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RESEARCH OF THE STRESSED AND DEFORMED STATE OF A METAL STRIP DURING THE BROACHING PROCESS

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In papers [2, 4, 5] the solution relations and the algorithm of the method of block iterations of solving linear and nonlinear equations by the semivanalytic finite element method for curvilinear inhomogeneous prismatic bodies are realized. In paper [1], a numerical study of the convergence of solutions was performed, and a wide range of test problems for bodies with smoothly and abruptly changing physical and geometric characteristics in elastic and resilient-plastic formulation was considered. In paper [6], to confirm the reliability of the results obtained on the basis of the semi-analytical finite element method, the effectiveness of this approach for the calculation of curvilinear inhomogeneous prismatic objects is shown. Solving control problems of the theory of elasticity, thermoelasticity and thermoplasticity, as well as problems of shape change makes it possible to draw conclusions about the reliability of the results of the study of a selected class of objects based on the developed methodology and implements its application package.

In this work, using the methodology outlined in the above works, the solution of the spatial problem of plastic deformation of a prismatic body was solved on the basis of the semi-analytical method of finite elements, and the process of broaching a strip in the process of metal embossing was analyzed. The purpose of this study is to determine the spatial picture of the stress-strain state of the strip during drawing and to compare the spatial resolution with the flat one. A comparison of the parameters of the stress-strain state of the workpiece during the broaching process, obtained in flat and spatial settings, allows us to conclude that the research must be carried out on the basis of spatial calculation.

Keywords: finite element method (FEM), semi-analytical finite element method (SAFEM), stress-strain state, elastic and elastic-plastic deformation, shape change, strip broaching, metal embossing, flat and spatial production.

Introduction. The broaching operation is used to increase the length of the workpiece by reducing its cross-section (Fig. 1, 2). The contact of the workpiece and the tool during broaching is not carried out over the entire surface of the workpiece, but only on its part, i.e. There are quite extensive external zones that do not interact with the tool.

Broaching is an important operation of processing metals by pressure, this method is used during the production of many important parts of energy and transport engineering. The development of broaching technology requires a correct assessment of the nature of the stressed-deformed state of the workpiece.

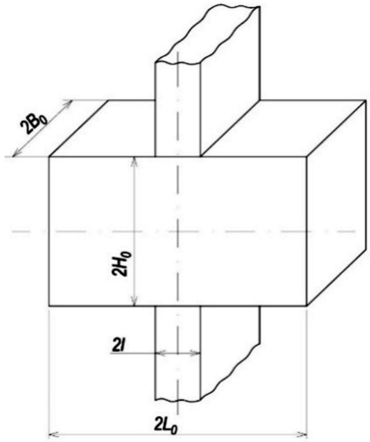


Fig. 1. The workpiece is in an undeformed state

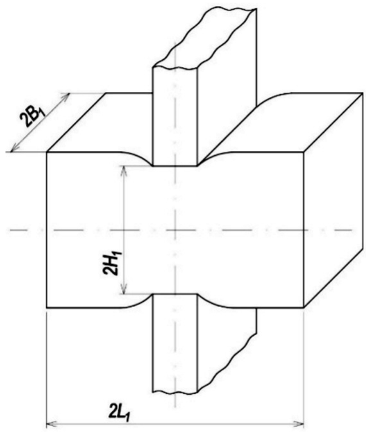


Fig. 2. The workpiece is in a deformed state

Obtaining such information is possible only on the basis of numerical methods, among which the finite element method has become the most common. There are known publications [3, 7] in which the broaching process is considered by FEM in a flat setup.

Analysis of the process of broaching a strip of rectangular section. Consider a stretch of strip, the dimensions of the cross-section of which are in theundeformed state $2H_0$=$2B$=80 mm, its length $2L_0$=130 mm, and the length of the working part of the striker $2L$= 25 mm. The workpiece material is D16 alloy. The physical characteristics of the material are taken in accordance with the strain hardening curve schedule at T = 450 ºC.

To substantiate the adequacy of the initial ratios of the deformation process, the trajectories of points C and D lying on the surface of the freely deforming body were constructed (Fig. 3). Their configuration is close to a straight line, which indicates the correctness of the selection of the state levels.

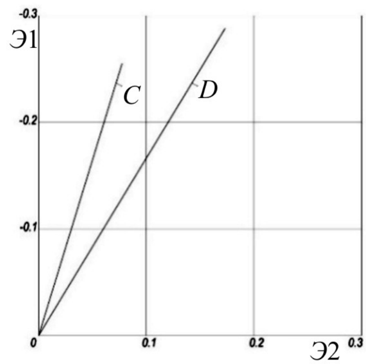


Fig. 3.Trajectories of points C and D

The calculation scheme is shown in Fig. 4. In the plane of the longitudinal section, a grid of finite elements is drawn, uneven in the $Z^{2'}$, direction, along the $Z^{3'}$axis, expansion into a series of polynomials was used. The movement of the tool was modeled by the problem of rigid shifts $\Delta U^{1'}$ in the direction $Z^{1'}$.

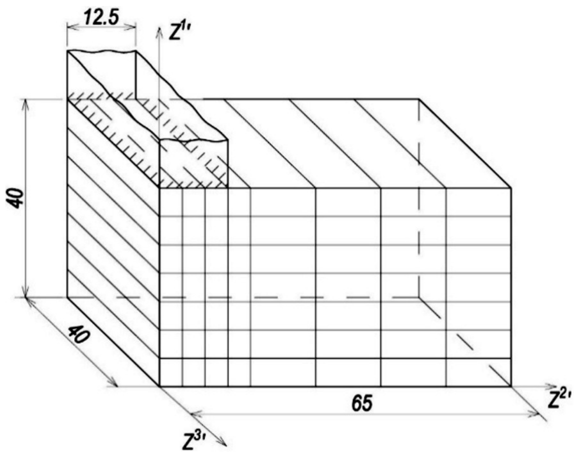


Fig. 4. Settlement scheme

As experiments show [8, 9], with the selected ratios of the geometric dimensions of the working part of the hammers and the cross-section of the workpiece, there is no contact sliding during broaching between dry rough plates. Therefore, boundary conditions corresponding to complete "sticking" are adopted on the contact surfaces of the workpiece and the tool. When solving the problem in a flat setting, the absence of displacements $U^{3'}$ of the side surface of the body was assumed to simulate the conditions of plane deformation in the $Z^{3'}$ direction.

The plastic deformation process is considered up to the degree of height compression, which is 18.8%.

To substantiate the reliability of the obtained results, a number of convergence studies were conducted depending on the number of finite elements in the plane $Z^{3'}= 0$, the number of retained members, the expansion along $Z^{3'}$, the size of the step in the displacement parameter, and the accuracy of solving systems of nonlinear equations.

It was found that to approximate the object, it is sufficient to use a grid with a total number of nodes in the plane of the longitudinal section, equal to 96, and to keep the first 5 expansion members along $Z^{3'}$. Thickening the mesh of finite elements by 1.5 times and increasing the number of retained expansion members by 2 times leads to a refinement of the result by less than 3 The size of the step of the forced shift $\Delta U^{1'}$ is chosen equal to 1,5 mm and has little effect on the convergence of the result.Thus, increasing the step by 3 times resulted in a loss of calculation accuracy by only 1%. The study of the accuracy of solving systems of nonlinear equations showed that for this problem, convergence was achieved at $\xi=10^{-5}$. An increase in the ξparameter by an order of magnitude resulted in a refinement of 1,7%.

One of the variants of the position of the approximating grid in the deformed state is presented in fig. 5.

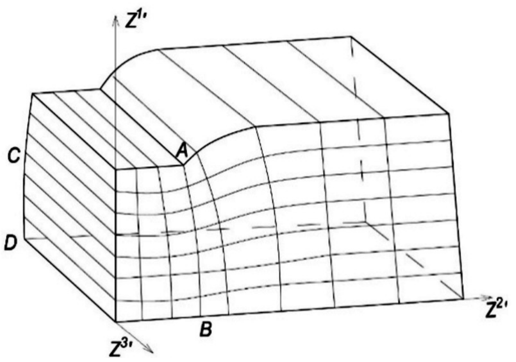


Fig. 5. The approximating grid in a deformed state

To detail the change in body shape during stretching, consider the movement of the most characteristic parts of the body. In Fig. 6 (a,b), 7 shows the graphs of the movements of points $U^{3'}$ of the lateral surface of the body in the transverse plane of symmetry, $U^{3'}$ in the longitudinal plane of symmetry, and $U^{2'}$ along the line AB in the longitudinal plane of symmetry at different stages of broaching. Numbers 1 indicate the curves obtained at ξ_1=3,8%, numbers 2 – at ξ_1=11,3%, 3 – at ξ_1=18,8%. The dashed line (Fig. 8) shows the corresponding plot $U^{2'}$, built based on the results of solving the planar problem.

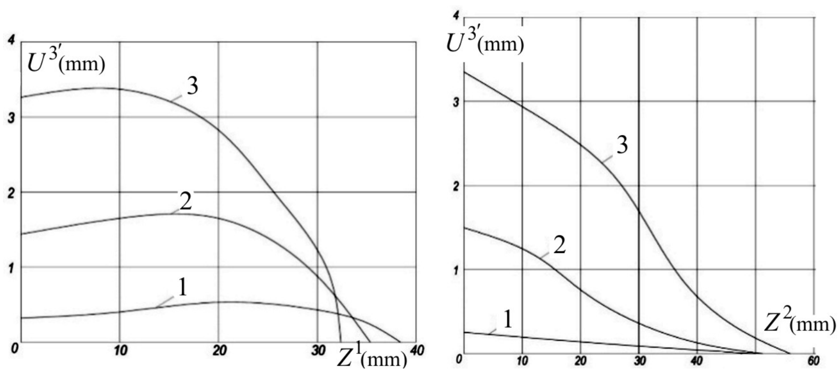


Fig. 6. Plots of movements $U^{3'}$

The main difference between the spatial solution and the planar solution is that the barrel formation occurs not only in the plane $Z^{3'}$=0, but also along the entire side surface of the workpiece (Fig. 6 (a),(b)).

Accounting for movements $U^{3'}$ leads to a significant quantitative change in the pattern of movements of body points in the longitudinal plane of symmetry (Fig. 7). In the area of maximum displacements $U^{2'}$ the planar solution gives a result that is overestimated by almost 60% compared to the spatial solution.

Plots of deformations along the $Z^{1'}$ coordinate on the axis of symmetry of the workpiece at the maximum degree of compression are presented in Fig. 8 (a). The planar solution (dashed line) gives the longitudinal strains ε_{22} the axis of symmetry by 60% overestimated compared to the three-dimensional one. The lower level of ε_{22}, deformations obtained in the spatial setting is due to the consideration of shape change along $Z^{3'}$ and, therefore, the presence of ε_{33}deformations. A similar discrepancy in results is also observed from the comparison of ε_{22}, graphs constructed along the longitudinal axis of symmetry of the workpiece (Fig. 8 (b)).

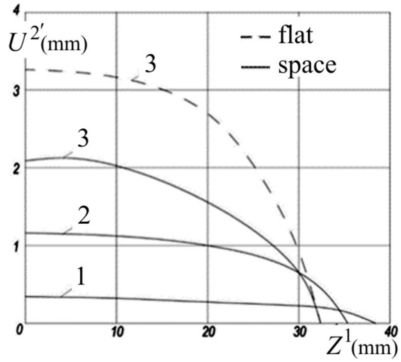
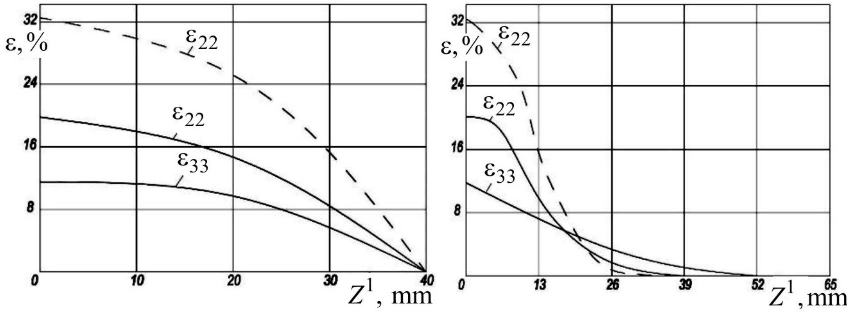


Fig. 7. Plots of movements $U^{2'}$



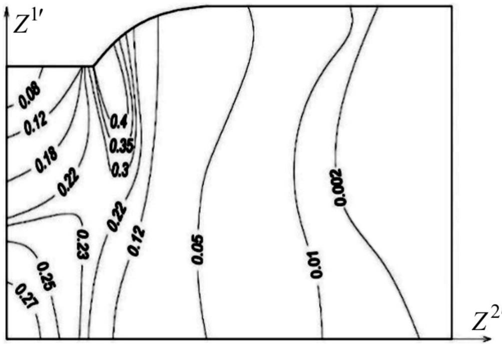
(a) (b)

Fig. 8. Plots of deformations

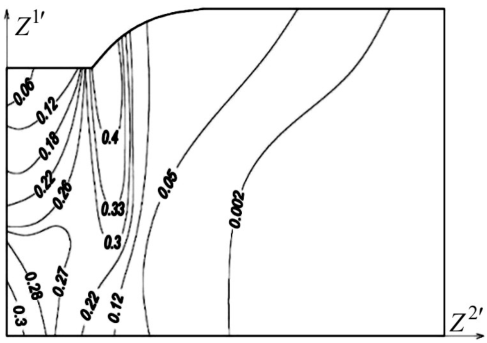
In Fig. 9 (a), (b) shows the isolines of the intensity of plastic deformations in the longitudinal section of the body in the $Z^{3'}$=0 plane, respectively, for the spatial and planar resolution. It turned out that in this field, the distribution of plastic deformations, obtained by both calculation options, is quite close.

The stress plots $\sigma^{1'}\sigma^{1'}$, constructed along the vertical axis of symmetry of the workpiece (Fig. 10) for the planar and spatial solutions, have qualitatively the same character. At the boundary of the region of difficult deformation in both cases, an increase in compressive stresses is observed, and in the near-contact region, they are somewhat reduced. This is in good agreement with the results given in [7] taking into account a flat calculation.

Quantitative discrepancies between the values of $\sigma^{1'}\sigma^{1'}$ obtained in the three-dimensional and planar setting in the region of the maximum amount to approximately 60%.



(a)



(b)

Fig. 9.Isolines of intensity of plastic deformations

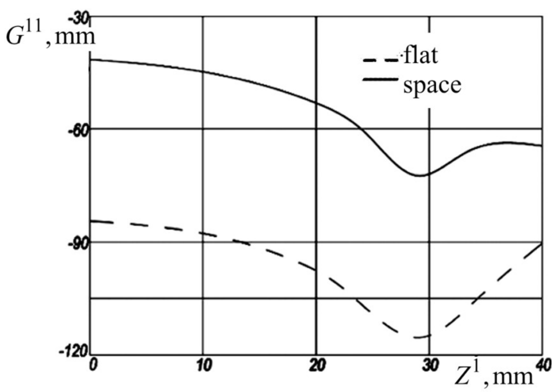


Fig. 10. Plots of voltage $\sigma^{2'}\sigma^{2'}$

One of the important characteristics of the considered process is the broaching effort. The graphs of the dependence of the broaching force on the degree of deformation in height are shown in Fig. 11.

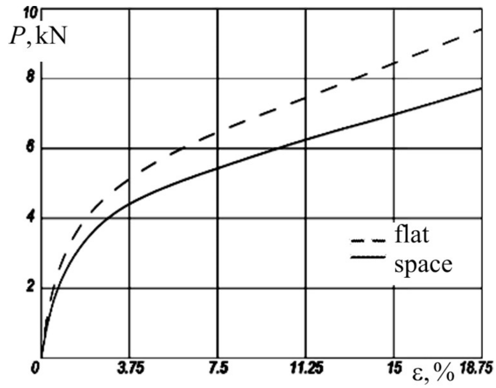


Fig. 11. Graphsofthefallowofsusillabroachesinthedegreeofdeformationinheight

Their comparison shows that at the maximum degree of deformation, the planar solution gives a result more than 30% higher in comparison with the spatial solution.

Conclusion. Thus, the comparison of the parameters of the stress-strain state of the workpiece during the broaching process, obtained in the flat and spatial settings, allows us to conclude that the research must be conducted on the basis of spatial calculation.

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Максим'юк Ю.В., Кузьмінець М.П., Мартинюк І.Ю., Максим'юк О.В.

ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ МЕТАЛЕВОЇ СМУГИ У ПРОЦЕСІ ПРОТЯЖКИ

У роботах [2,4,5] реалізовано розв'язувальні співвідношення та алгоритм методу блочних ітерацій розв'язання лінійних і нелінійних рівнянь напіваналітичним методом скінчених елементів для криволінійних неоднорідних призматичних тіл. У роботі [1] виконано чисельне дослідження збіжності розв'язання, розглянуто широке коло тестових задач для тіл з плавно і стрибкоподібно мінливими фізичними та геометричними характеристиками в пружній і пружно-пластичній постановці. В [6] для підтвердження достовірності одержуваних результатів на основі напіваналітичного методу скінчених елементів, показано ефективність застосування даного підходу для розрахунку криволінійних неоднорідних призматичних об'єктів. Розв'язання контрольних задач теорії пружності, термопружності та термопластичності, а також задач формозмінення дає можливість зробити висновок про достовірність результатів дослідження виділеного класу об'єктів на базі розробленої методики та реалізує її пакет прикладних програм.

У даній роботі, використовуючи методику, викладену в наведених вище роботах, було виконано на основі напіваналітичного методу скінчених елементів розв'язання просторової задачі пластичного формозмінення призматичного тіла і проведено аналіз процесу протягування смуги в процесі обробки металу тисненням. Мета цього дослідження полягає у визначенні просторової картини напружено-деформованого стану смуги у процесі протяжки та зіставленні просторового розв'язання з плоским. Зіставлення параметрів напружено-деформованого стану заготівки в процесі протяжки, отриманих у плоскій та просторовій постановках, дозволяє зробити висновок, що дослідження необхідно проводити на базі просторового розрахунку.

Ключові слова: метод скінченних елементів, напіваналітичний метод скінченних елементів, напружено-деформований стан, пружне та пружно-пластичне деформування, формозмінення, протяжка полоси, обробка металу тисненням, плоска та просторова постановка.

Maksimyuk Yu.V, Kuzminets M.P., Martyniuk I.Yu., Maksimyuk O.V.
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In this work, using the methodology outlined in the above works, the solution of the spatial problem of plastic deformation of a prismatic body was solved on the basis of the semi-analytical method of finite elements, and the process of broaching a strip in the process of metal embossing was analyzed. The purpose of this study is to determine the spatial picture of the stress-strain state of the strip during drawing and to compare the spatial resolution with the flat one. A comparison of the parameters of the stress-strain state of the workpiece during the broaching process, obtained in flat and spatial settings, allows us to conclude that the research must be carried out on the basis of spatial calculation.

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Максим'юк Ю.В., Кузьмінець М.П., Мартинюк І.Ю., Максим'юк О.В. **Дослідження напружено-деформованого стану металевоїсмуги у процесі протяжки** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – Київ: КНУБА, 2022. – Вип. 109. – С. 229-238.
В данійроботі, використовуючи методику, викладену в роботах [1,2,4-6] було виконано на основі напіваналітичного методу скінчених елементів розв'язання просторової задачі пластичного формозмінення призматичного тіла і проведено аналіз процесу протягування смуги в процес обробки металу тисненням. Мета цьогодо слідження полягає у визначенні просторової картини напружено-деформованого стану смуги у процесі протяжки та зіставленні просторового розв'язання з плоским. Зіставлення параметрів напружено-деформованого стану заготівки в процесі протяжки, отриманих у плоскій та просторовій постановках, дозволяє зробити висновок, що дослідження необхідно проводити на базі просторового розрахунку.
Табл. 0. Іл. 11. Бібліогр. 9 назв.

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Maksimyuk Yu.V, Kuzminets M.P., Martyniuk I.Yu., Maksimyuk O.V. **Research of the stressed and deformed state of metal stripin the broaching process** // Strength of Materials and Theory of Structures: Scientific-&-Technical collected articles. – Kyiv: KNUBA, 2022. – Issue 109. – C. 229-238.
In this work, using the methodology outlined in works [1,2,4-6], the solution of the spatial problem of plastic deformation of a prismatic body was solved on the basis of the semi-analytical method of finite elements, and the analysis of the strip broaching process in the process of metal embossing was carried out. The purpose of this study is to determine the spatial picture of the stress-strain state of the strip during drawing and to compare the spatial resolution with the flat one. A comparison of the parameters of the stress-strain state of the workpiece during the broaching process, obtained in flat and spatial settings, allows us to conclude that the research must be carried out on the basis of spatial calculation.
Table 0. Fig 11. Ref. 9.

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