bases, method and means of measurement; 7) unorganized change of bases in the process of fixing the machined object; 8) insufficient qualification of the worker and some others

One of the main reasons generating errors of installation, is the wrong choice of technological and measuring bases, especially at the first operation. Therefore, the role and importance of the first operation is considered first.

In the first operation of manufacturing a part from a workpiece, two main tasks are accomplished:

1) relationships are established that determine the distances and rotations of the surfaces that result from machining relative to the surfaces that remain unmachined;

2) the distribution of the actual machining allowances between the surfaces to be machined.

The correct solution of both problems has a decisive influence on the number of transitions and operations of the technological process, its labor intensity, cycle and cost of processing.

When solving the first problem, we are usually guided by the need to ensure that the part fulfills its service purpose when working in the machine. For some parts, their executive surfaces are left without machining due to the complexity of their shape, while the surfaces of the main and auxiliary bases are machined. If these parts are not machined to the required accuracy, the distances and relative rotations of the actuating surfaces with respect to the surfaces of the main bases, the parts will not fulfill their service purpose correctly.

Some parts have requirements that require these relationships to be established:

1) obtaining uniformity in the wall thickness of a part in order to provide sufficient strength or dynamic balance to the part.

2) Providing the necessary clearance between the free and other surfaces of two parts located or traveling a short distance one from the other when operating in a machine.

In solving the second problem, the first operation is guided by three basic considerations: 1) the need to maintain a dense homogeneous layer of material on the surfaces of the part subjected to the most intensive wear during its operation in the machine, in order to increase their wear resistance; 2) the need for uniform distribution of the machining allowance on each individual surface and primarily on the encompassing and internal surfaces (grooves, cast holes, etc.);

3) the need to increase the productivity of machining by reducing the amount of material to be removed in the process of machining.

The necessity of uniform distribution of machining allowance on each of the surfaces, especially on covering and internal surfaces, is explained by the fact that non-uniform allowance always generates fluctuations of cutting force, causing vibrations and elastic movements in the technological system, generating an increase in the error of dynamic adjustment of dimensional and kinematic chains.

The result is an increase in random machining errors, obtaining incorrect geometric shape of machined surfaces, increase in the size dispersion field, increase in surface roughness, etc.

The need to reduce these errors forces to carry out machining at reduced modes or to introduce additional passes or even whole transitions and operations into the technological process, which is associated with loss of productivity and additional costs.

The need to ensure uniform allowance on internal surfaces (surfaces of grooves, holes, etc.) is primarily due to the fact that the dimensions of holes and grooves limit the geometric dimensions of cutting and auxiliary tools, in particular, mandrels, boring bars etc.

The resulting insufficient rigidity of the tool forces machining at reduced modes or with a large number of passes or transitions, often associated with the change of cutting tools, which causes an increase in labour intensity of machining.

Uniformity of the allowance on the surfaces of parts allows: 1) improve machining accuracy at the first operations and thus reduce the number of passes and transitions; 2) reduce energy costs and equipment amortisation, as machines with lower motor power can be used; 3) increase machining productivity at subsequent operations.

When distributing the machining allowance between several surfaces, especially parallel ones, the largest part of it should be removed from less critical surfaces with smaller overall dimensions, if possible.

All the above tasks are solved at the first operation by correct selection of technological bases.

In order to economically produce good parts, it is necessary to study the influence of all the above factors on machining accuracy in order to be able to manage them to achieve the task by increasing the refinement given by the technological system. Information about these errors is individual - it is specific to a particular plant, process and process system, and is also time variable. To obtain this information requires its collection on the basis of the past and current state of the plant, its analysis and systematisation. At the same time, some of the information changes instantly and cannot be systematised or depends on third-party producers [29].

Installation error is the deviation of the actual position of the workpiece or product achieved during installation from the required position. Basis error is the deviation of the actually achieved position of the workpiece or product during basing from the required position. The required position of the workpiece (product) is understood as such a position of the setting elements that the coordinate system of the workpiece coincides with the coordinate system of the machine or fixture. When machining a batch of workpieces on a tuned machine tool, it is not the actual basing error of each workpiece that is considered, but the basing error - the size dispersion field of all workpieces, which has the smallest and largest limit values. The maximum possible datum errors can be determined for each datuming scheme by calculation [28].

The datum error δb (Figure 6) is characterised by the limit positions of the workpiece bore axis Z_1 relative to the fixture pin axis Z:

$$\delta_{b\ max} = 0 \pm (D_{max} - d_{min}) / 2 \quad (3)$$

The scheme of cylindrical workpiece installation in the prism for bald milling is shown in Figure 7.

The two circles show the smallest and largest diameter of the workpiece in the batch with axes C‘ and C’‘, When making a dimension, the basing error is determined by the difference in the limiting dimensions from the measuring base (formers A’ and A‘’) to the tool set to the dimension (point A‘’) [28]:

$$\delta b\ h_1 = OA' - OA'' = TD/2\ (1/\sin\alpha/2 + 1),$$

By analogy for dimensions h_2 and h_3:

$\delta b\ h_2 = TD/2 \cdot (1/\sin\alpha/2 - 1)$; $\delta b\ h_3 = TD/2 \cdot 1/\sin\alpha/2$

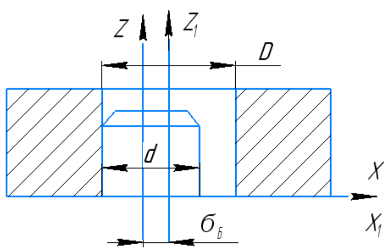


Fig. 6. – Occurrence of a datum error:
Z - fixture coordinate system; Z_1 - workpiece coordinate system

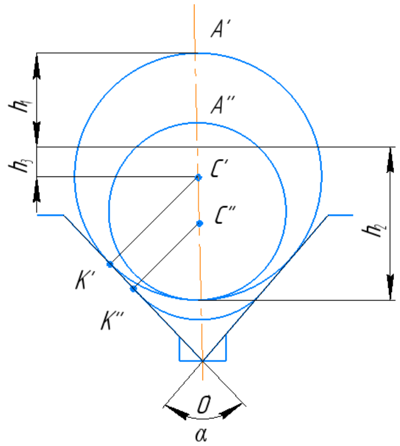


Fig. 7. – Occurrence of basing errors

The basing error can be reduced and even eliminated either by selecting a more correct basing scheme or automating the process, or by making the base elements of the fixture more accurate to the workpiece itself (base hole diameter). For example, mandrels with a taper of 1.5° ... 5.0° are used in order to eliminate the gap in the joint, for example, unclamping mandrels of collet and cam type or hydroplastic mandrels.

The clamping error is caused by the displacement of the workpiece or its elastic deformations under the action of clamping forces. Due to fluctuations in compressed air pressure in the network, oil pressure in hydraulic systems, fluctuations in magnetic, electromagnetic or manual clamping forces, clamping forces are not constant. Elastic forces are also variable due to variations in physical and mechanical properties and dimensions in workpiece cross-sections. In the practice of predicting the clamping error, the data of average error scatter fields for typical fixtures are given. This error, like the basing error, is only part of the total fixture error. The scattering field of installation error is equal to the sum of scattering fields of all errors: basing, clamping and fixture [28, 33, 34].

A great contribution to the development of the school of computer-aided design was made by scientists Shvoev V.F., who was directly engaged in the development of methodology of systems of computer-aided design of technological processes of mechanical processing, Zhetesova G.S. - development of mathematical models and software for design and technological support for the production of mining equipment, Nikonova T.Yu. [35] - development of mathematical models and software for processing by methods of plastic deformation, Yurchenko V.V. [29]- was engaged in the development of systems of computer-aided design of technological processes of mechanical processing of parts of mining machines. However, so far, as the analysis of existing CAD systems has shown, the possibility of objective decision making has not been solved.

Thus, based on the analysis of the theoretical foundations of technology design and computer-aided design systems, the following conclusions can be drawn:

- the solution of the majority of automated technological design tasks is based on the use of professional knowledge and experience of the designer, i.e. trained and constantly improved specialised human intelligence;
- the formulation of the overwhelming number of design tasks is difficult or non-formalisable;

- decision-making is based on the use of TTP, GTP and CTP;
- the existing theoretical and methodological bases of design do not allow to develop CAD TA that meet the requirements of modern production [29].

Conclusions

The developed quantitative indicators for the assessment of manufacturing manufacturability significantly deepen and expand our knowledge gained in the process of working with manufactured parts. They help to take into account the peculiarities of technological preparation, especially in the conditions of production of diverse products, which makes them indispensable in modern industry.

The obtained results and created forma lised methods of using new quantitative indicators allow making forecasts at early stages of formation of technological processes of parts manufacturing regarding the probability of using optimal technological bases. Together with the already existing indicators they provide a more detailed view of the compliance of the design of manufactured parts with the requirements and processing methods, which allows making more accurate and well-founded predictions about the performance of production systems in the manufacture of specific parts.

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