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Strength Assessment of a New Adaptive Tooling Design

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Abstract. This article discusses the current scientific and technical challenge of improving the efficiency of processing complex spatial shapes of body and thin-walled parts in small-batch production. Traditional tooling often does not provide the required rigidity and flexibility, which leads to vibrations and deformations of workpieces. The authors propose an innovative design for adaptive tooling, a distinctive feature of which is the use of a polymer concrete base and a matrix of telescopic pins positioned by stepper motors. The main focus of the work is on evaluating the strength and load-bearing capacity of the new design using the finite element method (FEM) in the Ansys Discovery 2024 R2 software package. During simulation modeling, the behavior of the system under the influence of a significant static load of 100,000 N was investigated. S275N steel was used for the pins and epoxy-based polymer concrete for the frame. The analysis results showed high rigidity of the system. The maximum displacements were only 4.53 µm and were localized at the tops of the pins, without exceeding the elastic deformation zone. The study of equivalent stresses according to Mises confirmed that the peak values (4.58 MPa) are many times lower than the yield strength of steel (237 MPa). The use of polymer concrete is justified by its ability to effectively dampen vibrations and ensure geometric stability at low levels of internal stresses. It has been established that the critical value of the coefficient ($n > 1.5$) is reached at loads exceeding 550–600 kN, which is equivalent to a workpiece weight of more than 56 tons. Thus, the developed tooling is a promising solution for precision machining of heavy and complex parts, combining adaptability, vibration resistance, and high load-bearing capacity.

Keywords: displacements, stresses, safety factor, pins, polymer concrete

Introduction

Modern trends in mechanical engineering, such as product clustering and the transition to small-batch production with a wide range of products, place increased demands on the flexibility of technological processes [1, 2]. A particular challenge is the clamping of complex spatial shapes for machining of body, cast, and thin-walled parts [3]. Housing parts occupy a special place in mechanical engineering, instrument making, and aviation technology, as they are characterized by complex spatial geometry, the presence of thin-walled elements, covers, stiffening ribs, and internal cavities [4, 5].

Their processing is associated with a number of technological problems that require solutions and experimental design proposals. These problems include:

- high flexibility and low rigidity of housing parts, which leads to deflection and vibration during machining. These phenomena reduce dimensional accuracy and surface quality [6, 7];
- the complexity of fixing parts with complex geometry, especially thin-walled elements and covers, where traditional fixtures do not provide reliable fastening without deformation [8, 9];
- the need for individual tooling for each product series, which increases costs and setup time. According to research, the cost of designing and manufacturing fixtures can be up to 10-20% of the total cost of the production system [10, 11];
- the influence of thermal and dynamic loads, since metal bases of fixtures are subject to thermal deformation and do not dampen vibrations well, which reduces process stability [12, 13];
- limited capabilities of existing universal systems, since modular and reconfigurable fixtures often remain highly specialized and do not provide adaptation to complex-shaped body parts [14, 15].

The development of a new tooling design allows for the fastening of products with various geometries, tolerances, and accuracy requirements, which is particularly relevant for machine-building industries with small and medium-scale production [16].

Strength assessment based on the finite element method is an important stage in modern mechanical engineering design [17]. The transition from traditional analytical calculations to digital testing in software packages such as Ansys Discovery allows engineers to study the behavior of complex assemblies in detail long before the first prototype is manufactured. The use of FEM analysis allows the stiffness of the system to be assessed under the influence of high and varied technological loads [18]. The FEM method allows the distribution of internal forces that tend to return the structure to equilibrium to be visualized. Analysis of equivalent stresses according to Mises makes it possible to identify the most loaded elements. The use of modern software packages allows for the effective combination of materials with different physical and mechanical properties [19]. Comparing the physical and mechanical properties of different materials in a single design in a digital environment helps to justify their use. Strength calculations allow the safety margin of the design to be determined. Modeling also helps to construct a graph of the safety factor as a function of the applied force, which allows predicting the maximum capabilities of the equipment: for example, determining the weight of the workpiece at which the structure will transition from the elastic deformation zone to the critical zone. Strength calculations allow determining the strength margin of the structure. Modeling also helps to determine the dependence of the safety factor on the applied force, which allows predicting the maximum capabilities of the equipment [20].

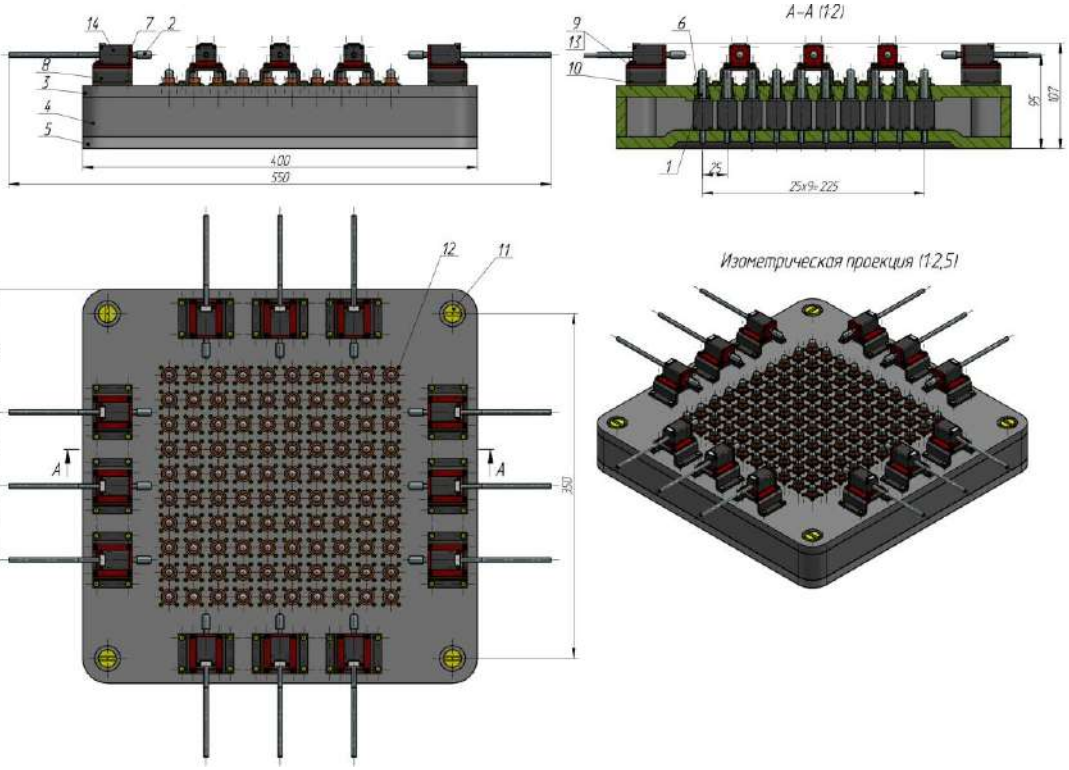
Thus, strength assessment using the FEM method at the design stage allows:

- eliminating the risk of residual deformations;
- reducing the cost of manufacturing expensive specialized fixtures and visualizing stress concentration points in order to improve the design;
- evaluate the versatility of designs that can automatically adapt to the complex geometry of workpieces.

The purpose of this article is to conduct an FEM analysis to evaluate the strength of an innovative design for technological equipment and determine its load-bearing capacity under the intense loads of modern production.

1. Materials and methods

The adaptive technological equipment under development with a polymer concrete-based pin table (Figure 3) forms a support surface for the specific geometry of the cover, reduces vibration, and ensures versatility when processing body parts.



1 – screw assembly; 2 – screw assembly; 3 – top plate; 4 – wall; 5 – bottom plate; 6 – guide; 7 - holder; 8 - stand; 9 – M2 bolt; 10 – M3 bolt; 11 – A.M12 screw; 12 - A.M2 screw; 13 – M2 nut

Fig.3. - Adaptive tooling with a pin table

The design of the adaptive technological equipment includes:

- a polymer concrete base, which provides high vibration resistance and low thermal deformation compared to metal counterparts;
- a matrix of telescopic pins located in the working area of the table (400×550 mm), allowing the formation of a support surface according to the geometry of the part being fixed;
- a drive mechanism that moves the pins with stepper motors and ensures positioning accuracy and the possibility of automatic readjustment.
- a modular assembly that simplifies maintenance and replacement of individual elements.

Adaptive tooling was modeled using Ansys Discovery 2024 R2 software.

Adaptive tooling modeling was performed in several stages:

- creation of a 3D model of adaptive tooling (Figure 4);
- selection of material and specification of physical and mechanical properties for S275N steel pins, as well as upper and lower plates of Polymer concrete (epoxy-based) tooling (Table 1);

- fastening of the equipment with a sliding screw thread (Figure 5);
- applying load across the entire surface of the fixture pins (Table 2, Figure 6);
- creating contact connections - 202 contact pairs.

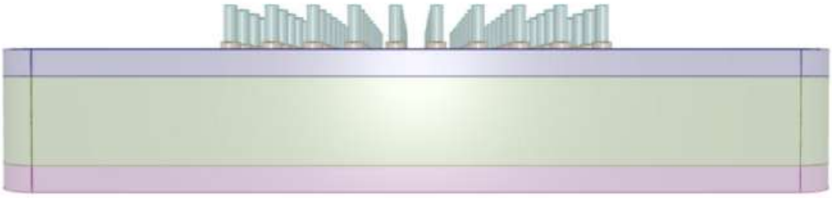


Fig. 4 – 3D model of adaptive process equipment with a pin table

Table 1. Materials Structural steel, S275N

Parametr	Value	Value
Material	Structural steel, S275N	Polymer concrete (epoxy-based)
State	Solid	Solid
Density	7850 kg/m³	2460 kg/m³
Young's modulus	$2{,}1 \bullet 10^{11}$ Pa	$3{,}5 \bullet 10^{10}$ Pa
Poisson's ratio	0,305	0,22
Shear modulus	$8{,}05 \bullet 10^{10}$ Pa	$1{,}43 \bullet 10^{10}$ Pa
Bulk modulus	$1{,}79 \bullet 10^{11}$ Pa	$2{,}08 \bullet 10^{10}$ Pa
Tensile yield strength	$2{,}37 \bullet 10^{8}$ Pa	$2 \bullet 10^{7}$ Pa
Tensile ultimate strength	$4{,}23 \bullet 10^{8}$ Pa	$3 \bullet 10^{7}$ Pa
Thermal expansion coefficient	$1{,}2 \bullet 10^{-5}$ 1/°C	$1{,}4 \bullet 10^{-5}$ 1/°C
Thermal conductivity	50,4 W/m·K	1,2 W/m·K
Specific heat	0,479 kJ/kg.C	0,9 kJ/kg.C
Embodied energy	2,02e7 J/kg	2,8e7 J/kg
CO_2 footprint	2,03 kg/kg	2,5 kg/kg
Potential to recycle	True	False
Description	Structural steel, S275N, normalized Data compiled by Ansys Granta, incorporating various sources including JAHM and MagWeb. ANSYS, Inc. provides no warranty for this data.	Polymer concrete (epoxy-based), mineral aggregate bonded with thermosetting resin. Data compiled from manufacturer datasheets, academic literature, and engineering handbooks. Typical values for structural and machine-base applications. ANSYS, Inc. provides no warranty for this data.
Class	Metals - ferrous	Composites
Subclass	Microalloy and high strength steels	Polymer matrix composites – mineral filled

Table 2. Application of loadings

Name	Total force	Remote
Remote Distributed Force 2	100000 N	0,0375 m

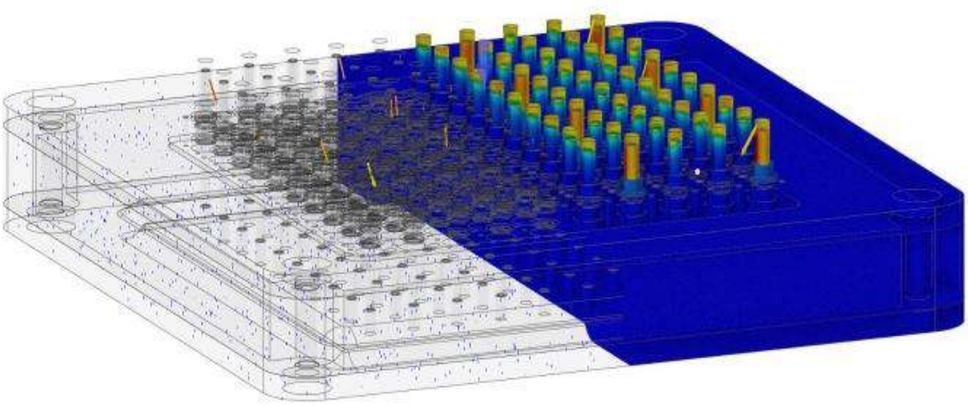


Fig. 5. – Fastening the tooling with the thread of the sliding screw

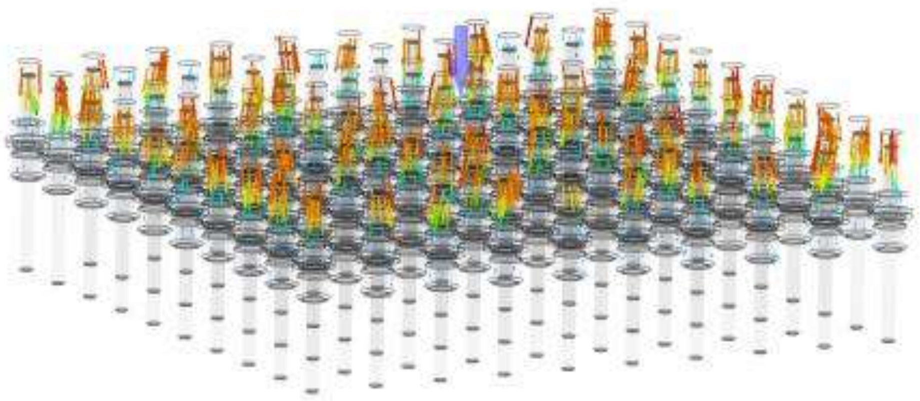


Fig. 6. - Load application across the entire surface of the fixture pins

The load-bearing capacity of the new adaptive tooling design was determined based on the calculation of the safety factor [21]:

$$n = \frac{\sigma_y}{\sigma_{eq}} \quad (1)$$

σ_y – yield strength, MPa;
σ_{eq} – equivalent stresses, MPa.

For objects ensuring load-bearing capacity, the safety factor must be $n \geq 1.5$.

2. Results and discussion

As a result of the adaptive tooling strength simulation, the following parameters were obtained:

- displacements (Figure 7);
- principal stresses (Figure 8);
- equivalent von Mises stresses (Figure 9);
- pin reaction force (Figure 10).

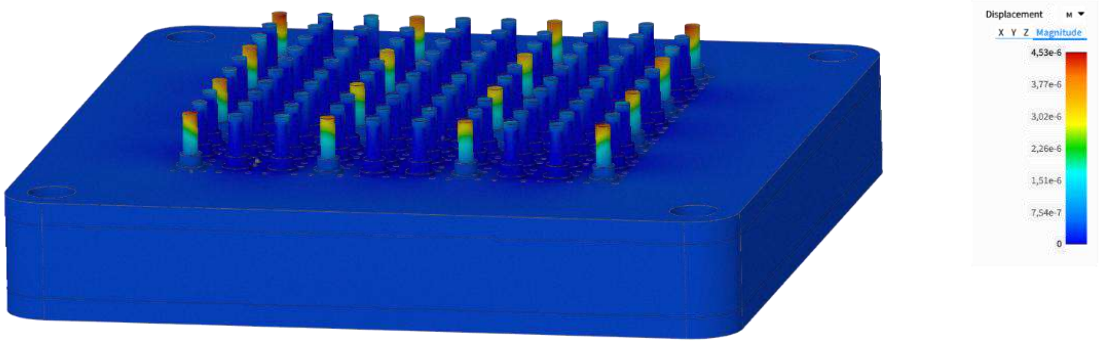


Fig. 7. – Displacements in adaptive technological equipment

According to the visualization of the results in Figure 5, the maximum displacement in the system is approximately 4.53 µm. This value is localized at the top of the telescopic pins, which were directly subjected to a distributed load of 100,000 N. The minimum displacement is 0, corresponding to the areas of rigid fixation of the tool base along the threads of the retractable screws. The maximum displacement of less than 5 µm under a colossal load of 10 tons indicates the extremely high rigidity of the system. Under real metalworking conditions, such deformations have virtually no effect on the dimensional accuracy and surface quality of the part. Displacements of a few microns at the tops of the S275N steel pins indicate elastic deformation of the elements. This confirms that the telescopic mechanism is capable of withstanding technological cutting forces without residual deformation or loss of positioning accuracy. The use of polymer concrete (epoxy-based) instead of traditional metals ensures not only geometric stability but also effective vibration damping. Figure 5 shows that the massive base remains virtually motionless (dark blue), serving as a reliable foundation for the pin matrix.

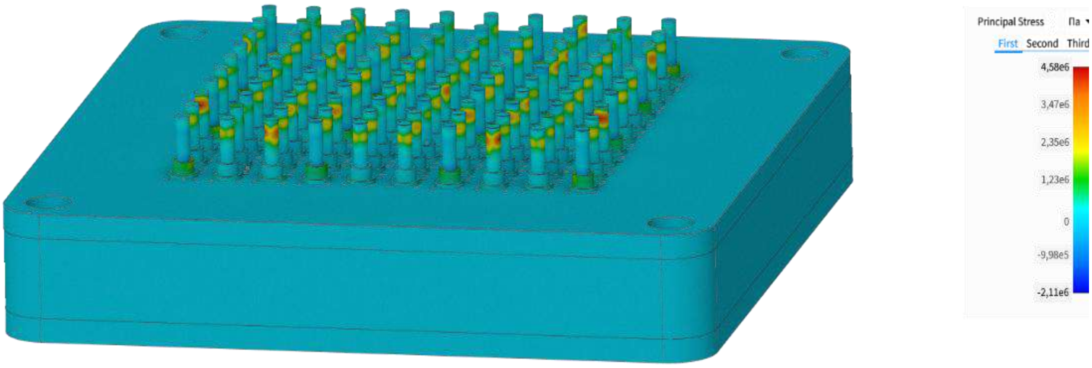


Fig. 8. – Principal stresses in adaptive technological equipment

When a total force of 100,000 N is applied to the pin surface, internal forces are generated in the metal (S275N steel), which tend to return the structure to equilibrium. The pins act as intermediate links, absorbing the pressure from the workpiece and transferring it to the polymer concrete base. Since the Young's modulus of steel (2.1 × 10 Pa) is significantly higher than that of polymer concrete (3.5 × 10 Pa), the steel matrix of the pins bears the primary structural stresses. An analysis of the principal stresses allows us to determine the risk of material failure. The fact that the maximum stress (4.58 MPa) is significantly lower than the yield strength of steel (237 MPa) and the strength of polymer concrete confirms the high safety margin of the structure under the given load. The stress distribution in the polymer concrete base confirms its role as a damper; low stress values with a high base mass contribute to the effective damping of dynamic loads.

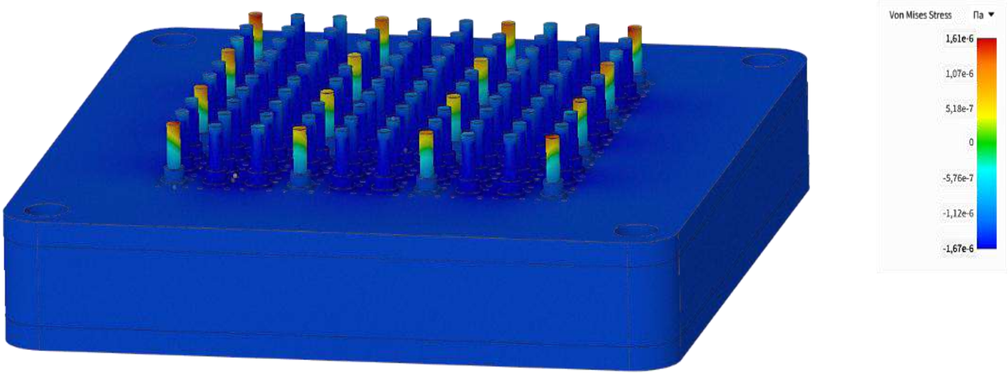


Fig. 9. – Equivalent stresses according to von Mises

An analysis of the von Mises equivalent stresses shows that the telescopic pins are the most heavily loaded elements of the system. The image clearly shows that the maximum stress values are at the top of the pins, which directly contact the workpiece, as well as in the areas where they interface with the upper platen guides. The symmetrical distribution is due to the geometry of the fixture itself-a matrix of pins arranged in a 400 x 550 mm table working area. Since the load is applied to the entire surface of the pins, the stress pattern exhibits a pronounced regularity. The uniformity of the color spectrum on most pins confirms that the adaptive system effectively distributes forces, minimizing the risk of critical stress concentrators at individual points. The polymer concrete base, meanwhile, remains in the zone of minimal stress (≈1.6 Pa), demonstrating its high rigidity and ability to absorb the resulting loads without significant deformation. The use of S275N steel for pins is justified because it withstands specified forces without the risk of plastic deformation, maintaining the positioning accuracy of the part. Uniform von Mises stress distribution ensures that during machining, thin-walled housing parts are not subject to localized overloads that cause deflection or microcracks.

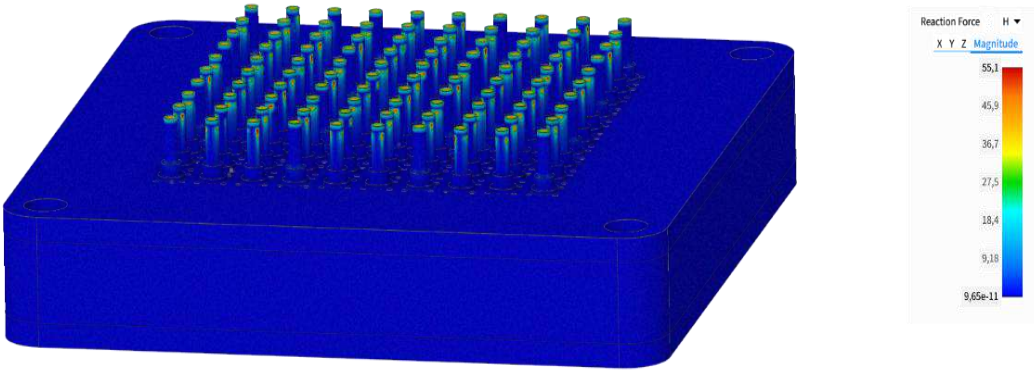


Fig. 10. - Pin reaction force

The reaction force on the pins reaches a maximum value of 55.1 N. Figure 10 shows that the greatest load is concentrated at the upper ends and the mating surfaces of the extended pins, indicated by the red and orange colors on the spectrum. In the areas of the base and elements not in contact, the reaction force approaches zero (approximately 9.65×10^{-11} N), which corresponds to the blue color on the scale.

The pins (the matrix of telescopic pins) form a support surface for the specific geometry of the part. Consequently, reaction forces arise precisely at the points of contact between the fixture and the workpiece in response to an applied external force of 100,000 N. Using the matrix of pins allows the total clamping force to be distributed across multiple support points. The polymer concrete base in which the pin guides are installed has higher internal damping compared to metal. The distribution of reaction forces through a solid polymer concrete slab effectively dampens vibrations arising during machining. The maximum reaction values at the pin ends confirm that the drive mechanism and threaded locking provide the rigid hold necessary to maintain dimensional accuracy.

To determine the maximum workpiece weight that the adaptive tooling can support, simulations of loading with various static loads were conducted, after which a safety factor was determined. The safety factor for various loading forces is shown in Figure 11.

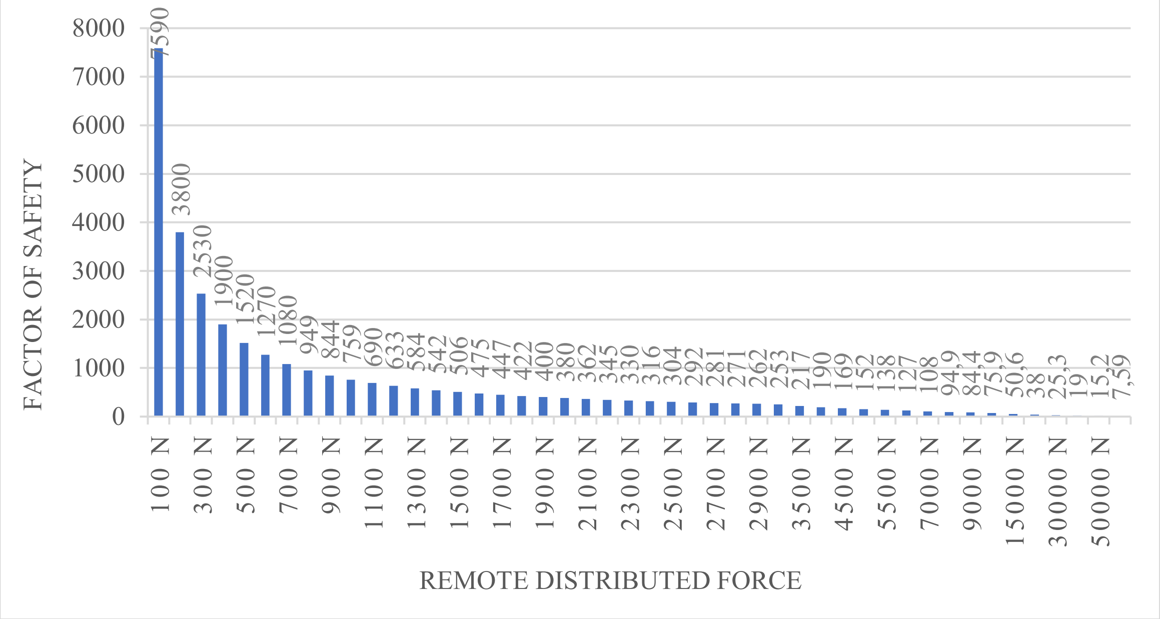


Fig. 11. – Dependence of the safety factor of the equipment on the remote distributed force

The graph in Figure 11 demonstrates an inverse relationship between the magnitude of the applied remote distributed force and the safety factor. As the load on the tool pins increases, the safety factor naturally decreases. According to the graph, this factor corresponds to a load of 100,000 N. This is equivalent to a workpiece weight of approximately 10,197 kg (approximately 10.2 tons). Extrapolating the graph data, one can assume that the safety factor becomes critical (below 1.5) when the load exceeds 550,000–600,000 N. This corresponds to a workpiece weight of over 56–61 tons.

Conclusions

The following results were obtained from the simulation:

1) A finite element analysis (FEM) performed in Ansys Discovery demonstrated the sufficient structural strength of the developed adaptive tooling. When applying a static load of 100,000 N, the maximum displacements in the system were only 4.53 µm. These deformations were localized exclusively at the tips of the steel pins and were elastic in nature. Under real-world production conditions, such microscopic displacements do not affect the dimensional accuracy or surface quality of the machined part, confirming the tooling's suitability for precision machining.

2) The use of polymer concrete (epoxy-based) as the base material proved to be a successful choice. Due to its lower Young's modulus compared to steel, the base acts as an effective damper, absorbing vibrations and dynamic loads. The massive base remains virtually motionless under load, ensuring geometric stability and high vibration resistance, which is critical for reducing tool wear and preventing microcracks in components.

3) The use of a matrix made of S275N steel effectively absorbs process forces. Maximum von Mises equivalent stresses are concentrated in the contact zones of the pins with the workpiece and guides, but their peak value (4.58 MPa) is many times lower than the yield strength of steel (237 MPa). The regular structure of the pin table ensures uniform distribution of forces, eliminating the formation of dangerous stress concentrators, which is especially important when clamping thin-walled and complex body parts prone to deformation.

4) Calculation of the safety factor (n) confirmed the high reliability of the design. Under a standard load of 10 tons, the system maintains a multiple safety factor. Extrapolation of simulation data shows that the critical safety factor ($n > 1.5$) will only be achieved for loads exceeding 550–600 kN (56–61 tons). This allows the tooling to be used for a wide range of heavy components without risk of failure.

5) The proposed adaptive tooling is a promising solution for modern mechanical engineering, combining high load-bearing capacity.

6) Future research will focus on assessing the vibration resistance of the adaptive tooling.

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