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TOLERANCE ANALYSIS OF STRUCTURAL FUNCTIONAL GROUPS

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Abstract: This paper aims to provide designers with more powerful and flexible tolerance analysis (hereafter TA) tools. By using the offered flexible tools, designers will gain knowledge that will enable them to optimize the properties of TA more effectively in an environment of rapid increase in the demands placed on them. This includes ensuring assembly, interchangeability, high accuracy, low production times, low costs and functionality at the required change in operating temperatures.

KEYWORDS: tolerance, linear dimensional circuits, nonlinear dimensional circuits

1 Introduction

1.1 Functional dimensional conditions

A dimension is a numeric value expressed in the proper measurement units (mm) and graphically displayed on the technical drawing, along with lines, markings, and annotations, so that the feature is fully identified. Dimensions determine the size and relative position of shape features. On the product drawing, they are assessed considering:

- the function of the product [F].
- the process of its manufacture and assembly/dismantling [M], [A/D].
- the method of checking its dimensions [C].
- optimization of dimensional functional conditions [O].

1.2 Starting Points for Correct Dimensioning

Implementation of the following system (order is not related to importance)

$$F - V - M/D - K - O \quad (1)$$

it will allow designers to unambiguously assess the suitability of dimensioning any structural-functional element.

The criterion "O" will help us decide on the method of dimensioning, for example, a groove for a flexible ring to minimize the clearance (dimensional functional condition) between the side of the bearing and the ring.

We continue in such a way that we proceed from the principle of setting the worst possible state of the dimensional chains about the requirement of minimizing clearance.

The dimensioning case according to Fig. 1, a)

This method of dimensioning the position of the groove is unsuitable, as it is necessary to secure the "v" to secure the mounting of the ring. It follows that the Fa must be tolerated to the plus. Since the end face of the shaft journal is not a functional surface, the position of this surface should not be tolerated (unnecessary extra costs).

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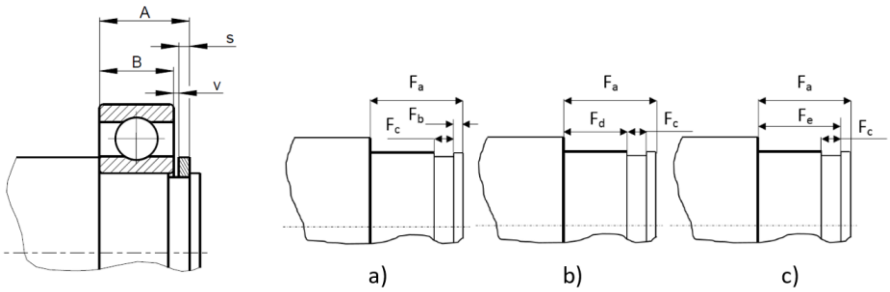

Fig. 1 Minimization of the functional condition V -> min

Dimensioning case according to Fig. 1, b)

In this case, we must first find, due to, the magnifying (F_a; F_c) and decreasing (B; s) string members. It can be seen from the picture that all the mentioned dimensions increase the clearance, and therefore the required optimization does not occur, and therefore we cannot recommend this method of dimensioning either.

Dimensioning case according to Figure 1, c)

In this case, increasing the size of the F_c member does not affect the clearance size, otherwise, everything else is the same as in the previous case. This method of dimensioning is therefore the most suitable, as at least partial optimization of the functional condition has been achieved.

The aim of this study is to create such methodologies and principles that will be based on a uniform basis and will primarily reflect the needs of the constructors. This post focuses primarily on issues related to the optimization of dimensional functional conditions determined by dimensional circuits to achieve the highest possible functionality of the designed machine parts under changing external conditions (especially ambient temperature) and at the same time mutual assembly, interchangeability, high accuracy while achieving low production times and low costs.

2 Materials and Methods

2.1 Dimensional circuits (strings)

According to the arrangement, dimensional circuits are divided into:

- Linear circuits.
- Nonlinear circuits (planar and spatial).

2.2 Linear circuits (1D)

A linear dimensional circumference is a set of dependent parallel dimensions that are connected in such a way that they form a geometrically closed circuit. These can be dimensions that determine the relative position of features on a single part or dimensions of multiple components in a part family.

The accuracy of production and assembly interchangeability of individual ma-chine parts is primarily influenced by the choice of limit deviations and the way in which they are calculated. Therefore, the efficiency of production and operation depends on it. Three basic methods are used in technical practice to solve tolerance relationships in dimensional chains:

1. Arithmetic calculation method.
2. Statistical calculation method.
3. Group interchangeability method.

2.2.1 Arithmetic method of calculation – WC method (Worst Case)

The most used method is sometimes also referred to as the maximum-minimum calculation method. It is based on the condition of compliance with the required limit deviation of the closing element for any combination of the sub-members actual dimensions, i.e., the upper and lower limit dimensions. This method guarantees complete assembly and operational interchangeability of the components. However, when a higher precision of the clamping element is required, it leads to too narrow tolerances of the sub-members, leading to high production costs.

If we accept a stricter requirement for the tolerance of the closing member and the circuit contains a smaller number of members, it is advisable to use the WC method. It is most often used in piece or small-batch production.

2.2.2 Statistical Calculation Methods

Statistical methods for calculating dimensional chains are based on the calculation of probabilities. These methods assume that in the case of a random selection of com-ponents during assembly, extreme values of deviations rarely occur for multiple sub-members at the same time, as they are composite probabilities. It is equally unlikely that the extreme value of deviations will occur in the production of individual dimensions on one part. Thus, with a pre-selected risk of rejection of some components, the tolerances of the sub-members in the dimensional chain can be increased.

The statistical method guarantees only partial assembly interchangeability, with a small percentage of unfavourable cases (rejects). However, the larger tolerances of the partial dimensions lead to a reduction in production costs. If we do not require complete assembly interchangeability of machine parts and we are primarily interested in saving production costs, it is advisable to use this method.

The dimensions of the clamping element show a certain dispersion from the centre of the tolerance zone. The frequency of occurrence of individual dimensions follows the laws of mathematical statistics and in most cases corresponds to a normal distribution (Laplace's Gauss).

2.3 Basic tolerance analysis

- Linear dimensional circuits on a single part (WC <-> RSS).
- Linear dimensional circuits in a part group (WC <-> RSS).

When choosing a suitable solution, it is necessary to carefully consider the relation-ship between the selected size of production tolerances and the expected yield of the production process. By increasing the tolerances used, we will reduce the direct costs associated with machining the part, but the losses caused by the increased incidence of defective products will increase. The resulting solution must then be chosen in such a way that the total cost of production is as low as possible.

2.4 Deformation of the system due to temperature change

The previous considerations assumed that the designed part would work at temperatures close to the basic temperature of 20°C (68°F), at which the dimensions and tolerances of the sub-members were determined. In the case of components working permanently at higher operating temperatures, deformation of the component dimensions occurs during operation. To check the resulting dimension of the clamping element (functional conditions), the arithmetic method "WC" or the statistical meth-od "RSS" can be used.

If the temperature of components whose dimensions are part of the dimensional chain changes, it is necessary to check whether the requirements for functional conditions are met even at the extreme values of the temperature interval. If it is a dimensional functional condition (clearance), where it is primarily necessary to observe its permitted lower limit "LL", i.e., for it to exist between opposite surfaces to ensure mutual assembling of the clearance (there must be no overlap).

2.5 Advanced Statistical Analysis (6 Sigma)

The "6 Sigma" method is a modern statistical method for assessing the quality of production processes. Its use is suitable when higher quality production processes is required and for large production volumes, where the mean value of the process characteristics may shift. The concept of this method is to achieve such a goal that the mean value of the characteristic of the process is far from 6 from both tolerance limits. For such a suitable production process, even with the assumption of a shift in the mean value of 1.5 achieved a ratio of 3.4 non-compliant products per million produced (ppm).

2.5.1 Group interchangeability method

The selective assembly method is used in mass and large-scale production of precision products where the in-service interchangeability of components within the prod-uct is not required. After classifying the TP into groups according to the degree of accuracy achieved, it is possible to proceed with the assembly of the TP. The manufacturing dimensions of the components can be prescribed with greater tolerances. The narrowed tolerance of the resulting dimension is then achieved by purposeful grouping (combination) of sorted subgroups.

Statistical tolerance (ST) – prescribes the necessity of assigning parts to each other in an assembly based on a statistical evaluation of partial dimension tolerances. This approach makes it possible, even if the tolerance range of the dimensions of the sub-elements is extended, to increase the accuracy of the assembly.

In real practice, the selective assembly method is usually used only to produce structural-functional units (groups) where the operational interchangeability of com-ponents within units is not required. The requirement to ensure that some of the com-ponents are interchangeable significantly reduces the advantages of selective assembly.

The production of rolling bearings is a typical example suitable for the use of the selective mounting method. When solving bearings using the classic "Worst Case" method, the bearing will be completely assembled serviceable interchangeable with all components, but to comply with the required radial clearance, it would be necessary to produce bearing components in the accuracy grade IT 3. Obviously producing with such a high degree of accuracy would be prohibitively expensive. By using the selective assembly method, components can be produced with significantly lower precision. The solution of the selective assembly task itself consists of two parts:

- The composition of the dimensional chain.
- Pairing of machine parts.

The selective mounting method guarantees only partial (group) assembly inter-changeability within selected mounting combinations. Therefore, if a partial part is worn out or damaged during operation, the entire assembled part must be replaced. Therefore, the selective assembly method is used to produce precision products that do not require in-service interchangeability of components within the product.

2.5.2 Optimization of the number of assembled products

However, when mounting a bearing, it is not expedient to assemble the bearings by simply randomly selecting machine parts and trying to match them to the proposed permissible mounting combinations.

If the selective assembly method is to be effective, it is necessary to solve the problem of optimal selection (combination) of machine parts. Machine parts must be grouped in such a way that with a given number of manufactured parts, it is possible to assemble the maximum possible number of products that meet the requirements imposed on the closing member (in our case, on the dimensional functional condition (clearance)).

In addition to the requirement to assemble the maximum number of products, there is often a requirement in practice to minimize the number of assembly combi-nations that will be used to assemble the product. Minimizing the number of combi-nations used leads to simplification and acceleration of assembly and thus to cheap-er production. In some practical applications, both criteria are equally important.

2.6 Nonlinear circuits (2D, planar and 3D, spatial).

2.6.1 Planar Chains (2D)

The dimensions are laid out in one or several parallel planes.

2.6.2 Spatial Chains (3D)

The dimensions lie in non-parallel planes.

There are two types of problems when dealing with tolerance relationships in dimensional chains:

2.6.3 Tolerance analysis – direct tasks, control tasks

Based on the known limit deviations of all sub-members, the limit deviations of the closing member are determined. Direct tasks are computationally unambiguous and are usually used to check components and assembly units manufactured according to a given drawing.

2.6.4 Tolerance synthesis – indirect, structural problems

Based on the known limit deviations of the closing element given by the functional requirements, the limit deviations of the partial members are designed. Indirect tasks are solved in the design of functional and assembly groups.

Two calculation methods are used to solve tolerance relations in dimensional chains:

- "Worst Case" method.
- "Monte Carlo" method.

The accuracy of production and the mutual interchangeability of machine parts during assembly is influenced by tolerance sizes and methods of calculating deviations of dimensional elements. Therefore, the efficiency of production and operation depends on it.

2.6.5 Statistical method of calculation – MC method (Monte Carlo)

The "MC" method guarantees only partial assembly interchangeability, with a small percentage of unfavourable cases (defective machine parts). However, the larger tolerances of the partial dimensions, lead to a reduction in production costs. If we do not require complete assembly interchangeability of machine parts and we are primarily interested in saving production costs, it is advisable to use this method (mass and high-volume production).

2.6.6 Nonlinear dimensional circuits (two-dimensional, 2D) – "Worst Case"

The non-linear (flat) arrangement of dimensions is schematically drawn in the fig.3. The constraint of dimensions in a nonlinear perimeter is determined by the angle formed by the directions of the dimensions.

The first-order differential equation is sufficient with small tolerances with respect to the nominal dimensions.

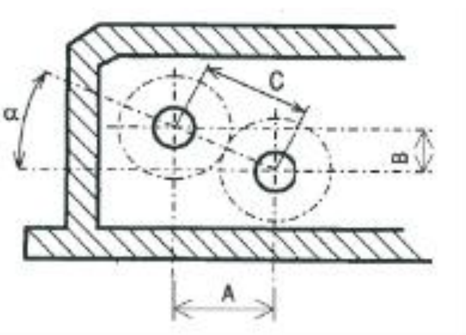

Fig. 2 Axial distance for housing the gears in the gearbox housing.

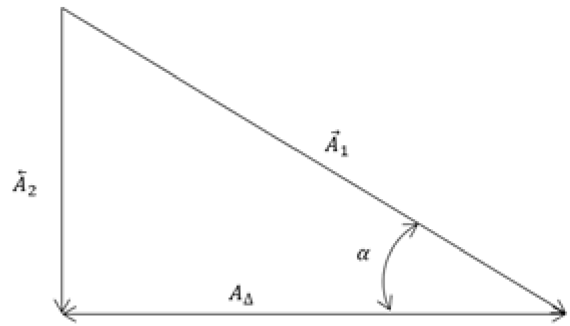

Fig. 3 Dimension String - 2D

$$T_{A_\Delta}^{(1)} = \sum_{i=1}^{n} \left| \frac{\partial A_\Delta}{\partial A_i} \right| T_{A_i} \tag{2}$$

In the case of large tolerances with respect to nominal dimensions, it is preferable to use a differential equation of the second order (here we present the case for two partial terms).

$$T_{A_\Delta}^{(2)} = \frac{1}{2}\left(\sum_{i=1}^{n=2} \left| \frac{\partial^2 A_\Delta}{\partial A_i^2} \right| T_{A_i}^2 + \left| \frac{\partial A_\Delta}{\partial A_1 \partial A_2} \right| T_{A_1} T_{A_2} \right) \tag{3}$$

Taylor's residuum (approximation error)

When approximating the values of a function *f(x)* by the relevant Taylor polynomial $T_n(x)$ degrees *n* we are interested in the "error" of the approximation, i.e., the difference in the actual value *f(x)* and polynomial values $T_n(x)$. We will mark it as $R_n(x)$ which is derived from the word residue.

Taylor's theorem

Let the function *f(x)* has a derivative to order in the vicinity of x_0 *(n+1)*. Then, for every *x* in this neighbourhood, there is ζ between the points x_0 and x such that Taylor's residue $R_n(x) = f(x) - T_n(x)$ can be expressed in the form:

$$R_n(x) = \frac{f^{n+1}(\zeta)}{(n+1)!}(x - x_0)^{n+1} \tag{4}$$

The Taylor residue (in the so-called Lagrange form) has the form (*n+1*) of the Taylor polynomial, just a derivative of the order *n+1* is not at the point x_0, but at the point ζ lying between x_0 and *x*.

In order not to have to distinguish whether *x* is less or greater than x_0, the point can be ζ written in the form:

$$\zeta = x_0 + z(x - x_0), kde\ z\ \epsilon(0,1) \tag{5}$$

In this case:

$$\zeta_{A_1} = \left(A_1 - EI_{A_1}\right) + zT_{A_1} \tag{6}$$
$$\zeta_{A_2} = \left(A_2 - EI_{A_2}\right) + zT_{A_2} \tag{7}$$

$$R_1(A_{\Delta max}) = \frac{1}{2}\left(\left|\frac{A_2^2}{\left(\zeta_{A_1}^2 + A_2^2\right)^{\frac{3}{2}}}\right| T_{A_1}^2 + \left|\frac{A_1^2}{\left(\zeta_{A_2}^2 + A_1^2\right)^{\frac{3}{2}}}\right| T_{A_2}^2 + \left|\frac{A_1 A_2}{\left[\zeta_{A_1}^2 + \zeta_{A_2}^2\right]^{\frac{3}{2}}}\right| T_{A_1} T_{A_2}\right) \tag{8}$$

Maximum value of the closing member:

$$A_{\Delta max} = \sum_{i=1}^{m} \vec{\xi}_i \vec{A}_{imax} + \sum_{j=m+1}^{n} \overleftarrow{\xi}_j \overleftarrow{A}_{jmin} \tag{9}$$

Upper deviation of the closing member:

$$ES_{A_\Delta} = \sum_{i=1}^{m} \vec{\xi}_i \, ES_{\vec{A}_i} + \sum_{j=m+1}^{n} \overleftarrow{\xi}_j \, EI_{\overleftarrow{A}_j} \tag{10}$$

Minimum value of the closing member:

$$A_{\Delta min} = \sum_{i=1}^{m} \vec{\xi}_i \vec{A}_{imin} + \sum_{j=m+1}^{n} \overleftarrow{\xi}_j \overleftarrow{A}_{jmax} \tag{11}$$

Lower deviation of the closing member:

$$EI_{A_\Delta} = \sum_{i=1}^{m} \vec{\xi}_i \, EI_{\vec{A}_i} + \sum_{j=m+1}^{n} \overleftarrow{\xi}_j \, ES_{\overleftarrow{A}_j} \tag{12}$$

where

$$\vec{\xi}_i = \frac{\partial A_\Delta}{\partial \vec{A}_i}; \; \overleftarrow{\xi}_j = \frac{\partial A_\Delta}{\partial \overleftarrow{A}_j} \tag{13}$$

They express the relative slope of the dimension directions.

Nominal dimension of the closing member:

$$A_\Delta = \sum_{i=1}^{m} \vec{\xi}_i \vec{A}_i + \sum_{j=m+1}^{n} \overleftarrow{\xi}_j \overleftarrow{A}_j \tag{14}$$

2.7 Comparison of methods

Solving the above case with the help of sw. MITCalc (Mechanical, Industrial and Technical Calculations) tools – Tolerance analysis of planar and spatial dimensional chains.

The results obtained using the "Worst Case" method are identical to the results of the analytical method mentioned in the previous paragraph. The use of the "Monte Carlo" method leads to an expected reduction in the tolerance of the closing member and thus to the expected refinement of the distance between the holes in the gearbox housing intended for bearings. This is because, according to the method, reaching the boundary values of the partial dimensions, given by the upper and lower deviations of the dimension, is very unlikely and we consider only the chosen part of the Gaussian probability distribution (in our case $\pm 3\sigma$).

3 Results and Discussion

3.1 Solution of a functional unit - machine safety switch

The switch can perform the following functions:

F1:

The switch is designed for the safety of the machine operator. The machine can only be started if the operator constantly presses the safety switch button to ensure that it does not interact with moving or otherwise dangerous parts of the machine.

F2:

The switch is designed to safely shut down the machine in case of any critical condition caused by the operation of the machine that could cause a violation of the safe-ty of the machine's operation.

Note: Equipping machines with a safety button are determined by the relevant legislation of the country in which the machine is operated.

To always ensure the correct operation of the safety switch, it is necessary to ensure that the requirements for the parameters of the properties of the active element (microswitch), which are specified by the component manufacturer, are met.

To ensure reliable operation of the safety switch, the limits of the switching zone of the actuator (microswitch) must be strictly observed. Position of the > power button 3.3 [mm] – microswitch contact released 0.5 [mm] < position of the < switch button 1.5 [mm] – microswitch contact in the switching zone.

Attention! If the position of the power button < 0.5 [mm] occurs, there is a high prob-ability that irreversible damage to the microswitch will occur.

The required position states of the contact surface of the button can be achieved by determining the correct dimensional parameters of the individual machine parts and their tolerances, i.e., the correct geometric specification of the product (GPS).

3.2 Structure of Safety Switch

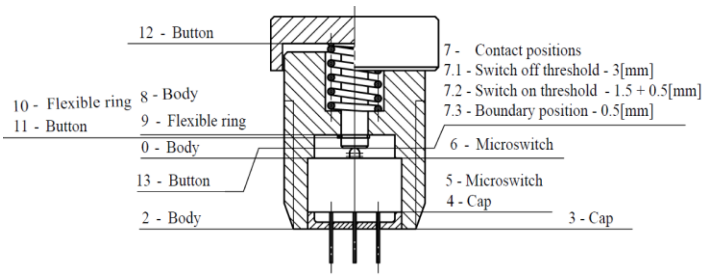

Fig. 1 Switch in the off position (Switch – off)

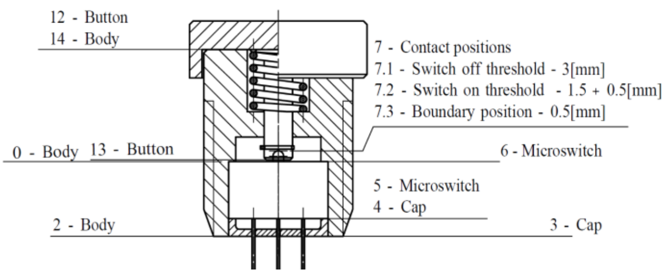

Fig. 2 Switch in the on position (Switch – on)

Reliable switch-on of the safety switch

Parameter *X1* (*["13"- "7.3"],* correct setting prevents damage to the microswitch)

The result of solving a dimension chain:

The *X1* element is larger than zero and therefore the limit of *0.5* for compression of the microswitch contact, which is given by its design (part manufacturer), is not exceeded.

Parameter *X2* (*["13"- "7.2"],* correct setting ensures reliable activation of the microswitch)

The analysis showed a problem where *X2max > 0* and the microswitch would not be activated. This problem must be gradually solved by optimizing the individual parameters of the dimensional chain so that, if possible, higher tolerance values are maintained and there is no significant increase in the production costs of the product.

3.2.1 Optimization of the dimensional chain parameters of the safety switch

As a result of the optimization of the dimensional chain, the parameter *X1* is greater than zero at both boundaries and thus corresponds to the specified functional conditions, and the parameter *X2* is less than zero at both boundaries and thus corresponds to the specified functional conditions.

From the results of the solution, it was clear that after the optimization of the dimensional parameters of some of the machine parts of the design group, the parameter was refined, and the previously set goal was achieved. It was achieved that the parameters *X ["13"- "7.1"]*, *X1* and *X2* meet the requirements that had to be ensured for the reliable operation of the safety switch after optimization. For the changed specification of the requirements for the design of the safety switch, the required boundary conditions are met and the switching of the microswitch is ensured reliably. The extreme position *"7.3"=0.5[mm]* is not exceeded and therefore damage to the micro-switch by excessive pressure on its contact is prevented. Thus, it can be said that the safety switch, after modification, is designed to meet the requirements of its functionality and high on/off reliability for two design specifications.

3.3 Solution of the functional unit – seizing of the ram guide of the press

In the press, see Fig. 6, there were problems with the correct determination of the clearances in the ram guide so that at low ram temperatures there was not too much clearance in the guide and, on the contrary, when the ram was heated there was no loss of clearance in the guide and thus no seizing or blocking of the ram movement see Fig. 7.

Thus, the ram gradually heats up during the press operation. The temperature progression of the ram is shown in Fig. 8.

Destructive damage to the bronze liner of the press guide can be seen in Fig. 9.

3.3.1 Optimization of the dimensional chain parameters of the ram guide of the press

If the temperature of the components whose dimensions are part of the dimensional chain changes, it is necessary to check whether the requirements for functional conditions are met even at the extremes of the temperature range. In our case, it is a dimensional functional condition (clearance), where it is necessary to observe its permissible lower limit "LL", or that there is clearance in the sliding line of the press ram (there must be no overlap). Compliance with the permissible upper limit "UL" is a critical requirement in this case and must therefore also be optimised depending on the temperature distribution in the press ram.

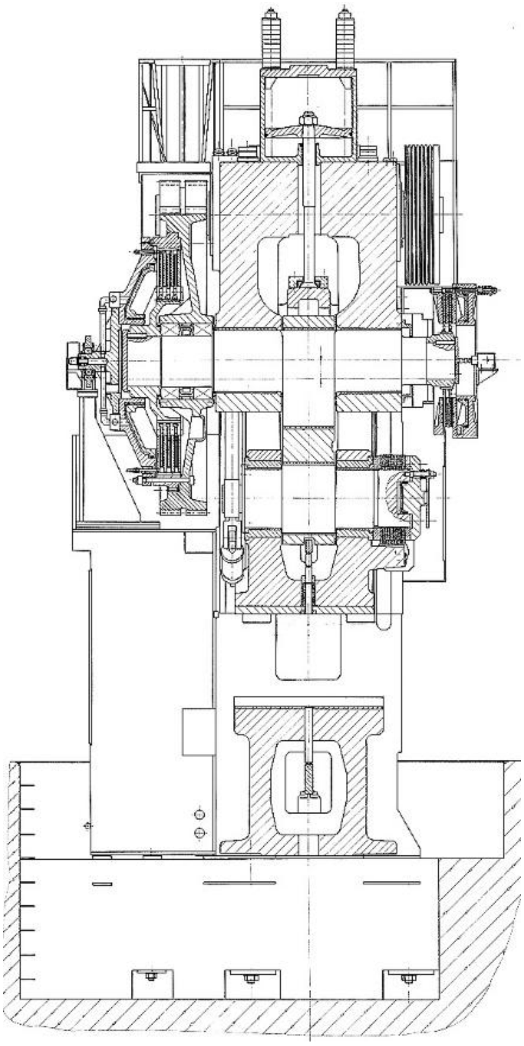

Fig. 6. General view of the press assembly

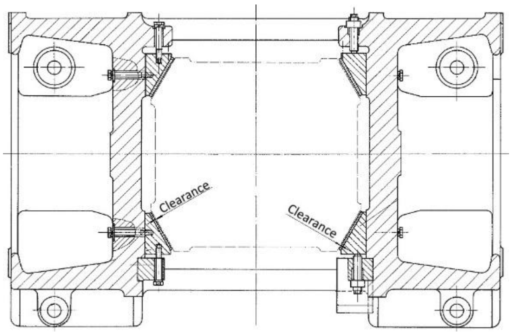

Fig. 7. Stand cut with ram guide

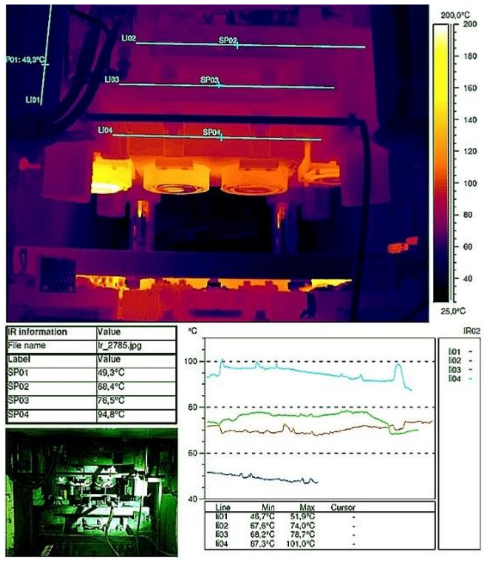

Fig. 8. View of the temperature distribution on the ram of the press (SP02 is the bottom of the ram)

Fig. 9. Damaged (broken) slide plate of the ram guide

The MITCalc (Mechanical, Industrial and Technical Calculations) software tool and the arithmetic calculation method - the "WC" (Worst Case) and "RSS" (Statistical Calculation) methods were used to optimise the dimensional functional conditions and design the modification of the ram guide surfaces. The deformation of the ram of the press due to temperature change significantly affected the magnitude of clearances in its guides. In determining the clearances, the first approximation was based on the assumption stated in the standards that tolerances and deviations of geometric parameters apply to machine parts at a temperature of 20 ˚C. Depending on the temperature changes, the initial face clearance decreases and therefore, if critical temperatures are exceeded, the sliding bronze surface of the ram guide may be seized or destructively damaged.

Based on tolerance analysis, the clearances in individual parts were determined and shape optimization of the ram guide surface of the press was performed so that the limiting clearances before ram heating were not too large and approximately corresponded to the specified values $v_{opt}^{SP2} = 0{,}6\ [mm]$ and $v_{opt}^{SP4} = 0{,}9\ [mm]$. After the maximum possible heating and considering the temperature field distribution in the ram of the press, the clearance in the guide should be approximately $v_{opt}^{Heat} = 0{,}2\ [mm]$ according to the dimensional analysis.

On the basis of the results obtained by means of tolerance analysis, optimised dimensional conditions were determined in various parts of the guide surfaces of the ram and the shape of the guide surfaces was modified in such a way that the damage to the guide surfaces of the bronze plates of the guide during the operation of the press no longer occurs and that at least the minimum clearance always remains in the guide of the ram of the press even at its maximum heating and thus destructive damage to the bronze plates of the guide of the ram no longer occurs.

CONCLUSION

The article focuses on research of the dimensional chain optimization process and the creation of such methodologies and principles that will be based on a uniform basis and will reflect the needs of industrial enterprises. At present, almost none of the designers in manufacturing companies are deeply involved in the issue of dimensional chains and conducting a thorough tolerance analysis. The resulting dimensional functional conditions are not clearly defined, and their specification and definition of boundary conditions is very vague, and therefore suitable conditions are not created for the development of well-functioning technical devices even under the assumption of changing external conditions acting on them. The main objective is to achieve high operational reliability and long service life of the machines and equipment produced.

Since statistical methods of tolerance analysis and synthesis are not usually used in the design and optimisation of functional conditions, this results in unnecessary additional costs, which are then adversely reflected in the price of the product and thus in a reduction in the competitiveness of the production company.

The principles presented in this article allow finding and correctly defining individual dimensional functional conditions and their boundary values and optimizing them under the influence of different external and internal influences. Using the proposed methods and using specialized software tools, it is facilitated to ensure the requirements of product properties and in particular to ensure assembleability, interchangeability, high accuracy, low production times, low costs and functionality at the required change of operating temperatures [12, 13].

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