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CONSIDERATIONS REGARDING THE OPTIMAL DIMENSIONAL DESIGN OF MACHINING TECHNOLOGIES

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Abstract: *The paper discusses the design methodology of the technological processes of mechanical processing, taking into account the fact that these processes are determined by the interaction in tolerances of four distinct systems such as the part, the blank, the technological process and the technological system, each of which has its own dimensional structure. Formally, geometrically, the optimality of the technological process is determined by the similarity of the graphs of the technological and constructive dimensional relations. The dimensional structures with the fewest elements in the dimensional chains are optimal because each of these elements causes an increase in the tolerance of machining allowances removed in the next technological phase and affects the technological assurance of the process.*

Key words: *optimality, dimensional structure, dimensional chain, tolerance, technological assurance, machining allowance*

1. INTRODUCTION

The traditional technological design, as well as the one assisted by the computer (Computer Aided Process Planning - CAPP) can be defined as a function of transforming the specifications of the constructive project into a set of sequential specifications in time - technological process of processing a part from a initial semi-finished form into a good final for assembly form. Process sequences are described as organization (structure), as parameters, as machinery and tools used. The selection of technological bases and the optimal allocation of technological tolerances are critical in any machining process planning. To reduce the machining time and cost, an optimal process plan must be developed [1].

With the use of sophisticated CNC machine tools associated with higher labor costs, concurrent optimization of machining process parameters and tolerance allocation plays a vital role in manufacturing parts economically. Thus, efforts to simultaneously optimize the dimensional structures of the part and the technological process are fully justified [2, 3, 4].

The approach in tolerances is one of the important aspects both for the functionality of the part and for its manufacturing cost, being a key technique in the integrated environment of computer-aided design and computer-aided manufacturing [5]. The authors note that conventional design and manufacturing systems involve two sequential and separate stages of tolerance design procedures. The first aspect is relevant to dimensional tolerances of product parts, and the second is relevant to dimensional tolerances formed in the manufacturing process.

The tolerance approach plays an important role in the product design and manufacturing processes. Allocation of technological tolerances is a design tool to reduce the total cost of production while ensuring the required level of quality [6, 7]. Specifying of the tolerances is an important part of mechanical design. Constructive dimension tolerances strongly influence the functional performance and manufacturing cost of a mechanical product. Smaller tolerances normally produce higher quality, functionally better performing mechanical systems. At the same time, smaller tolerances lead to excessive production costs for a given application. Balancing performance and manufacturing costs by identifying optimal constructive tolerances is a major concern in modern designing [8]. Machining process optimization techniques were adopted with three combined objectives: minimization of tolerance summation, minimization of manufacturing costs, and minimization of quality loss.

One of the graphical tools used to determine the working dimensions and their tolerances is the tolerance chart. The identification of dimension chains is an important step in the tolerance chart methodology. Optimization of process parameters is another area of interest in the allocation of tolerances. The aim is to find the parameters that minimize the total manufacturing cost, with a constraint on the tolerances [6, 7].

Usually, to solve these problems, the tolerance chart and effective methods of tracking the dimension chain are used, thus establishing the relationship between the machining data and the allocated tolerances [9]. The main purpose of the tolerance chart is to determine the working dimensions and to optimally allocate the tolerance values to the working dimensions, so that the cost objectives are met.

It can be noted that the analyzed works do not take into account the technological system inside which the dimensional interaction in tolerances manifests itself during machining.

2. SYNTHESIS OF OPTIMUM COMPLEX TECHNOLOGICAL DIMENSIONAL STRUCTURES

In engineering, synthesis is usually called a design procedure, as a result of which different elements are combined into a single whole: a system, a machine, a device, a process, etc. In technical sciences, the extension of the concept of synthesis is usually divided into three components: design synthesis, parameter synthesis, and structure synthesis. Procedures of the latter type are among the most complex and least studied.

In modern conceptual design models, the synthesis of new technological solutions is based on the determination of the relationships between the function of the developing technology and its structure for manifestation under the given conditions. The technology must achieve functionality in accordance with the formulated objective. Thus, the technology determines the composition of the structural elements, which, being assembled through connections, constitute the actual technology [10, 11].

The notion of technological function is known, which refers to the ability of a technological system to perform a technological task under certain conditions. The problem is to develop a structure of technological process that fulfills the given technological function and corresponds to a set of additional conditions. The development of this synthesis model can be done by the method of directed graphs, which is one of the most effective methods of structural synthesis.

The part for which the technological process of mechanical processing is designed is characterized by the constructive dimensional structure that reflects, first of all, its functionality. The nature of the constructive dimensional structure is defined by the designer who takes into account the technological assurance with machine tools, but not at the expense of the functionality of the part.

One of the most complicated problems during the development of the technological manufacturing process is the synthesis of the dimensional structure. It is necessary to do not only the dimensional analysis of a developed technological process, but also to create an optimal dimensional structure on this basis.

Constructive, technological dimensional structures and those of technological systems can be successfully represented by graphs, which reflect each dimension and its tolerance, as well as the position in the dimensional chains.

The analysis of the dimensional structures, the allocation of technological tolerances, the determination of the tolerances of the machining allowances (Ad) is carried out, as a rule, by means of the tolerance diagrams with the solution both in the "maximum - minimum" and in the "maximum - minimum with error compensation effects" [10, 11].

In the technological design, the constructive dimensional structures of the object-type part and blank and the process-type dimensional structures of the CNC technological system and of the designed technology interact and form a single system (fig. 1).

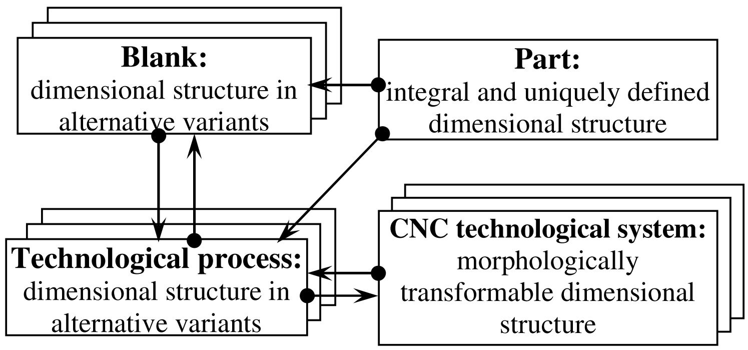


Fig.1. Interaction of objects - factors at the design of dimensional technological structure

The constructive dimensional structure of the piece is unique and integral and represents the starting point for the technological design. This structure is not one to choice, but it can be modified within the limits of respecting the functionality due to the necessity of technological adaptation, becoming unique and integral again. Equivalent changes can also be made in the dimensional structure of the part so that the critical dimensions (participating in the assembly) are not altered in the sense of precision.

At the same time, the constructive dimensional structure of the semi-finished product is one in alternative versions. The representative variants are chosen in such a way that the transition from one variant to another changes the precision and, consequently, changes the number of technological phases necessary for processing the surfaces. This fact substantially changes the results of technological design. The dimensioning of the blank is done in accordance with the particularities of its methods of obtaining, in one variant some dimensions may be present, and in another they may be missing. Within these particularities there is no reason to size the blank differently from the part. Thus, the constructive dimensional structure of the blank in the variants will be similar to the dimensional structure of the part.

In CNC machine tools, tool movements can be programmed relative to the origin of the coordinate system (absolute coordinate system), or relative to a specially selected origin - usually on the base surface of the device or, as the case may be, of the part (floating coordinates), or each time in relation to the previous position of the tool (relative or incremental coordinate system). Regardless of which coordinate system is used in programming, the machine tool control unit will convert it to the absolute coordinate system. In other words, a CNC machine tool uses a unique measuring system to control the movement of the tool. This means that the nominal value of the tool movement, after a series of movements, is equal to the sum of the nominal values of the movements.

From what has been related, it can be seen that the dimensional structure of the CNC technological system is morphologically transformable (fig. 2). The distances between the base points are programmable in absolute coordinates in relation to a position considered "zero" (1-3, 1-2, 1-4, 4-5, 4-6, 4-7, 12-11, 12-10) and in relative coordinates (4-7, 7-12, 12-11, 11-9, 9-8). Branch positions (1, 4, 12) can be saved as "floating zero". In technological terminology, each specific position is associated with the locating datum surface (LDS), and the distances between the positions with the formed technological dimensions.

Thus, the dimensional structure of the technological process can be created from elements - nodes presented in the CNC dimensional structure. If we consider the association of the structural elements of the technological system in the time, we can ascertain the existence of a dimensional structure of the technological system.

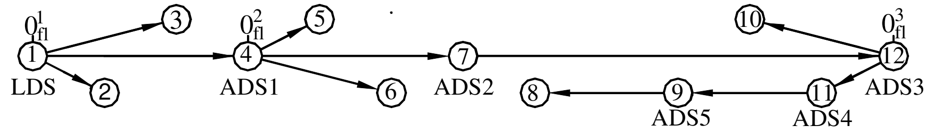


Fig.2. Dimensional structure of the morphologically transformable technological system. LDS - Locating Datum Surface, ADS - Adjustment Datum Surface, 0_{fl} - floating zero

It can be concluded that an integral dimensional structure of the technological process is optimal if it is similar to the constructive dimensional structures of the piece and the semi-finished product and is fully ensured by a similar dimensional structure of the technological system. In the work [12] the optimality of the dimensional structure of the technological process was conditioned by the similarity of the technological dimensional structure with the constructive dimensional structure of the piece, so that each constructive dimension $B_c(T_{Bc})$ is formed exclusively by its own technological dimension $B_t(\omega_{Bt})$ (fig. 3). This optimal technological structure ("how?") must ensure the shortest possible path to the realization of the constructive dimensional structure of the part ("what?"), starting from the dimensional structure of the blank ("from what?"). Technological assurance is provided by the CNC technological system.

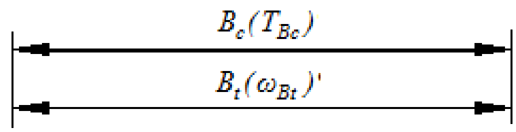


Fig.3. Optimal elementary dimensional structure [12]

Figures 4 and 5 show examples of technological dimensional structures created respecting the principle of similarity with the constructive dimensional structures of the part, blank and of the technological system.

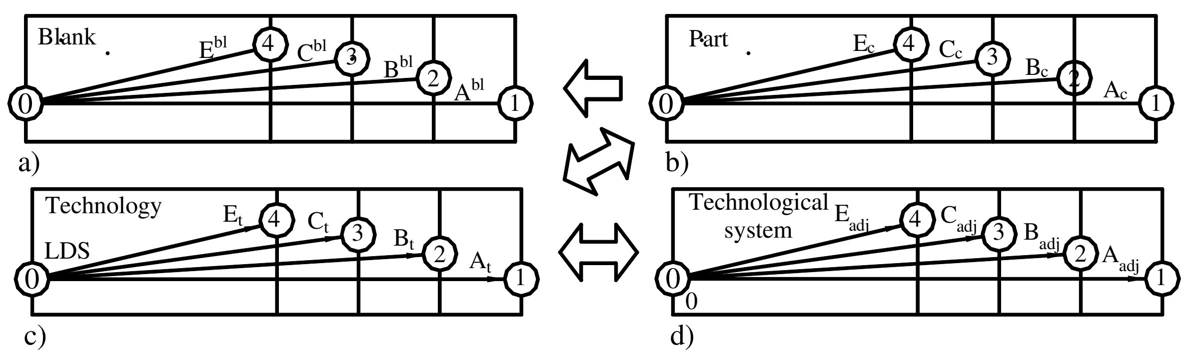


Fig.4. Examples of similar dimensional structures, variant of dimensioning from a single locating datum surface: constructive, technological and "zero CNC"

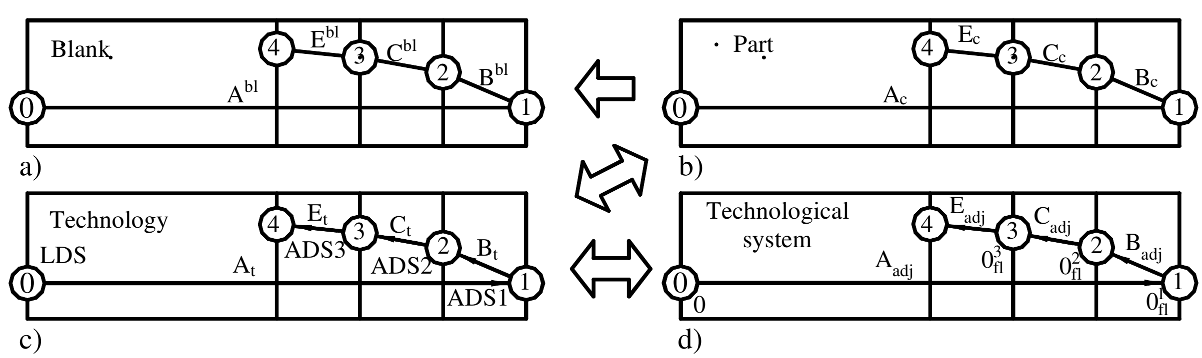


Fig.5. Examples of similar dimensional structures, variant of dimensioning in chain from the locating datum surface: constructive, technological and "zero CNC"

Dimensional structures are represented by not oriented (constructive for the part and blank) and oriented (for the technology and technological system CNC) graphs.

The synthesis of the technological dimensional structure begins with the analysis of the constructive dimensional structure of the piece in the form of a graph of linear constructive dimensional links (fig. 6). Based on this graph, the graph of technological dimensional links is elaborated respecting the principle of similarity of graphs, a principle that ensures the optimality of elementary technological dimensional structures (fig. 7). Through this similarity, the objective of having an optimal technology is formulated. Thus, each constructive dimension is formed by its own technological dimensions ($A_c \equiv A_t$, $B_c \equiv B_t$, $C_c \equiv C_t$,...). At the same time, there is a check of technological support, i.e. if the graph of technological dimensional links includes dimensional structures that can be created by the technological system.

The graph of linear technological dimensional links reflects the dimensional structure

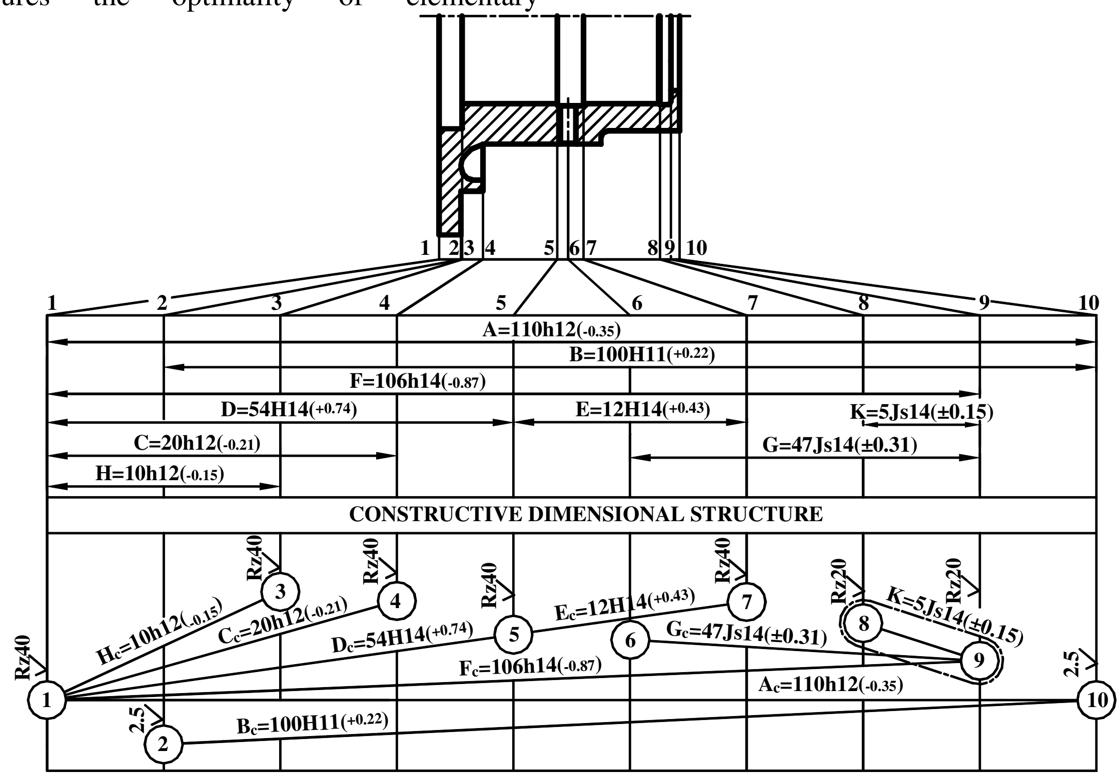


Fig.6. Constructive dimensional structure of the part in the form of an undirected graph (case study)

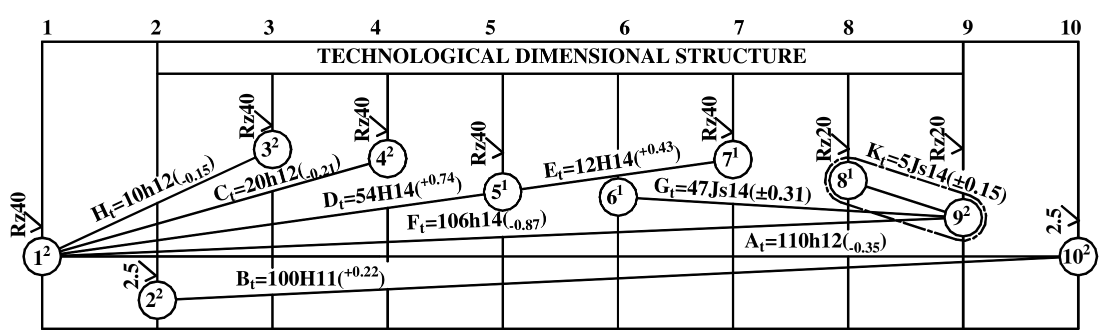


Fig.7. Technological dimensional structure in the form of an undirected graph similar to the constructive one (case study)

of the designed technology, but more specifically the number of states of the processed surface, which is equal to the number of technological elements carried out to form the target technological dimension. It is observed that when processing a certain surface, all the dimensions given from this surface are changed, but only one of them is the target dimension.

The next stage is the synthesis of technological dimensional structures on installations. The installation is that entity of the technological process, where the complex dimensional structures are formed from primary elements, as shown in figure 8. Within the installations, the dimensional relationships between the formed technological dimensions, their tolerances and the tolerances of machining allowances are established. Also within the installations, the beneficial effects of error compensation for precision are manifested more stably. The dimensional structures of the installations can be "assembled" as finite entities or they can be developed at other installations. In the case of machining on CNC machine tools and machining centers, the "assembly" of dimensional structures formed at different installations is often produced automatically with technical resources of the technological system (without human intervention) and with high precision.

One of the main problems of the installation is the choice of possible orientation and fixing schemes. In the graph of technological dimensional links, the locating datum surfaces represent a beginning of chaining or bifurcation of the technological dimensions formed and ensured by the CNC technological system. The graphs of constructive linear dimensional links have the ability to suggest the most correct solutions in this sense. The graph presented as an example in figure 6 has two poles 1 and 10 correlated by the A_c dimension. Surfaces 1 and 10 can and must be used as installation bases with action in the direction of the formation of technological dimensions.

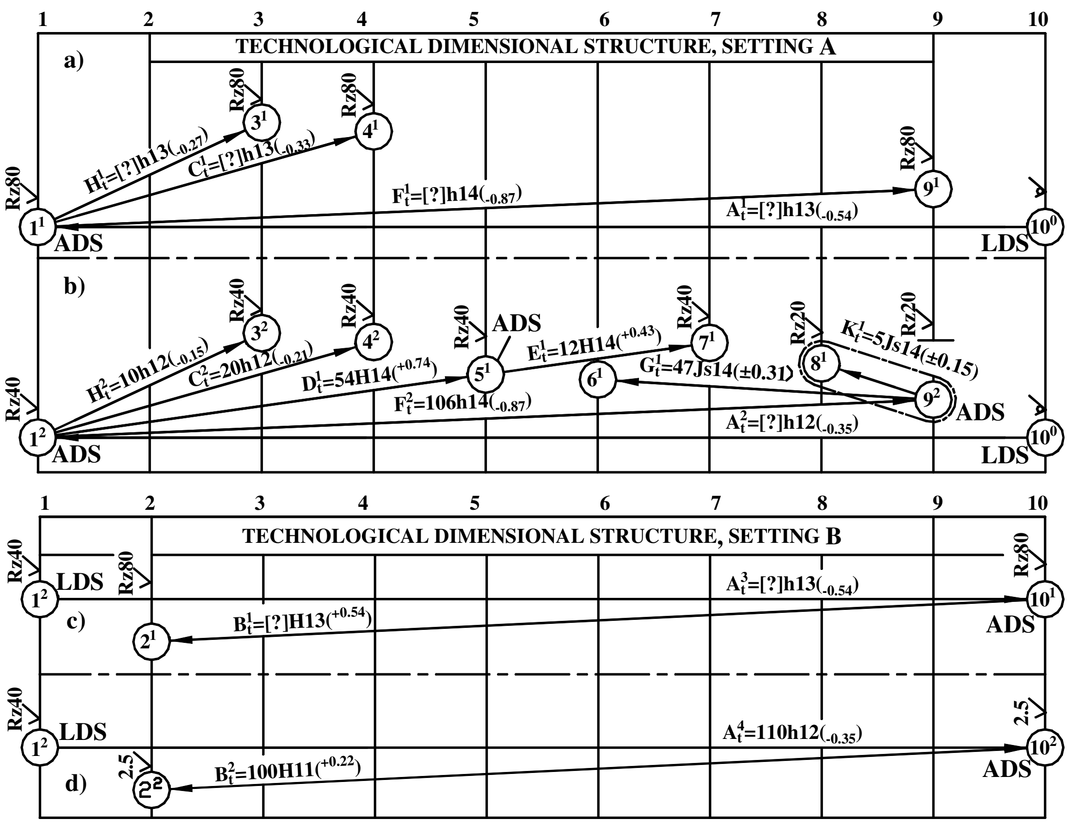


Fig.8. Technological dimensional structures in the form of oriented graphs divided by installations and groups of technological elements (case study)

Figure 8 shows the graphs of the linear dimensional relationships for two installations with their division into size groups formed by technological elements of increasing precision. At the first installation as the locating datum (LDS) the surface 10 is taken in the initial state 0 on the blank (10^0).From this base the dimension A_t^1 is formed. Surface 1 in state 1 (1^1) becomes the adjustment datum (ADS), from which the technological dimensions (H_t^1, C_t^1 and F_t^1) are formed (fig. 8,a). In CNC terms the nominal position of the newly formed surface 1^1 represents a floating zero. The second group of technological dimensions is formed in the same regime, except that the technological dimensions (D_t^1, E_t^1 and G_t^1) are added, which must be formed in relation to surface *1* definitively machined (1^2). The dimension K_t^1 is not formed by adjustment and is determined by the width of the machining tool.

3. OPTIMUM MACHINING SCENARIOS

The technological process is designed in the form of a not oriented graph of technological dimensional links similar to the graph of constructive dimensional links. This graph, in fact, reflects the state of the precedents technological dimensions in a chronological sense. In reality, in the technological process intermediate technological dimensions are formed, which are characteristic of the series of technological elements. There is a need to constitute intermediate dimensional structures reunited in installations. This can be done in variants, each of which represents specific conditions for ensuring accuracy.

From a geometric point of view, the similarity of the graphs of the constructive and technological dimensional links reflects the elementary structural optimality - a constructive dimension is formed by a series of its own technological dimensions (fig. 9). This series also includes machining allowances as component elements of dimensional chains. Machining allowances have a geometric (nominal, tolerance) and structural character and are elements of connection and influence between different dimensional technological chains.

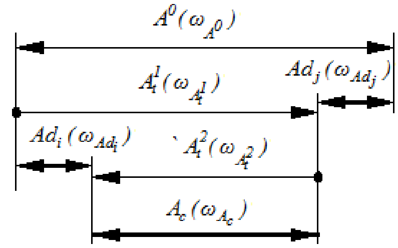


Fig.9. Example of a technological dimensional structure, where the machining allowances are closing elements

A second point that must be taken into account is the fact that the machining allowance also has a physic-technical parametric character, it represents the cutting depth with influences on the process. In this last sense, the machining allowance represents a parametric restriction.

In order to establish the order of the use of the technological bases and the order of the formation of the technological dimensions, we will analyze a dimensional structure (fig. 10) with "mirror" dimensions (A_t and E_t, B_t and E_t), but with chains of different lengths starting from the potential locating datum surface 1 and 8.

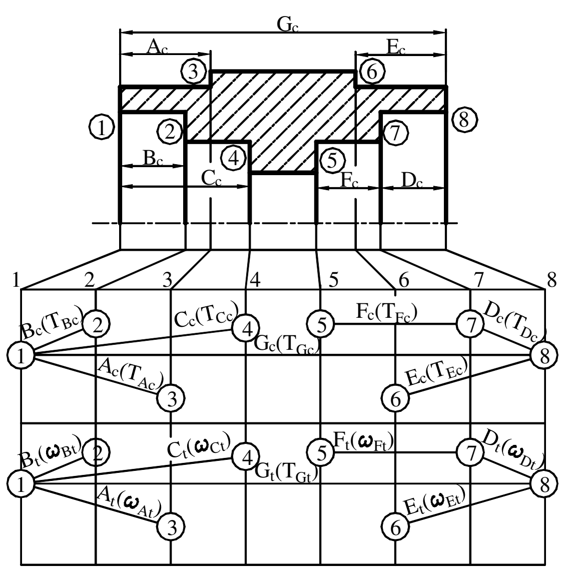
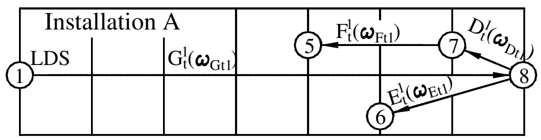


Fig 10. Similar not oriented graphs of linear constructive and technological dimensional links with "mirror" placed surfaces

Two dimensional chains are formed from surface 1: E_t - D_t - F_t (3 elements); G_t - E_t (2 elements), and from surface 8 there are three chains of two elements each: G_t - B_t, G_t - C_t and G_t - A_t. The graph of linear technological not oriented dimensional relations, similar to the graph of linear constructive relations, can be developed on installations in two variants. The comparison of the variants (scenario) is done according to the criterion of the tolerances of the machining allowances removed from the surfaces (fig. 11 - 14).



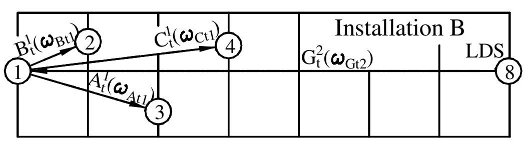
$Ad_8(\omega_{G^0}+\omega_{G^1});$

$Ad_6(\omega_{G^0}+\omega_{G^1}+\omega_{E^0}+\omega_{E^1})$

$Ad_7(\omega_{G^0}+\omega_{G^1}+\omega_{D^0}+\omega_{D^1});$

$Ad_5(\omega_{G^0}+\omega_{G^1}+\omega_{D^0}+\omega_{D^1}+\omega_{F^0}+\omega_{F^1}).$

Fig.11. Example of technological dimensional structure, scenario 1, installation A



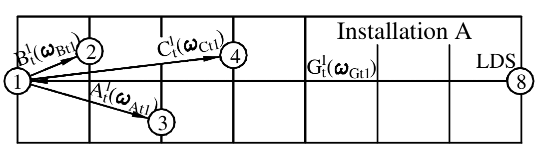
$Ad_1(\omega_{G^1}+\omega_{G^2});$

$Ad_3(\omega_{G^1}+\omega_{G^2}+\omega_{A^0}+\omega_{A^1});$

$Ad_2(\omega_{G^1}+\omega_{G^2}+\omega_{B^0}+\omega_{B^1});$

$Ad_4(\omega_{G^1}+\omega_{G^2}+\omega_{C^0}+\omega_{C^1}).$

Fig.12. Example of technological dimensional structure, scenario 1, installation B



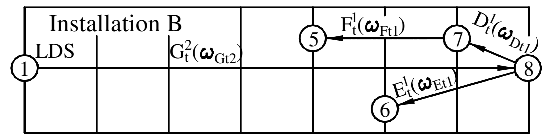
$Ad_1(\omega_{G^0}+\omega_{G^1});$

$Ad_3(\omega_{G^0}+\omega_{G^1}+\omega_{A^0}+\omega_{A^1})$

$Ad_2(\omega_{G^0}+\omega_{G^1}+\omega_{B^0}+\omega_{B^1});$

$Ad_4(\omega_{G^0}+\omega_{G^1}+\omega_{C^0}+\omega_{C^1}).$

Fig.13. Example of technological dimensional structure, scenario 2, installation A



$Ad_8(\omega_{G^1}+\omega_{G^2});$

$Ad_6(\omega_{G^0}+\omega_{G^1}+\omega_{E^0}+\omega_{E^1})$

$Ad_7(\omega_{G^1}+\omega_{G^2}+\omega_{D^0}+\omega_{D^1});$

$Ad_5(\omega_{G^1}+\omega_{G^2}+\omega_{D^0}+\omega_{D^1}+\omega_{F^0}+\omega_{F^1})$

Fig.14. Example of technological dimensional structure, scenario 2, installation B

The analysis of variants A and B shows that the geometric symmetry of the technological dimensions $B_t \leftrightarrow D_t$ and $A_t \leftrightarrow E_t$ on the graphs of the dimensional links does not ensure identical machining allowances. The tolerance structure of one of the dimensions includes the components $\omega_{G^0}+\omega_{G^1}$ much larger than the components $\omega_{G^1}+\omega_{G^2}$ of the other structure. The most vulnerable, in this sense, is the technological dimension F_t (the third in number in the chain) during the formation of which, depending on the scenario of the formation of the technological dimensions, machining allowances with different tolerances can be removed, and the difference is $\omega_{G^0}-\omega_{G^2}$. In one of the variants, the dimension's tolerance on the blank is taken into account, and in another variant - the tolerance of the same dimension after machining, that is, a substantially smaller one. Thus, one of the rule can be formulated following. As the first locating datum surface the surface is chosen (the node in the graph of linear technological dimensional links) through which chains with the most elements are formed. The locating datum surface interrupts the chain and thus the tolerances of the machining allowances are reduced. In the given example, this node is 8 through which a chain of three elements E_t - D_t - F_t is formed. At the next installation, the tolerance structure of all the machining allowances will include much lower tolerances of the technological dimensions formed by machining and the length of the dimensional chains becomes less important.

If the number of elements in the possible dimensional chains are equal (fig. 15), as the first locating datum surface, the node from the graph of technological linear dimensional links will be taken, which forms the chain with the largest sum of tolerances on the blank.

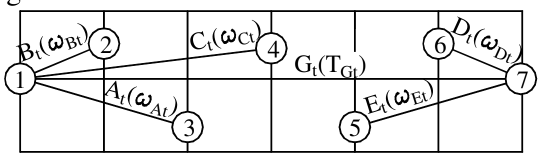


Fig.15. Graph of technological linear dimensional links with equal number of elements in chains

The precision of the last technological dimension in the chains will also be taken into account. Namely, when these dimensions are formed, the largest tolerances of the machining allowances are manifested, a fact that does not favor the technological assurance of precision.

4. CONCLUSIONS

From a geometric point of view, the similarity of the graphs of the constructive and technological dimensional links reflects the optimality of the structural elements - a constructive dimension is formed by a series of its own technological dimensions. This series also includes machining allowances - component elements of dimensional chains. The properties of a dimensional structure consisting of optimal dimensional elements may not be optimal due to non-optimal links established in the structure.

During machining, the tolerances of the technological dimensions manifest themselves differently, they decrease for the target dimensions and increase for the modified dimensions associated with the formation of another dimension - target. Said increase is determined by the position of the dimension in the chain counting from the locating datum surface and includes the tolerances of all previous dimensions in the chain. Finally, each technological dimension becomes a target dimension and achieves the required precision.

The size of the tolerance of the processing addition is determined by the position in the chain of the technological dimensions in the formation of which it participate, accumulating the tolerances of all current and historical target technological dimensions (inclusive of the blank).

In order to reduce the negative effects of increasing the tolerance of the machining allowances (cutting depth), the following will be taken into account when establishing the order of installation and machining:

- ✓ as the first locating datum surface, the surface is chosen (the node in the not oriented graph of linear technological dimensional links) through which chains with the most elements are formed, starting from the locating datum surface;
- ✓ if the number of elements in the dimensional chains are equal, as the first locating datum surface, the node from the not oriented graph of linear technological dimensional links will be taken, which forms the chain with the largest sum of tolerances on the blank;
- ✓ number of chains is also important, like this as the first locating datum surface, the node from the graph of linear technological dimensional links through which more dimensional chains are formed will be taken.

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Considerații privind proiectarea dimensională optimă a tehnologiilor de prelucrare mecanică

Lucrarea discută metodologia de proiectare a proceselor tehnologice de prelucrare mecanică, ținând cont de faptul că aceste procese sunt determinate de interacțiunea în toleranțe a patru sisteme distincte cum sunt piesa, semifabricatul, procesul tehnologic și sistemul tehnologic, fiecare dintre acestea are o proprie structură dimensională. Formal, geometric optimalitatea procesului tehnologic este determinata de similitudinea grafurilor relațiilor dimensionale tehnologic și constructiv. Optimale sunt structurile dimensionale cu cele mai puține elemente în lanțurile dimensionale deoarece fiecare dintre aceste elemente provoacă creșterea toleranței adaosului de prelucrare eliminat la următoarea fază tehnologică și afectează asigurarea tehnologică a procesului.

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