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MODELING OF A LATHE BED USING THE METHOD OF TOPOLOGICAL OPTIMIZATION

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Summary. *Based on the drawings of a typical construction of the bed of the 16K20 lathe, its 3D model was made. Its study was carried out using force factors. A conceptually new lightweight design of the bed was obtained by means of the Autodesk shape generator module, taking into account the power factors. The research method is a topological optimization of the model under study, which allows obtaining a new conceptual model of the lathe bed with acceptable stiffness and significant material savings. Materials for the manufacture of beds were studied and evaluated. As for the use of materials for the manufacture of the lathe bed, cast iron remains the most optimal material in terms of «mechanical characteristics – price – weight». We see its advantages in the balance of characteristics. The modeling data allows to see the internal stresses of the structure, deflection of the part, and displacement due to the applied force factors. The images of the 3D model demonstrate this clearly. The disadvantage of the shape generator is the inability to study a 3D model made of several materials, so the research was conducted for a homogeneous model. The undoubted advantage of a shape generator based on the finite element method is that it clearly shows the areas of the structure that are ballast and do not perceive any load. This allows the research engineer to optimize the design, taking into account the recommendations of the shape generator, accumulated knowledge and experience. Thus, we obtained a new conceptual model of the lathe bed for further theoretical experiments. The analytical calculation of the bed structure was also carried out using the above methodology. The values of lathe bed deflection and its influence on the deflection of the part were obtained. To expand the study, calculations were performed for parts of different lengths, namely 1000 mm and 1400 mm. This paper does not reflect the dynamic state of machining of parts in dynamics, but it allows to assess the weaknesses of the structure and identify trends in strengthening or lightening of individual areas. In particular, the use of topological optimization enables the estimation of possible material savings, which is relevant in the context of decarbonization of production and trends in sustainable development.*

Key words: *topological optimization, modelling, lathe-bed, 3D model, turning machines, efficiency of metal use, sustainable development.*

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Statement of the problem. Metal-cutting tools are metal constructions with heavy moving parts (milling machine table, spindle headstock, pinhole, etc.). Cast iron is the most commonly preferred casting material. It is used due to its strength, vibration and sound-absorbing properties, and resistance to force factors that arise during the processing of workpieces. Given the current trends in saving materials, reducing fossil energy sources, popularizing the decarbonization of industrial production, and implementing the concept of sustainable development at enterprises, an important task is to study the possibility of reducing the weight of the machine while maintaining its performance characteristics.

Analysis of the available research. In Ukraine, machine tool stiffness was studied by Strutynsky V. B., Yurchyshyn O. Y., Chupryna V. M. [2, 3], Dashchenko O. F., Kovalev V. D., Limarenko O. M. [4], heavy machine tools were investigated by Kovalev V. D., Antonenko Y. S., Shapovalov M. V. [5, 6]. Among the foreign research sources, it is worth highlighting the studies conducted by a group of scientists from Autodesk and Airbus [9, 10], the European defense and space company Airbus Defense and Space [10], and a paper by General Motors [11]. Papers [8–11] are not directly related to machine tool engineering, but they change approaches to the design of parts in general, which allows for a similar design with

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the same characteristics but with less weight. For a machine tool, reducing the mass of moving heavy parts means reducing the inertia of these components, and as a result, improving positioning accuracy.

Objective of the research is to study the effect of reducing the mass of the lathe-bed on its deformation value by 3D modeling and compare it with the analytical calculation performed according to the method [6].

Formulation of the problem. The main parameter of any machine tool is accuracy, which is determined by the maximum value of the workpiece processing error. During machining, the error value will vary depending on the machining point (cutter position relative to the workpiece position), irrational increase in cutting modes, tool errors, insufficient spindle stiffness, basing errors, and deformation of the MCT structure. When designing machine beds, designers are faced with the task of ensuring the maximum possible rigidity for a particular machine class and operating conditions. In other words, we need to estimate the amount of deformation at the point of the most likely maximum deflection. Since the bed is the main assembly for mounting other machine components, it can be the primary source of insufficient rigidity of the entire structure. This means that it must not only support the weight of the parts but also withstand the dynamic factors and vibrations that occur during the machining process.

Results of the research. To solve the above-described problem, a certain list of tasks has to be done, namely:

- analyze typical lathe-bed designs and materials for their manufacture;
- to perform 3D modeling of the lathe-bed of the most common lathe, for example, 16K20 in Autodesk Inventor CAD;
- to perform an analytical calculation of the elastic displacements of the lathe-bed using a known method;
- to study the 3D model of the lathe-bed in Autodesk Inventor CAD using the finite element method (FEM) and topological optimization;
- compare the results;
- draw conclusions.

Generally, the layout of a lathe is typical. In light and medium-sized machines, the bed is based on two pedestals, on which the speed box with spindle assembly (SA) is mounted on the left side and the pinion, which can be moved lengthwise along the bed guides, on the right side.

Currently, there are 2 ways to produce machine beds: casting and welding. Cast iron, concrete, or polymer concrete are used for casting, and steel is used for welded structures. Cast iron of types СЧ15 and СЧ20 remains a simple and relatively cheap material. It has good casting properties and low warping. Steel (St3, St4) with a thickness of 8 to 12 mm is used for welded beds. With the same load capacity, steel frames are much lighter than cast iron frames, as the elastic modulus of steel is 2 to 2.4 times higher than that of cast iron. Steel can withstand much higher impact loads, but has lower damping properties. Concrete also dampens vibrations well, which increases the dynamic rigidity of the machine, and is not sensitive to temperature, unlike cast iron. The same stiffness as a cast-iron frame is achieved by increasing the wall thickness, but the frame weight remains within acceptable limits since the specific gravity of concrete is 30% of the specific gravity of cast iron. A lathe-bed made of concrete is about 60% lighter, but after drying, it absorbs moisture, which causes volumetric expansion and, as a result, possible cracking, making it unsuitable for use as a lathe-bed material.

A comparison of material characteristics is shown in Table 1. Each category is assigned a score from 1 to 4. Where 1 is the worst, heavier, more expensive, and 4 is the best, lighter, cheaper.

Table 1

Comparative table of materials for the lathe-bed and methods of its production

Material	Concrete	Polymer concrete	Cast iron	Steel
Method of production	Casting	Casting	Casting	Welding
Temperature expansion	3	**4**	2	1
Strength of the material	2	1	**3**	**4**
Vibration resistance	3	**4**	2	1
Crack resistance	1	**4**	2	3
Weight	3	1	2	**4**
Price	4	1	2	**3**
Amount	**16**	**15**	**13**	**17**

Own development of the author.

As can be seen from the table, in terms of the number of points, preference should be given primarily to steel, concrete, polymer concrete, or cast iron. However, in my opinion, it is not the advantage of any one indicator that is important, which will result in a higher total score, but the balance of indicators. If look at the indicators of cast iron, they have average values compared to other materials. It is worth noting that modern lathe-beds are combined (cast iron + concrete), so the characteristics will be affected not only by the material but also by the shape of the construction, location of stiffeners, etc.

To perform a static analysis of the bed of the lathe 16K20, a 3D model of the bed was built in Autodesk Inventor. The digital prototype of the lathe-bed was studied using the Shape Generator module, which uses FEM to determine the loaded and unloaded areas of a structure or model. This means that the designer, at the design stage, can optimize the structure without compromising strength characteristics. Less weight means cheaper construction.

Partially the nameplate data were used as initial data, namely: the distance between the centers $L_1 = 1400$ mm, the distance from the cutter to the toolholder was taken to be $L = 700$ mm the diameter of the workpiece $d = 220$ mm, the cutting speed was $V_{\text{cut}} = 50\text{m/min}$, the distance from the lathe-bed to the centers was $H_1 = 215$ mm, and the rest of the dimensions (Fig. 2) were determined by measurement. The cross-section of the lathe-bed is shown in the figure.

Force factors were applied to the lathe-bed to model cutting forces, caliper weight, torques, etc. The value of the force factors was chosen to be the maximum in order to visualize the deflection of the model. To ensure the reliability of the study, 2 lathe-beds were modeled. First, a solid one, and after optimization, a lightweight one. The same loads were applied to both lathe-beds to assess the difference in stiffness.

Figure 1. 3D model of a solid lathe-bed of a turning machine mod. 16K20

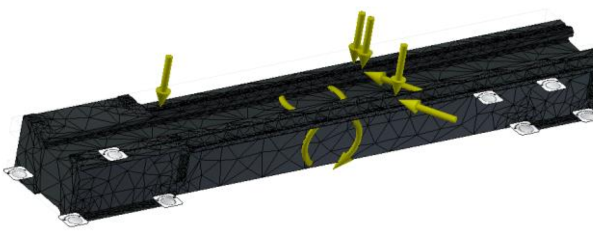

Figure 2. Calculation scheme of the bed of the turning machine mod. 16K20

The frame material is gray cast iron. The length of the frame is 2500 mm. The weight of the complete frame is 1328 kg.

Table 2

Physical and mechanical characteristics of the 3D lathe-bed model

Mechanical properties of cast iron			Strain			Characteristics of the frame			
Density, g/cm^3	Yield strength, MPa	Tensile strength, MPa	Young's modulus, GPa	Poisson's ratio	Shear modulus, GPa	Weight, kg	Area, m^2	Volume, m^3	Coordinates of center of mass, mm
7.15	119	276	90	0.3	34.62	1328.12	4.266	0.1857	x=-13.521 y=-151.202 z=1345.89

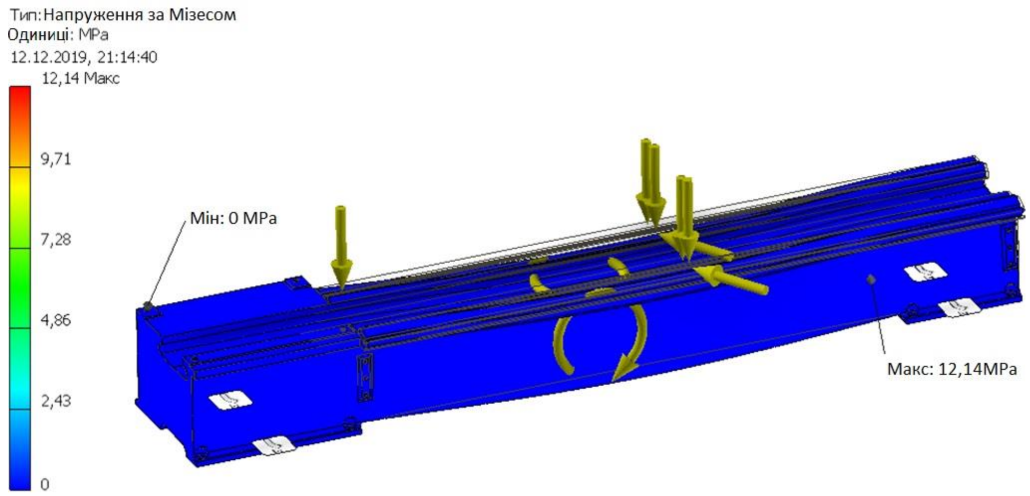

Figure 3. Stress-strain state of the bed-lathe model

After applying the force factors $M_{\text{tor}} = 3{,}917 \cdot 10^6$ Н · mm і $M_{\text{b}} = 4{,}35 \cdot 10^6$ Н · mm, calculated according to the method descriptions by author [6], the stress-strain state of the model was obtained (Fig. 3). The Mises stresses are in the blue zone and the maximum value is 12.14 MPa. However, the most interesting is the amount of displacement and deflection at the weakest point of the lathe-bed – in the middle (Fig. 3), since there are no additional supports in this place.

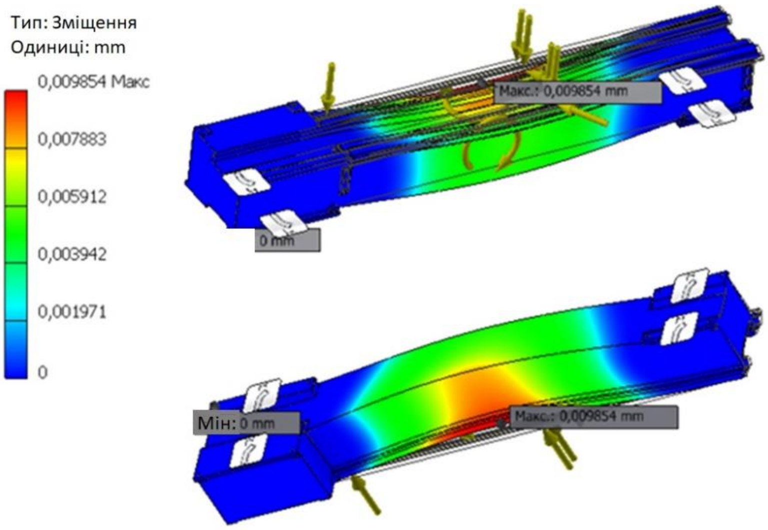

Figure 4. Deflection of the lathe-bed

Fig. 4 shows the deflection of the bed under the applied loads. The labels show that the maximum deflection in the middle of the bed is δ=0.009854 mm.

To estimate the material savings, the lathe-bed was modeled using the «Shape Generator» software module built into Autodesk Inventor, which allows for a new conceptual design by reducing weight while maintaining maximum rigidity. The algorithm of this program module works as follows. A researcher sets the pre-calculated loads in the 3D model, as well as the model areas that should not change (connection surfaces, bed guides, etc.), and then the shape generator calculates the distribution of material over the volume of shape of the part under study. As a result, the concept of the lathe bed is shown in Fig. 5. Fig. 6 shows a grid over a solid bed, which shows the areas of the structure that resist loads. Accordingly, other areas that are not marked with a grid are cut out of the 3D model, which reduces the weight of the studied bed.

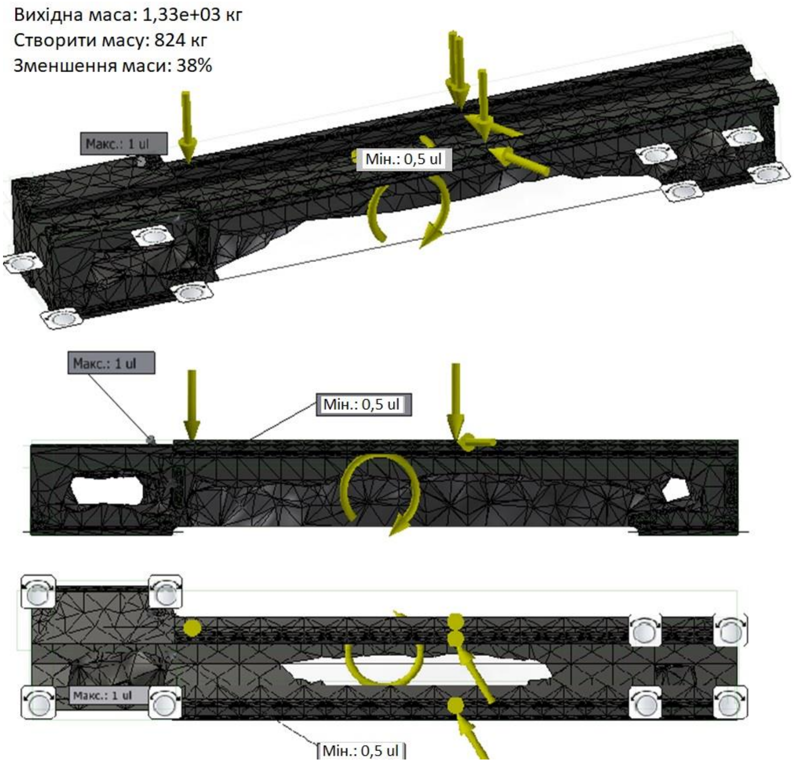

Figure 5. Conceptual model of the lathe-bed obtained using the shape generator

Fig. 6 shows the grid of the load-bearing area of the lathe-bed. The weight of the bed after topological optimization is 824 kg. The material saving is 38%.

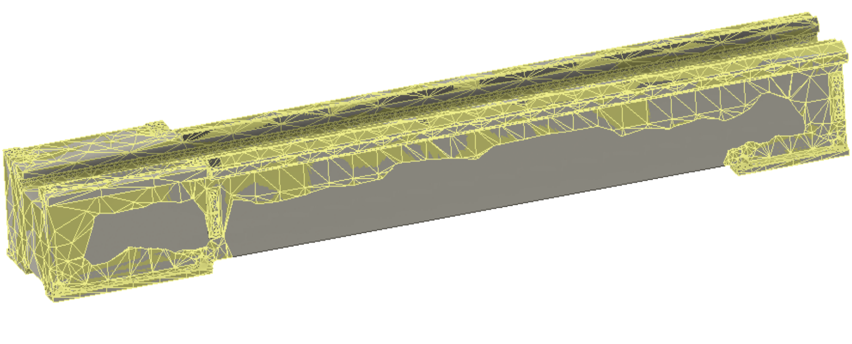

Figure 6. The grid model on the 3D model shows the elements that perceive the load

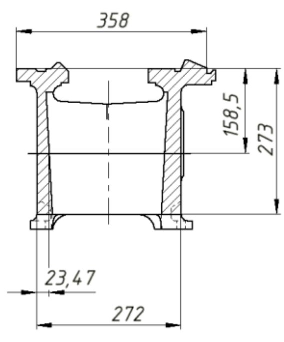

Figure 7. Cross-section of the 3D model of the lathe-bed

Table 3

Comparison of the results of modeling solid lathe-bed and lightened lathe-bed

Name	Minimum	Maximum	Minimum	Maximum
Weight	**1435.86 kg**		**761.9 kg**	
Mises stress	0.00031621 MPa	12.399 MPa	0.000857345 MPa	24.9722 MPa
1st principal stress	-2.97554 MPa	2.05148 MPa	-3.36948 MPa	4.6087 MPa
3rd principal stress	-12.7517 MPa	0.512344 MPa	-28.1447 MPa	1.22967 MPa
Displacement	0 mm	**0.00985401** mm	**0 mm**	**0.0441885 mm**
Safety factor	15	15	4.76531	15
Strain XX	-4.65305 MPa	0.946979 MPa	-11.5426 MPa	2.73307 MPa
Strain XY	-4.63156 MPa	1.96121 MPa	-9.23048 MPa	3.02944 MPa
Strain XZ	-2.68658 MPa	2.24636 MPa	-4.82782 MPa	2.49459 MPa
Strain YY	-9.38952 MPa	1.96246 MPa	-16.5602 MPa	2.5133 MPa
Strain YZ	-5.38606 MPa	4.88558 MPa	-10.3242 MPa	3.60001 MPa
Strain ZZ	-7.02659 MPa	1.68702 MPa	-12.0358 MPa	3.77799 MPa
Displacement along the X-axis	-0.00377238 mm	0.000133865 mm	**-0.0325724 mm**	**0.000177244 mm**
Displacement along the Y-axis	-0.0091384 mm	0.00141168 mm	**-0.0307107 mm**	**0.00444788 mm**
Displacement along the Z-axis	-0.00162634 mm	0.00220061 mm	**-0.00630393 mm**	**0.00748406 mm**
Equivalent deformation	0.00000000133839	0.0000538602	0.00000000892698	**0.000252169**
1st main deformation	-0.000000225622	0.0000181182	0.0000000051185	0.000116877
3rd main deformation	-0.0000611705	-0.000000000979953	-0.000285765	-0.00000000303817
Deformation XX	-0.0000170741	0.0000137118	-0.0000459578	0.0000493251
Deformation XY	-0.0000293709	0.000012437	-0.000133329	0.0000437586
Deformation XZ	-0.0000170368	0.0000142452	-0.0000697351	0.000036033
Deformation YY	-0.0000394336	0.00000906263	-0.000156746	0.0000404554
Deformation YZ	-0.0000341555	0.0000309817	-0.000149127	0.0000520001
Deformation ZZ	-0.000024341	0.0000154922	-0.000114101	0.0000544931

After optimization, a new lightweight bed was modeled (Fig. 8) and the stress-strain state was calculated (Fig. 9). The new lathe-bed weighs 761 kg, which is 63 kg less than the previous version.

Figure 8. 3D model of a lightweight lathe-bed

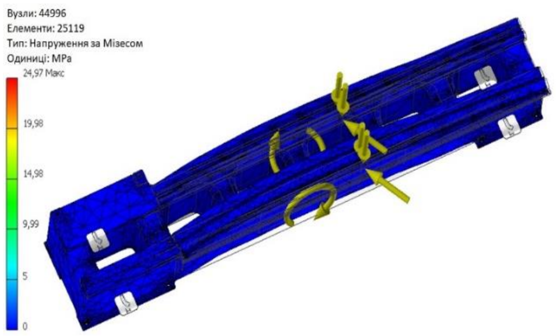

Figure 9. Stressed – deformed state of a lightweight lathe-bed

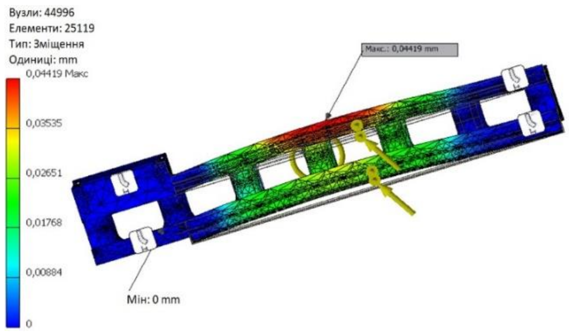

Figure 10. Displacement of the lightweight lathe-bed

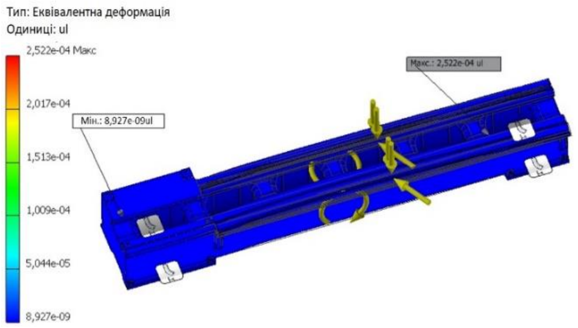

Figure 11. Equivalent deformation of a lightweight lathe-bed

Analysis of numerical results. From the study of solid models, it can be concluded that the stiffness of the machine bed and the structure as a whole is influenced by the materials, shape, and location of stiffeners. The purpose of the study was to obtain the deformation of the bed at maximum loads. Computer modeling has shown that the lightweight bed has larger axial displacements (Table 3), which is logical, because due to the reduction of the material, its stiffness has become less.

The comparative table shows that the maximum displacements along the X, Y and Z axes in the lightweight bed are almost 9 times greater, which is X=0.0325724 mm in the lightweight versus X=0.00377238 mm in the solid, along the Y axis almost 10 times Y=0.0307107 mm versus Y=0091384 mm, along the Z axis almost 4 times Z=0.00630393 mm versus Z=0.00162634 mm. The equivalent deformation also differs by a factor of 4.68 y=0.0000538602 mm vs. y=0.000252169 mm.

Based on the analytical calculations, the following results were obtained: torsional stiffness of the bed $GJ_{\text{tor}} = 3{,}001 \times 10^{12}$, displacement of the bed from bending at characteristic points, namely at 1/4, 2/4 and 3/4 of the length of the workpiece was $Y^{\Gamma}_{\text{b1}} = 0{,}057$ mm, $Y^{\Gamma}_{\text{b2}} = 0{,}106$ mm, $Y^{\Gamma}_{\text{b3}} = 0{,}062$ mm, and the displacement of the bed due to torsional deformation at these points was $Y^{\Gamma}_{\text{tor1}} = 0{,}074$ mm, $Y^{\Gamma}_{\text{tor2}} = 0{,}099$ mm, $Y^{\Gamma}_{\text{tor3}} = 0{,}074$ mm, respectively, the total deformation of the bed in the direction of the cutter axis was $Y_1 = 0{,}131$ mm, $Y_2 = 0{,}205$ mm, $Y_3 = 0{,}136$ mm. Mass of the workpiece with the specified length and diameter is $m = 418$ kg, which is always machined with an additional support – a lunette. Reducing the length of the workpiece to 1000 mm decreases the deflection by almost 2 times, namely $Y_1 = 0{,}073$ mm, $Y_2 = 0{,}109$ mm, $Y_3 = 0{,}076$ mm as shown in the graph in Fig. 12.

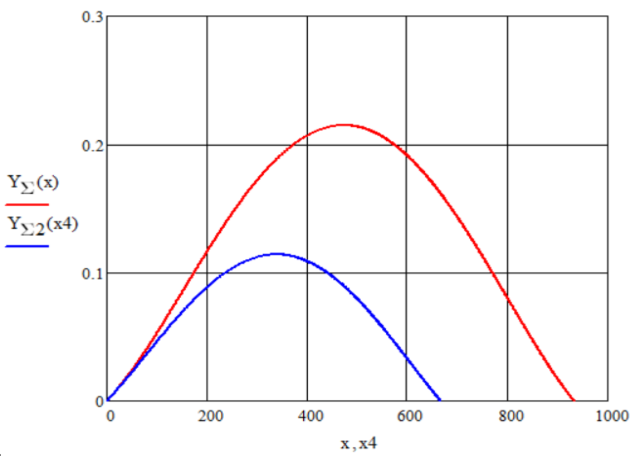

Figure 12. Deflection of parts 1000 mm and 1400 mm long

Conclusions. Modeling of lathe-beds using a shape generator allows obtaining an optimal design taking into account the distribution of material mass over the volume of the shape in terms of weight – stiffness, taking into account the specified force factors. This makes it possible to obtain not only geometric characteristics, deflection and stiffness, but also to effectively plan and forecast the production of machines. In general, the use of generative modeling proves that it is possible to obtain a structure with acceptable stiffness and significant material savings. Analytical calculations should be performed in connection with modeling. They make it possible to calculate the effect of the lathe-bed stiffness on the deflection of the part and complement the modeling methods. Based on the calculations, it is clear that at maximum cutting conditions, the deformation of the bed takes place and it directly affects the shape of the machined parts, namely, it creates barrel-shaped deviations from cylindricality.

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МОДЕЛЮВАННЯ СТАНИНИ ТОКАРНОГО ВЕРСТАТА З ВИКОРИСТАННЯМ МЕТОДУ ТОПОЛОГІЧНОЇ ОПТИМІЗАЦІЇ

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Резюме. *На основі креслень типової конструкції станини токарного верстата мод.16К20 виконано її 3Д модель. Проведено дослідження із використанням силових факторів. За допомогою модуля генератор форм від Autodesk отримано концептуально нову полегшену конструкцію станини із урахуванням силових факторів. Метод дослідження являє собою топологічну оптимізацію досліджуваної моделі, котра дозволяє отримати нову концептуальну модель станини з прийнятною жорсткістю та значною економією матеріалу. Проведено огляд матеріалів для виготовлення станин і дано їх оцінку. Стосовно використання матеріалу для виготовлення станини, то чавун, з точки зору «механічні характеристики – ціна – вага» залишається найоптимальнішим матеріалом. Ми бачимо його переваги у балансі характеристик. Дані моделювання дозволяють побачити внутрішні напруження конструкції, прогин деталі, переміщення від прикладених силових факторів. Наведені зображення 3Д моделі наочно це демонструють. Недоліком генератора форм є неможливість досліджувати 3Д модель із кількох матеріалів, тому дослідження проводилися для гомогенної моделі. Безперечною перевагою генератора форм, який працює на основі методу скінченних елементів, є те, що він наочно показує ділянки конструкції, котрі є баластом і не сприймають жодного навантаження. Це дозволяє інженеру-досліднику оптимізувати конструкцію з урахуванням рекомендацій генератора форм, накопичених знань та досвіду. Таким чином, ми отримали нову концептуальну модель станини для подальших теоретичних експериментів. Також проведено аналітичний розрахунок конструкції станини з використанням наведеної методики. Отримано величини прогину станини та її вплив на прогин деталі. Для розширення дослідження розрахунки проведено для деталей різних довжин, а саме 1000 мм і 1400 мм. Це дослідження не відображає динамічного стану механічної обробки деталей у динаміці, проте дозволяє оцінити слабкі сторони конструкції й визначити тенденції щодо підсилення чи полегшення окремих ділянок. Зокрема, використання топологічної оптимізації дозволяє оцінити можливу економію матеріалу, що актуальтно в умовах декарбонізації виробництва й тенденцій щодо сталого розвитку.*

Ключові слова: *топологічна оптимізація, моделювання, верстат, 3D модель, токарні верстати, ефективність використання металу, сталий розвиток.*

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