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Study of the effect of part geometry on the pressure rise law of the forming gas using computer simulation

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ABSTRACT

Introduction. Currently, in the industry, the method of superplastic molding (SPM) is used to manufacture complex-profile thin-walled parts, as well as elements of a hollow structure. To increase the efficiency of the SPM process, it is advisable to pre-form a nanostructured state in materials. The accuracy of the part geometry, the quality of the final product and the duration of the production process are significantly affected by the supply of forming gas using a gas distribution system (GDS). One of the key aspects of GDS operation is the identification of optimal gas supply modes for parts with different geometries. Computer modeling of the SPM process allows you to analyze molding modes without the need for expensive and lengthy real experiments. The study is aimed at identifying the relationship between the pressure increase of the forming gas and the geometry of the part. **Methods and materials.** Modeling and finite element analysis (FE analysis) of SPM parts of the "dome" type made of titanium alloy VT-6 with different thickness of workpieces and geometry was carried out using the MSC Marc software package. The results and discussion are given. The results of the FE analysis of the SPM process are given. In the course of research, it was found that when the thickness of the billet changes, the graphs of the forming gas supply do not change their behavior, but their scale changes. That is, while maintaining the running time of the main forming steps, the pressure of the forming gas is significantly increased, resulting in an increase in the supply rate of the forming gas. Three steps can be distinguished in the molding gas supply plots, and the gas pressure rise between the steps is non-linear. Depending on the shape of the part, these steps may vary. **Conclusion.** The obtained gas supply dependencies make it possible to form experience in working with the technological process of molding various parts, as well as to identify requirements for the development of promising gas distribution systems.

KEYWORDS: nanostructured materials, part, geometry, thickness, superplas-tic molding, molding gas pressure and feed rate, finite element analysis

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Исследование влияния геометрии детали на закон повышения давления формующего газа с применением компьютерного моделирования

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АННОТАЦИЯ

Введение. В настоящее время в промышленности для изготовления сложнопрофильных тонкостенных деталей, а также элементов полой конструкции используется метод сверхпластической формовки (СПФ). Для повышения эффективности процесса СПФ целесообразным является предварительное формирование в материалах наноструктурного состояния. Значительное влияние на точность геометрии детали, качество конечного изделия и продолжительность производственного процесса оказывает подача формующего газа, реализуемая с использованием газораспределительной системы (ГРС). Одним из ключевых аспектов работы ГРС является выявление оптимальных режимов подачи газа для деталей с различной геометрией. Компьютерное моделирование процесса СПФ позволяет анализировать режимы формовки без необходимости проведения дорогостоящих и длительных реальных экспериментов. Исследование направлено на выявление зависимости между повышением давления формующего газа и геометрией детали. **Методы и материалы.** Моделирование и конечно-элементный анализ (КЭ анализ) СПФ деталей типа «купол» из титанового сплава ВТ-6 с различной толщиной заготовок и геометрией проводилось с помощью программного комплекса MSC Marc. **Результаты и обсуждение.** Приводятся результаты КЭ анализа процесса СПФ. В ходе проведения исследований установлено, что при изменении толщины заготовки графики подачи формующего газа не изменяют своего характера поведения, но при этом изменяется их масштаб. То есть при сохранении времени протекания основных этапов формовки значительно увеличивается давление формовочного газа, что приводит к повышению скорости подачи формовочного газа. На графиках подачи формовочного газа можно выделить три этапа, и рост давления газа между этапами происходит нелинейно. В зависимости от формы детали данные этапы могут отличаться. **Заключение.** Полученные зависимости подачи газа позволяют сформировать опыт работы с технологическим процессом формовки различных деталей, а также выявить требования для разработки перспективных систем газораспределения.

КЛЮЧЕВЫЕ СЛОВА: наноструктурные материалы, деталь, геометрия, толщина, сверхпластическая формовка, давление и скорость подачи формовочного газа, конечно-элементный анализ

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Исследование выполнено в рамках программы Министерства науки и высшего образования Российской Федерации «ПРИОРИТЕТ 2030».

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INTRODUCTION

In modern high-tech industries, such as aircraft and mechanical engineering, complex-profile thin-walled parts, as well as elements of a hollow structure, are widespread. These parts can significantly reduce the mass of products, and complex geometry is often used to improve the performance of parts, which makes products competitive. For example, aircraft engine blades with complex geometry and hollow structure provide high thrust characteristics of gas turbine engines [1].

Traditional methods of manufacturing such parts are labor intensive and time consuming. In some cases, the use of such production methods is generally impossible. Therefore, the introduction of innovative technologies, such as the SPF method, becomes an urgent task [1–6]. This method makes it possible to manufacture parts of complex geometry and hollow structure with high efficiency, which is especially important for advanced industries.

The structure of the material is extremely important for the manifestation of superplasticity of parts. Thus, the formation of a nanostructured state of the material makes

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it possible to more efficiently mold more geometrically complex parts, which makes the SPF process more energy efficient.

One of the key aspects of SPF technology is the injection of blowing gas, which has a significant impact on the accuracy of the part geometry, the quality of the final product and the duration of the production process. Gas distribution stations [7–9] are used to supply gas to the process complexes of the SPF.

To create and justify the requirements for GDS, it is necessary to conduct a comparative analysis of gas supply modes for parts of different geometries. Computer modeling of the SPF process allows analyzing molding modes without the need for expensive and lengthy real experiments [10–18]. This analysis allows you to determine the optimal parameters for the production of parts of various geometries, ensuring high quality and accuracy of products. This significantly reduces time and financial costs, and also accelerates the introduction of SPF technology into production processes.

In addition, the analysis of gas supply modes in various parts helps to optimize the production of parts by the SPF method, which in turn affects the increase in the productivity of production lines, reducing the cost of materials and energy resources.

Thus, comparative analysis of forming gas supply modes is an important step in the development and optimization of the SPF technology.

The purpose of this work is to simulate (with FE analysis) the process of SPF of parts of the "dome" type with different thickness of blanks and geometry using the MSCMarc software package [19].

METHODS AND MATERIALS.

During the FE analysis, two types of part geometry were analyzed. For each type of geometry, three workpiece thicknesses are considered: 1, 2, and 3 mm. The considered material of the parts is titanium alloy VT-6 [20, 21].

The dome part is selected for investigation due to the fact that its optimal geometry allows to demonstrate the basic SPF processes. Geometry of this part is taken as a basis for scientific research and experiments in the direction of superplasty. Finite element computations were performed in the MSC Marc software package [19, 22–26].

Cross-sections of molds 1 and 2 into which the initial billet was formed are shown in Figure 1. The workpiece is a circle with a diameter of 200 mm of various thicknesses (1, 2 and 3 mm).

The finite element model of the workpiece surface is shown in Figure 2 and contains 14400 elements.

Fastening the workpiece simulates its clamping at the edges in a die fixture that fixes along all axes of freedom. Maximum forming gas pressure limit is 10 MPa.

The workpiece surface and shapes are shown in Figure 3.

RESULTS AND DISCUSSION

The results of the Form 1 stock calculation are shown below.

The results of the calculation of the workpiece with a thickness of 1 mm are shown in Figures 4–5. The maximum equivalent stresses in the workpiece are 38.9 MPa. Maximum pressure of forming gas is p = 0.32 MPa, time of forming process is t = 3061 s.

The results of the calculation of the workpiece with a thickness of 2 mm are shown in Figures 6–7. The maximum equivalent stresses in the workpiece are 38.7 MPa, the maximum pressure of the molding gas is 0.60 MPa, and the molding process time is 3061 s.

The results of the calculation of the workpiece with a thickness of 3 mm are shown in Figures 8–9. The maximum equivalent stresses in the billet are 38.6 MPa, the

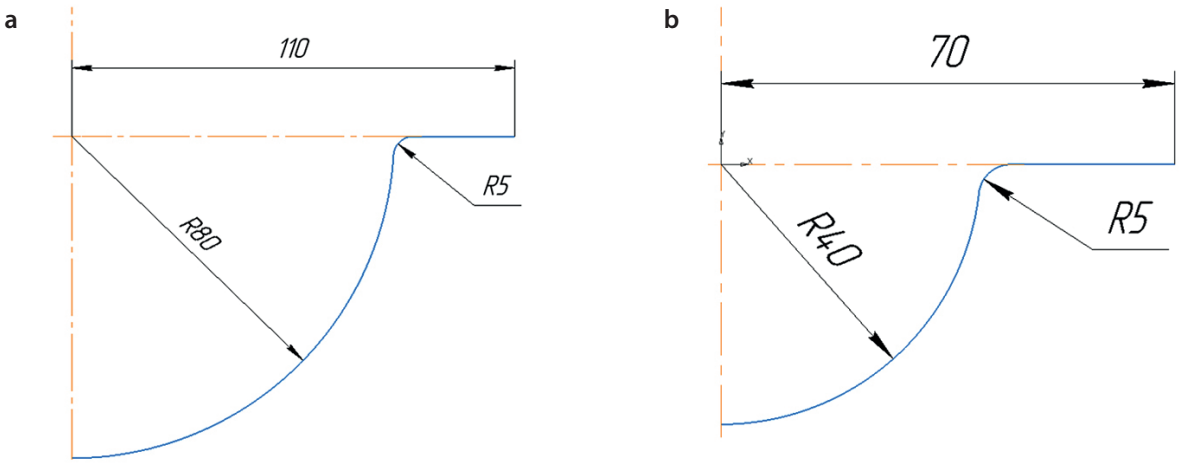

Fig. 1. Shape sections: a – form 1; b – form 2

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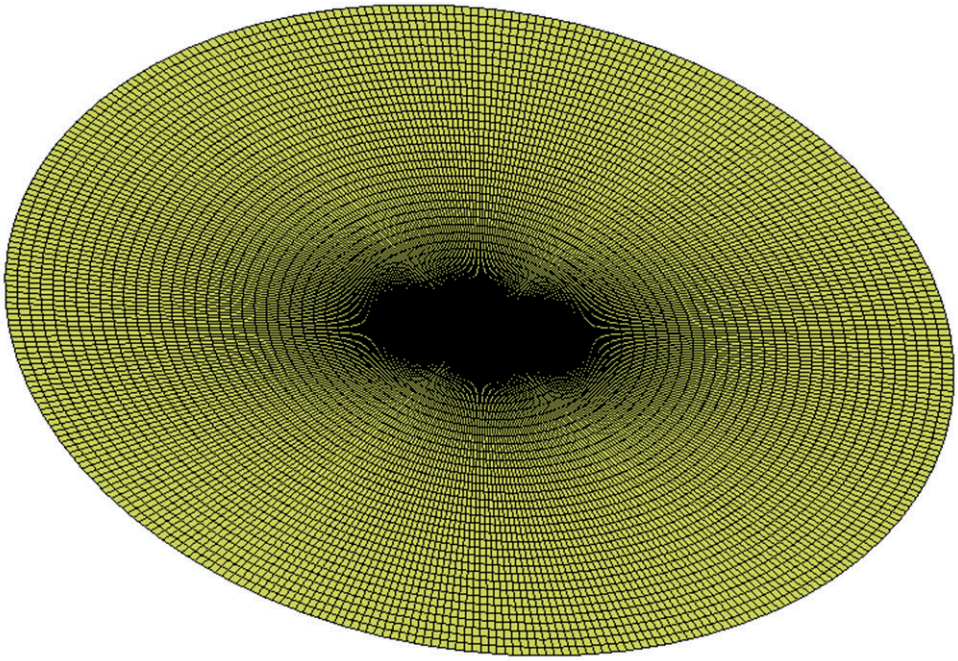

Fig. 2. FEM workpiece surface model

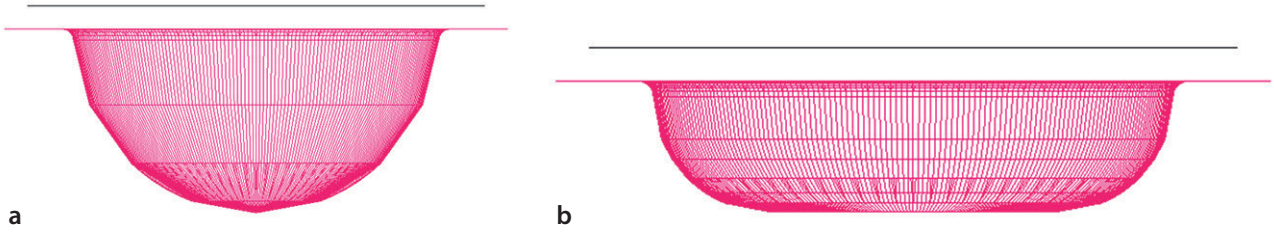

Fig. 3. Workpiece surface and shapes: a – blank with form 1; b – blank with form 2

maximum pressure of the molding gas is 0.91 MPa, and the molding process time is 3131 s.

It can be seen that as the thickness of the billet increases, the equivalent stresses in it practically do not change during the molding process. But this significantly increases the area of exposure to maximum equivalent stresses in the part. This should be taken into account when designing complex-profile products with "thin" places in geometry.

Equivalent plastic deformations with an increase in the thickness of the workpiece are also practically unchanged.

The law of gas supply does not change its behavior when the thickness of the part increases. However, it should be noted that with an increase in thickness by 1 mm, the process time remains practically unchanged (an increase of not more than 3%), and the maximum pressure of the forming gas increases significantly (when switching from 1 mm to 2 mm, an increase of 100%, when switching from 2 mm to 3 mm, an increase of 50%). If the behavior of the gas supply law is unchanged, this means that the gas supply speed in the main sections of the graph also increases significantly.

Divide the graph shown in Figure 8 into 3 main area (Fig. 10):

– area 1 – "opening" of the workpiece – at this stage the gas pressure overcomes the forces of resistance of the material to the flow;
– area 2 – the main stage of molding – plastic deformation of the workpiece occurs with increasing pressure;
– area 3 – "holding" – residual flow of material with slight pressure release.

We estimate the rate of gas supply (discharge) for each of the sections. Table 1 shows the gas feed rates for each section on different thickness blanks.

Analyzing the obtained results, it can be seen that the pressure increase (decrease) occurs non-linearly, both

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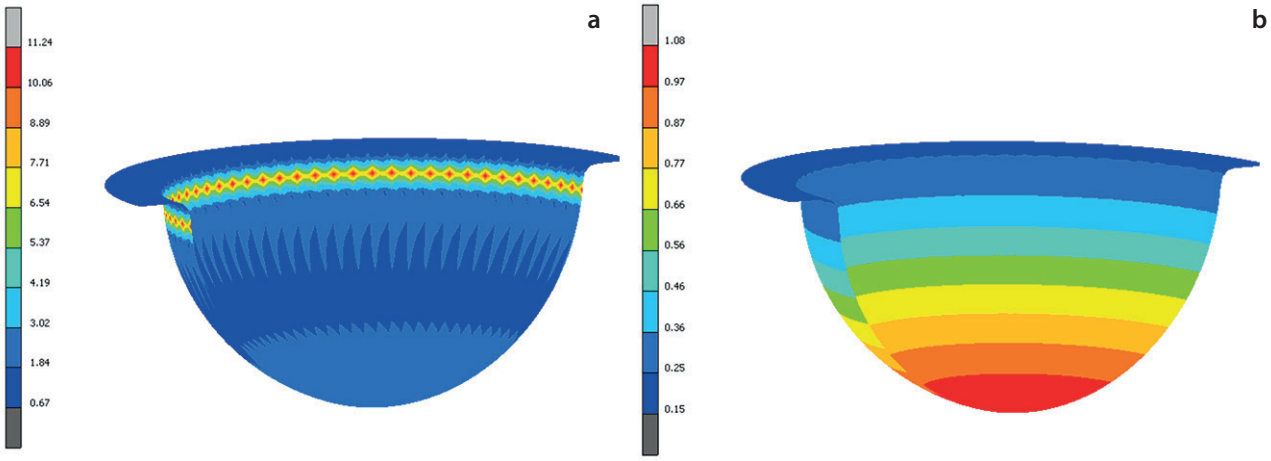

Fig. 4. Distribution of equivalent stresses in the workpiece with thickness 1 mm equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

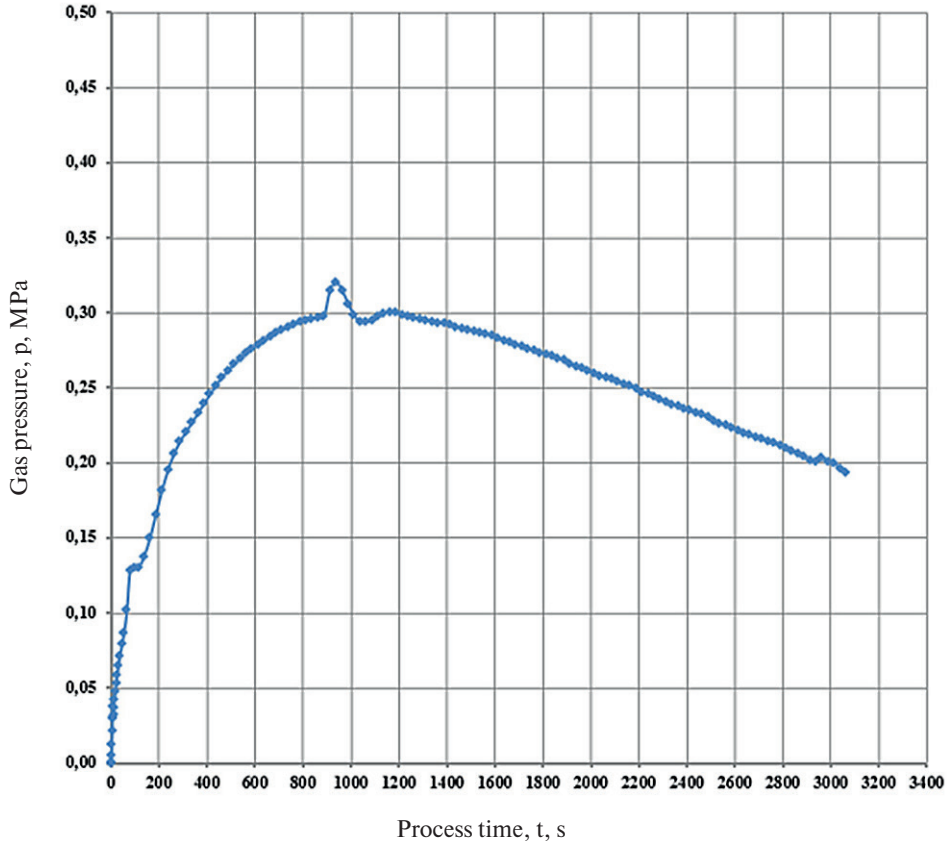

Fig. 5. Diagram of forming gas supply to the billet with thickness of 1 mm

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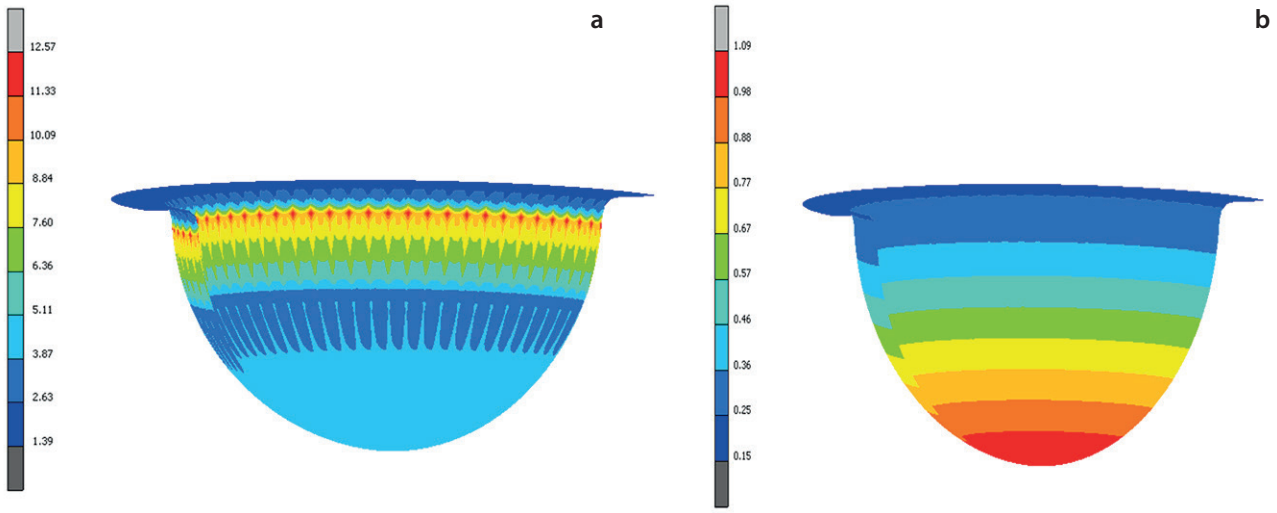

Fig. 6. Distribution of equivalent stresses in the workpiece with thickness 2 mm and equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

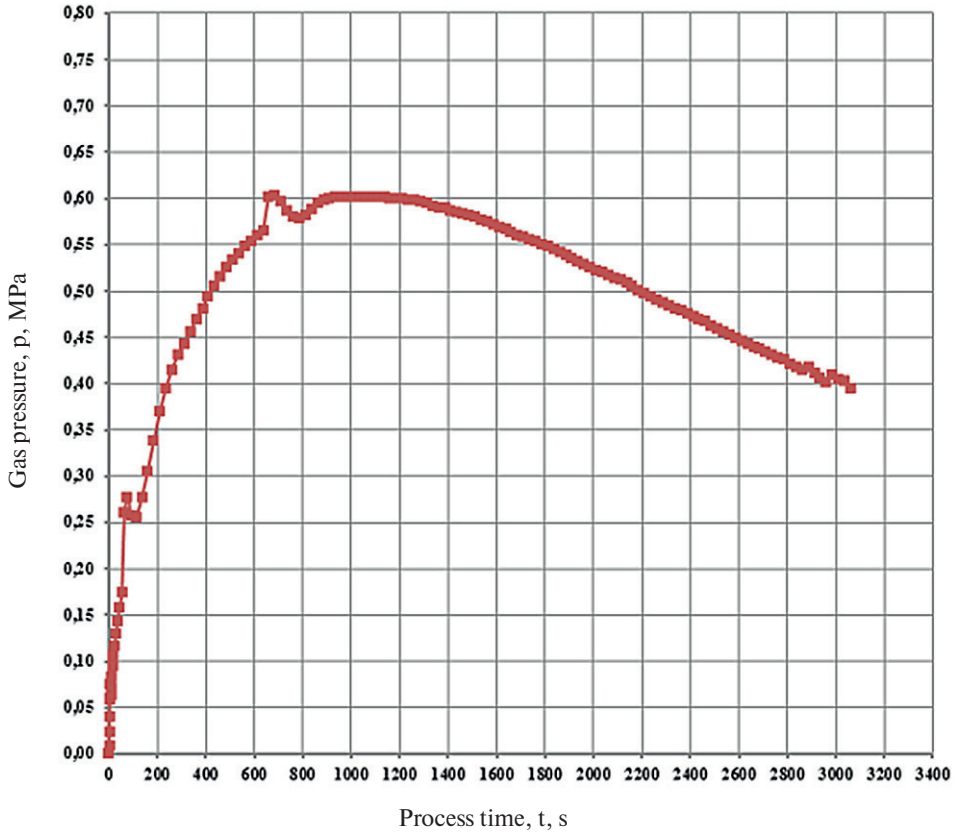

Fig. 7. Diagram of forming gas supply to the billet 2 mm thick, MPa/s

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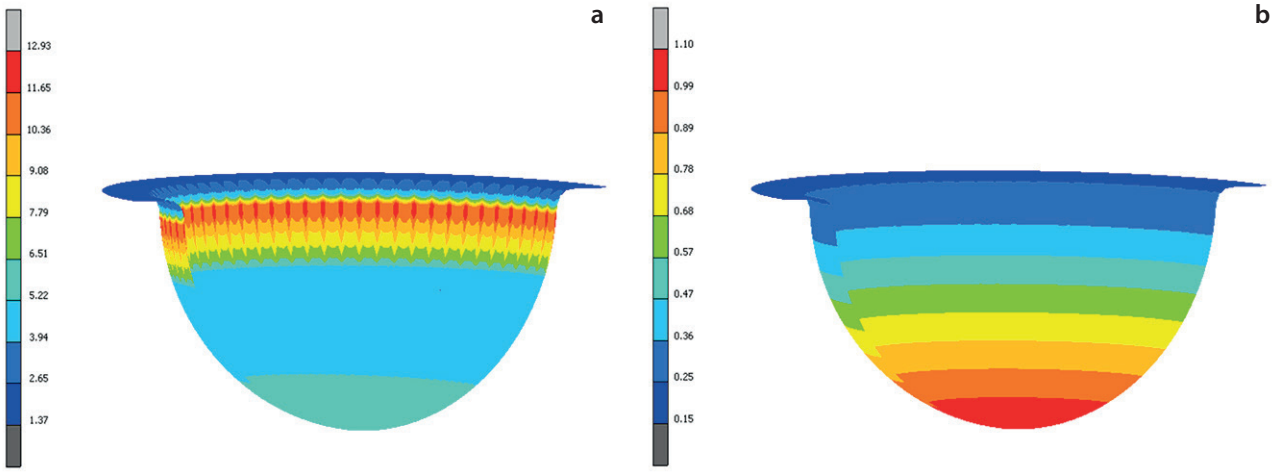

Fig. 8. Distribution of equivalent stresses in the workpiece with thickness 3 mm and equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

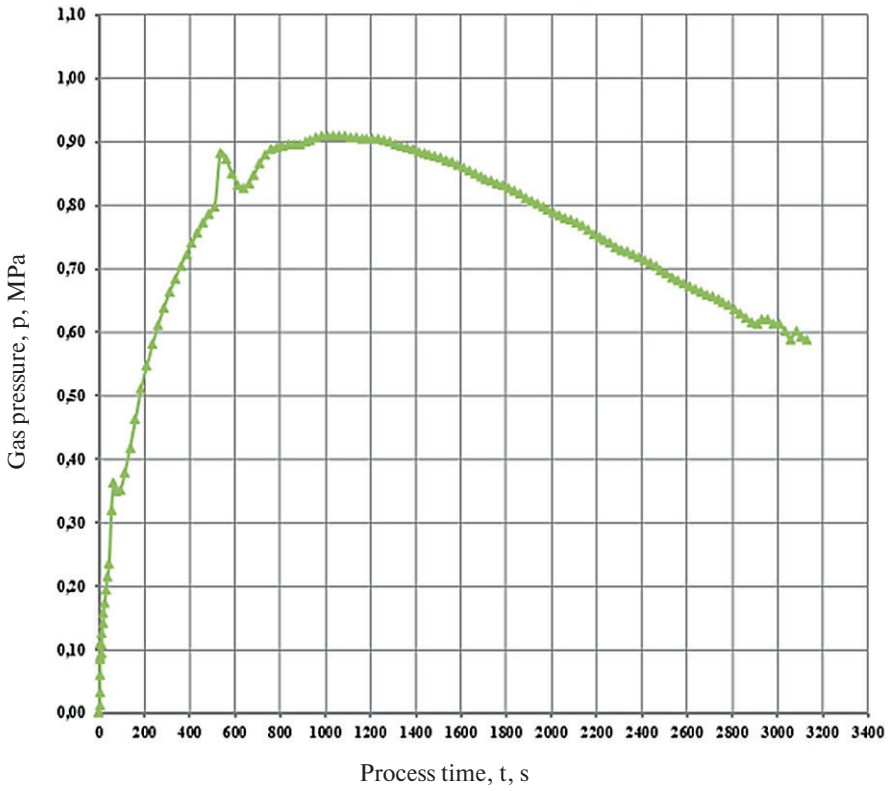

Fig. 9. Graph of forming gas supply to 3 mm thick preform

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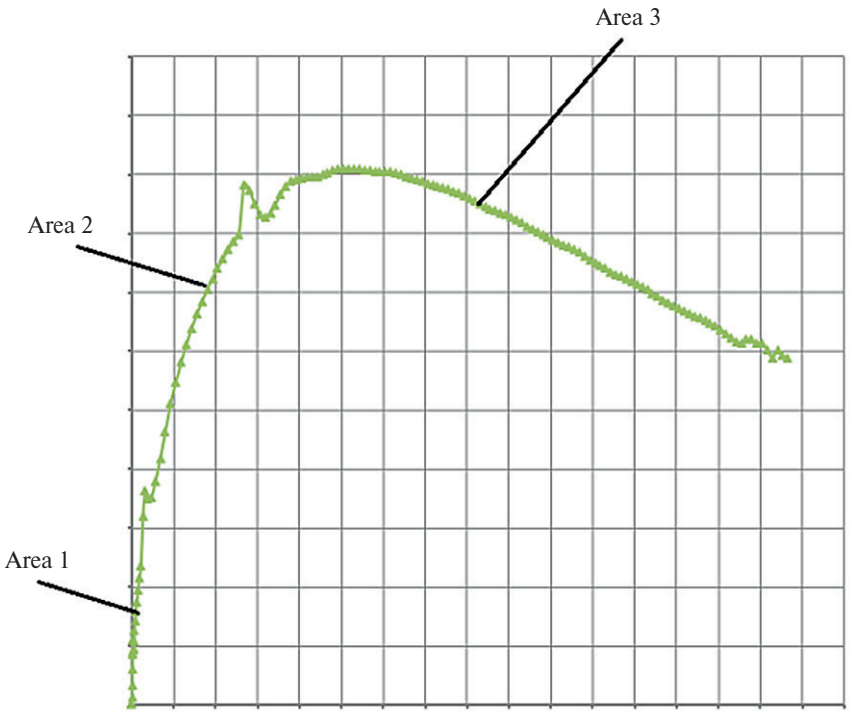

Fig. 10. Main sections of the gas supply schedule: area 1 – "opening" of the workpiece; area 2 – main forming step; area 3 – "exposure"

Table 1. Gas feed rates to Form 1 blanks of different thicknesses

Workpiece thickness, mm	Gas feed rate, MPa/s		
	Area 1	Area 2	Area 3
1	0.001700	0.000180	0.000051
2	0.002200	0.000410	0.000100
3	0.005700	0.000590	0.000150

between stages in a workpiece of the same thickness, and between the same stages in workpieces of different thickness.

The following are the results of the Form 2 billet calculation.

The results of the calculation of the workpiece with a thickness of 1 mm are shown in Figures 11–12. The maximum equivalent stresses in the workpiece are 38.9 MPa, the maximum pressure of the molding gas is 0.57 MPa, and the molding process time is 1564 s.

The results of the calculation of the workpiece with a thickness of 2 mm are shown in Figures 13–14. The maximum equivalent stresses in the billet are 38.7 MPa, the maximum pressure of the forming gas is 1.14 MPa, the molding process time is 1581 s.

The results of the calculation of the workpiece with a thickness of 3 mm are shown in Figures 15–16. The maximum equivalent stresses in the workpiece are 38.6 MPa, the maximum pressure of the molding gas is 1.68 MPa, and the molding process time is 1590 s.

From the obtained results, it can be seen that with an increase in the thickness of the workpiece, the equivalent stresses in it during the molding process practically do not change, as well as the zone of their influence.

Equivalent plastic deformations with an increase in the thickness of the workpiece are also practically unchanged.

The law of gas supply does not change its behavior when the thickness of the part increases. However, it should be noted that with an increase in thickness by 1 mm, the process time remains practically unchanged (an increase of not more than 1%), and the maximum pressure of the forming gas increases significantly (when switching from 1 mm to 2 mm, an increase of 100%, when switching from 2 mm to 3 mm, an increase of 47%). If the behavior of the gas supply law is unchanged, this means that the gas supply speed in the main sections of the graph also increases significantly.

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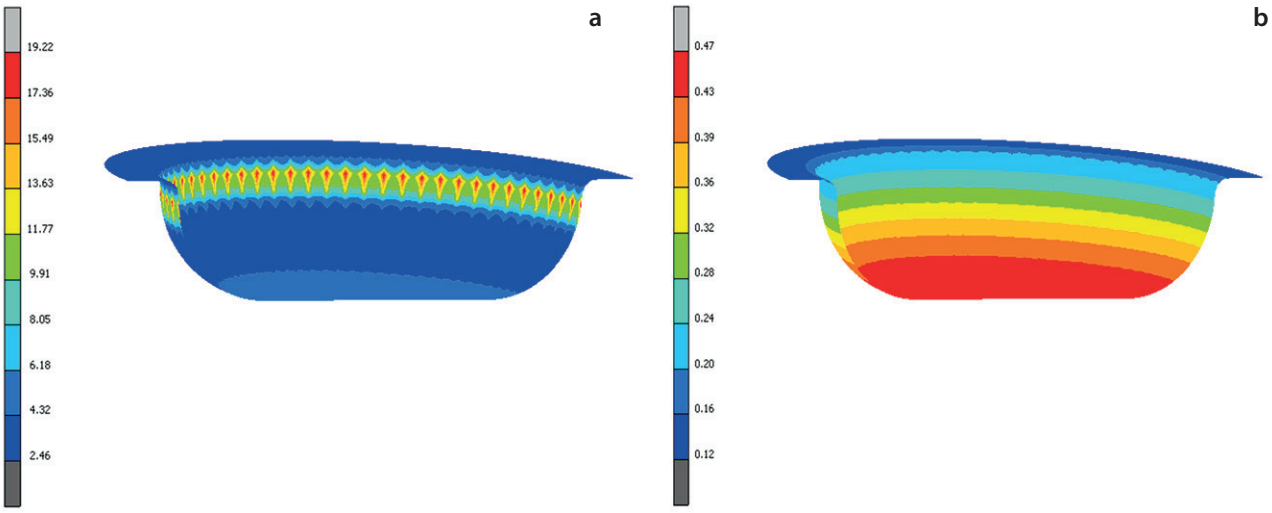

Fig. 11. Distribution of equivalent stresses in the workpiece with thickness 1 mm and equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

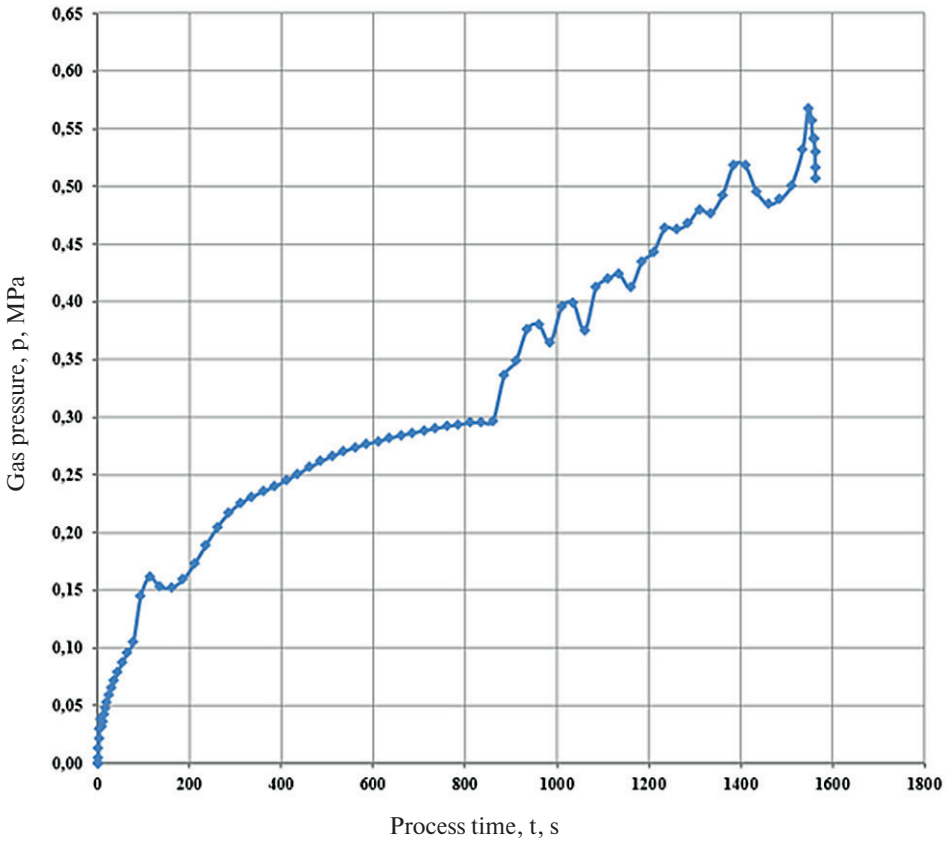

Fig. 12. Graph of forming gas supply to 1 mm thick preform

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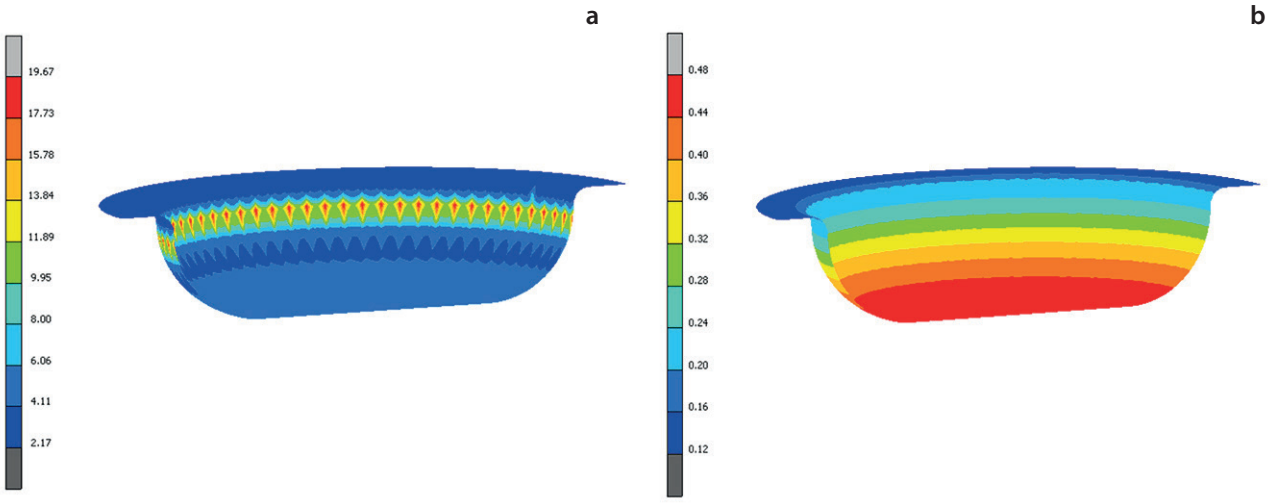

Fig. 13. Distribution of equivalent stresses in the workpiece with thickness 2 mm and equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

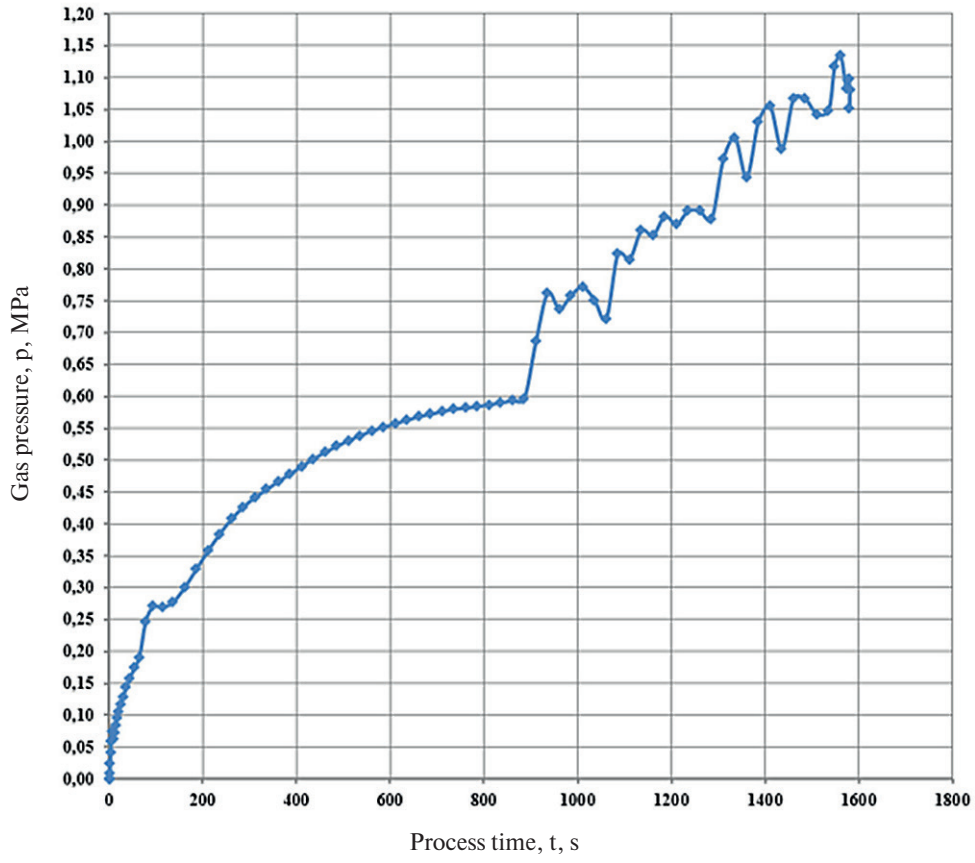

Fig. 14. Graph of forming gas supply to 2 mm thick preform

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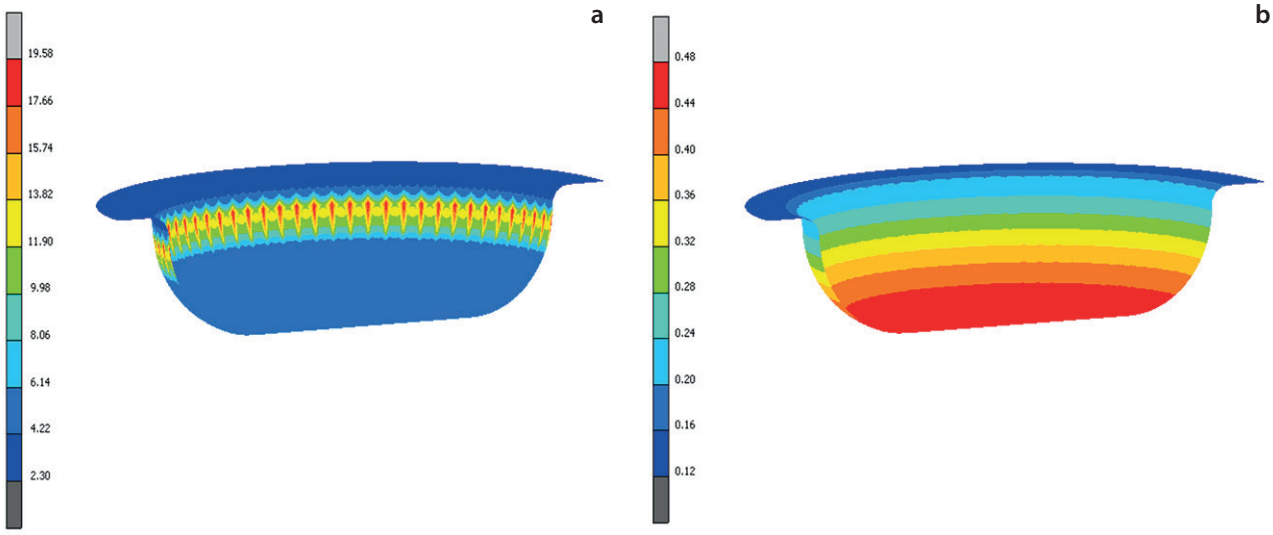

Fig. 15. Distribution of equivalent stresses in the workpiece with thickness 3 mm and equivalent plastic deformations: a – equivalent stresses in the part at the end of the molding process; b – equivalent plastic deformations of the part

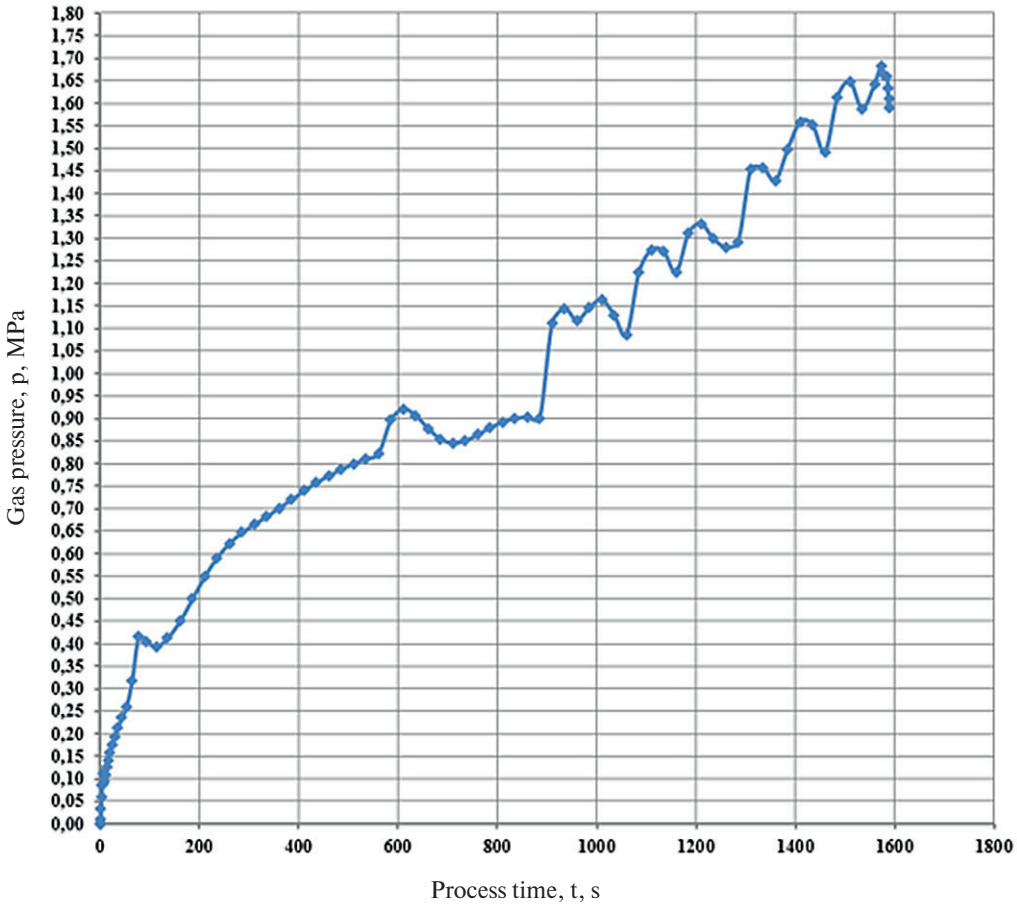

Fig. 16. Graph of forming gas supply to 3 mm thick preform

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Let's divide the graph shown in Figure 16 into 3 main area (Fig. 17):

- area 1 – "opening" of the workpiece - at this stage the gas pressure overcomes the forces of resistance of the material to the flow;
- area 2 – the main stage of molding - plastic deformation of the workpiece occurs with increasing pressure;
- area 3 – "preforming" - residual geometry forming.

Let's estimate the gas supply rate for each of the sections. Table 2 shows the gas feed rates for each section on different thickness blanks (in section 3 the rate is estimated from the averaged curve).

It can be seen that the pressure increase occurs nonlinearly, both between stages in a workpiece of the same thickness, and between the same stages in workpieces of different thickness.

Let us compare the moulding gas supply schedules of mould parts 1 and 2 with each other. As mentioned above, depending on the thickness of the workpiece, the behavior of the graphs does not change, only their scale changes, which entails a significant change in gas supply rates.

For comparison purposes, the superimposed plots are shown in Figure 18. It can be seen that step 1 and step 2 are approximately the same for both workpiece geometries. But stage 3 is radically different. For comparison, we give the thickness of the parts during the transition to the 3rd stage of molding in Figure 19a, b.

For analysis, geometry parts 1 and 2 with a stock thickness of 2 mm (parts with a stock thickness of 1 and 3 mm behave similarly). Figure 19a shows mold 1 with a preform thickness of 2 mm at 1111 seconds of the molding process at a gas pressure of 0.6 MPa. Figure 19b shows mold 2 with a preform thickness of 2 mm at 885 seconds of molding at a gas pressure of 0.62 MPa.

It can be seen that mold 1 has a depth significantly greater than mold 2. Because of this, at the beginning of the third stage of the molding process, the mold part 2 has already touched the bottom. But the part of the

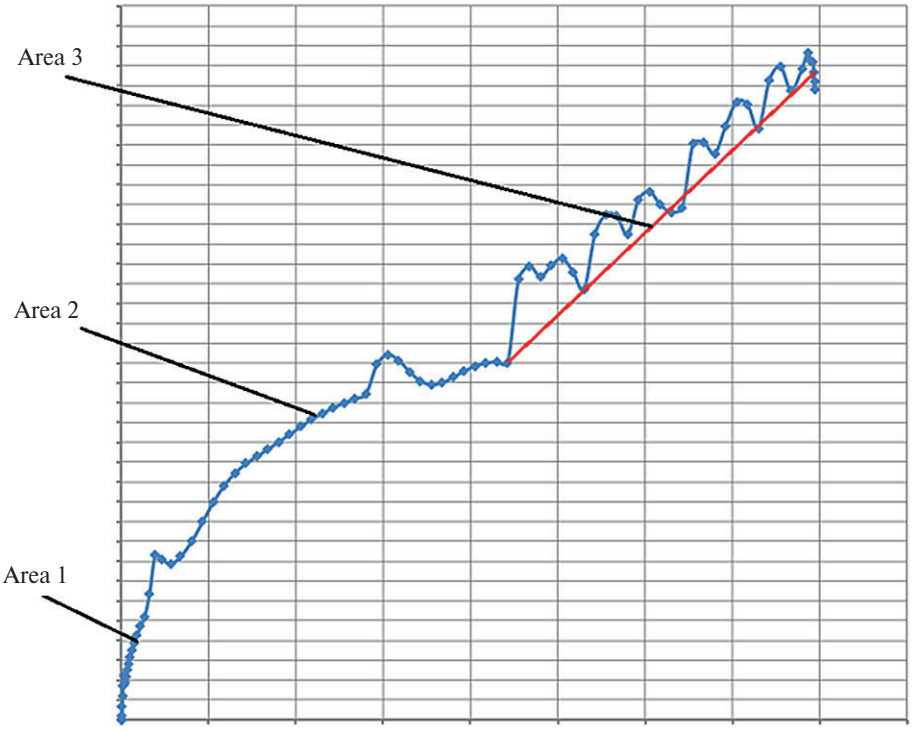

Fig. 17. Main sections of the gas supply schedule: area 1 – "opening" of the workpiece; area 2 – main forming step; area 3 – "preforming"

Table 2. Gas feed rates to mold 2 blanks of different thicknesses

Workpiece thickness, mm	Gas feed rate, MPa/s		
	Area 1	Area 2	Area 3
1	0.00140	0.00018	0.00030
2	0.00240	0.00043	0.00065
3	0.00540	0.00066	0.00098

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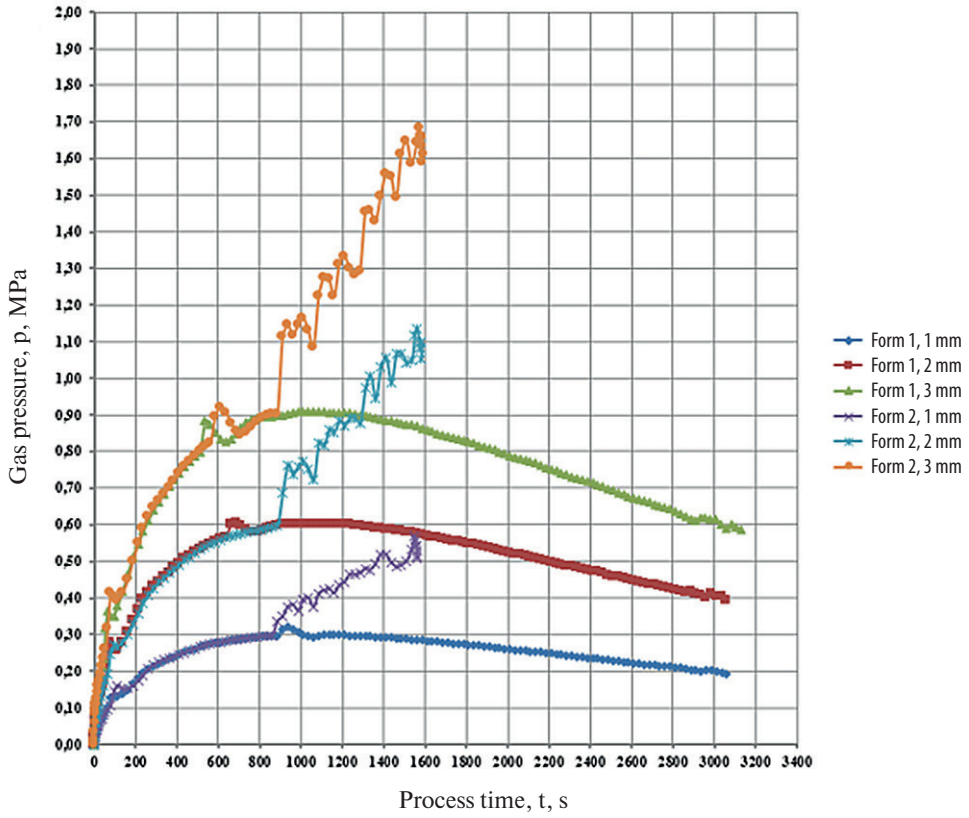

Fig. 18. Molding Gas Schedule Comparison

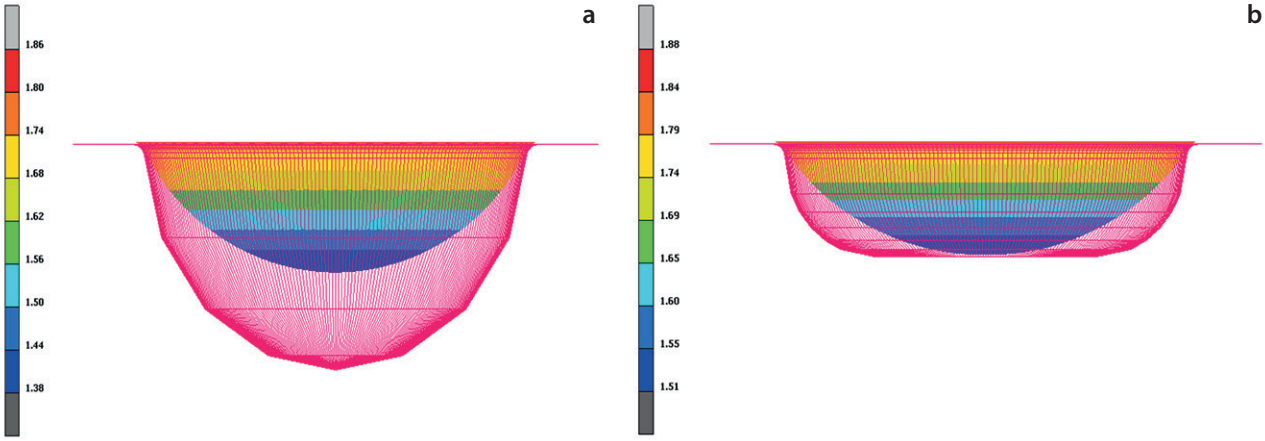

Fig. 19. Thickness of the part during the transition to the 3rd stage of molding: a – mold 1, workpiece 2 mm thick; b – mold 2, billet 2 mm thick

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mold 1 still has a significant margin in terms of distance to the bottom. Because of this, there is a risk of excessive thinning of the material during further stretching of the mould 1 until the bottom is touched, which may lead to tearing of the blank. In order to prevent this phenomenon, the molding step 3 of the mold 1 is carried out by releasing the pressure. At the same time, the formation of the workpiece continues, since the material is already able to deform with minimal forces.

At the same time, there is no danger of such a phenomenon in form 2. At this time, the plastic deformation degree of the material in the mold 2 is lower than that in the mold 1, therefore, it is necessary to increase the pressure growth rate of the forming gas as compared with step 2 to obtain the desired geometry. At this point, a new phase of material drawing begins, when the side zones of the elongated "dome" begin to form in a new way.

In conclusion, it is worth noting that during the study, the graphs of the supply of forming gas into a part of the "dome" type with different geometry and thickness of the workpieces were studied.

FE analysis of the SMA operations showed that when the thickness of the preform changes, the molding gas supply schedules do not change their behavior, but their scale changes. That is, while maintaining the running time of the main forming steps, the pressure of the forming gas is significantly increased, resulting in an increase in the supply rate of the forming gas.

Three steps are identified on the molding gas delivery schedules. The increase in gas pressure between stages occurs non-linearly. Depending on the shape of the part, these steps may vary. Thus, for mold 1, the third step is a "hold," in which the gas pressure is smoothly released, and in mold 2, in the third step, an "overmolding" occurs, in which the gas feed rate is increased compared to the second step. This is due to the fact that the shallower depth of the mold 2 reduces the plastic deformation of the workpiece, and as a result, a new phase of part molding appears. In mold 1, because of the greater depth, there is a risk of excessive thinning and breakage of the preform when the forming gas is supplied at this stage.

Thus, the analysis of gas supply schedules allows you to form experience with the technological process of molding various parts, as well as identify the requirements for the development of promising gas distribution systems.

REFERENCES

1. Temis Yu.M., Khudyakov A.P. Mathematical modeling of isothermal stamping and superplastic forming operations for manufacturing a hollow fan blade. *USATU Bulletin*. 2015;19(3):50–60.

2. Stroganov G.B. Novikov I.I., Boytsov V.V., Pshirkov V.F. *Use of superplasticity in metal forming*. Moscow: Mechanical Engineering; 1989.

3. Kaibyshev O.A. *Superplasticity of industrial alloys*. Moscow: Metallurgy; 1984.

4. Arabale V. Super-Plastic Forming of High Specific Strength Aluminum Al-loys. In: *International Conference on Automotive Materials & Manufacturing*. Pune, India; 2014.

5. Arabale V. Super-Plastic Forming of High Specific Strength Aluminum Alloys. *SAE Technical Papers*. 2014;4. https://doi.org/10.4271/2014-28-0040

6. Zhihao Du, Xinhua Gao, Xiangxiang Dai, Guofeng Wang, Shuobing Chen, Congzheng Zhang, et al. Structural optimization and direct reverse superplastic forming process for aluminum alloy multi cavities pallet. *Scientific Reports*. 2025;15:15508. https://doi.org/10.1038/s41598-025-00250-9

7. Isothermal stamping. Available at: URL: https://pressmash.ru/product/izotermicheskaya-shtampovka/ (access date 27.05.2026).

8. Akhunova A.Kh., Mulyukov R.R., Safiullin R.V. Finite element modeling of superplastic forming processes. *Chebyshevsky collection*. 2017;3(63):55–71.

9. Hot Forming & Superplastic Forming Press. Available at: URL: https://formingequip-en.com/1-1-hot-forming-superplastic-forming-presses.html (access date 27.05.2026).

10. Kruglov A.A., Karimova A.F., Enikeev F.U. Finite element modeling of folding during the superplastic forming of corrugated core panels. *Letters on Materials*. 2018;8(2):174–177.

11. Kruglov A.A., Musina R.Sh., Enikeev F.U. Computer modeling of the process of superplastic molding of hollow three-layer structures. *Mechanical engineering technology*. 2015;2:57–62.

12. Murzina G.R., Ganieva V.R., Kruglov A.A., Enikeev F.U. Modeling of the process of superplastic forming of hemispherical shells from blanks of different profiles. *Letters on Materials*. 2021;11(4):548–552.

13. Panchenko E.V., Alekseev P.A. Modeling of three-dimensional problems of superplastic formation of thin-walled shells. Forging and stamping. *Pressure treatment of materials*. 2012;3:28–32.

ISSN 2075-8545 (online)

14. Giuliano G., Polini W. FEM Analysis of Superplastic-Forming Process to Manu-facture a Hemispherical Shell. *Applied Sciences*. 2025;15(14):8080. https://doi.org/10.3390/app15148080

15. Michael J. O'Brien, Hubertus F. von Bremen, Minoru Furukawa, Zenji Horita, Terence G. Langdon. A finite element analysis of the superplastic forming of an aluminum alloy processed by ECAP. *Materials Science and Engineering*. 2007;456(1–2):236–242. https://doi.org/10.1016/j.msea.2006.11.116

16. Kandasamy J. FE Analysis of Superplastic Forming Complex Shapes in Aluminum-Coated Magnesium Alloys. In: *Recent Trends in Mechanical Engineering*. Singapore: Springer (Lecture Notes in Mechanical Engineering); 2021:247–259. https://doi.org/10.1007/978-981-15-7557-0_23

17. Murzina G.R., Zharmukhametova A.R., Ganieva V.R., Enikeev F.U. Method for calculating the parameters of superplasticity of titanium alloys based on the results of test forming into a rectangular matrix at constant pressure. *Bulletin of SUSU. Series: Mathematical modeling and programming*. 2023;16(1):96–107.

18. Kukhar V.D., Yakovlev S.S. Evaluation of stress-strain state in the manufacture of shells with external ribs. *News of Tula State University. Technical sciences*. 2023;2:530–536.

19. *Mentat User's Guide, Version 3.3*. Palo Alto: MARC Analysis Research Corporation; 1999.

20. Alabort E., Putman D., Reed R.C. Superplasticity in Ti–6Al–4V: Characterisation, modelling and applications. *Acta Materialia*. 2015;95:428–442. http://dx.doi.org/10.1016/j.actamat.2015.04.056

21. Shao-song Jiang, Zhen Lu, Xiao-dong He, Guo-feng Wang, Kai-feng Zhang. Superplastic forming Ti–6Al–4V titanium alloy cylinder with near uniform thickness distribution. *Transactions of Nonferrous Metals Society of China*. 2012;22(2):472–478. https://doi.org/10.1016/S1003-6326(12)61748-8

22. Kolesnikov A.V. Analysis of the possibility of pneumatic thermal forming of multilayer structures by virtual modeling. In: *Reshetnevsky readings*: *checkpoints of the XVI International. scientific. conf., dedicated to the memory of the gene. designer rocket space. systems acad. M.F. Reshetneva*. Under the general. ed. Yu.Yu. Loginova. Krasnoyarsk: Sib. state. aerospace. un-t; 2012. PART 2.

23. Rollin M., Penazzi L., Velay V., Dupuy A., Gallet S.A new numerical strategy for SPF pressure profile computing based on statistical strain rate controlling. *International Journal of Mechanical Sciences*. 2018;141:479–490. https://doi.org/10.1016/j.ijmecsci.2018.04.021

24. Stepanenko N.Yu., Chertovskikh S.V., Lukyanov V.V. The study of the formation of a hollow cellular structure with a given geometry. *Nanotechnologies in construction*. 2025;17(4):455–465. https://doi.org/10.15828/2075-8545-2025-17-4-455-465

25. Stepanenko N.Yu., Chertovskikh S.V., Lukyanov V.V. Optimization of the geometry of the characteristic section of a complex-profile thin-walled workpiece of the original geometry by modeling and finite element analysis. *Materials. Technologies. Design*. 2025;7(3):5–20. https://doi.org/10.54708/26587572_2025_73225

26. Stepanenko N.Yu., Chertovskikh S.V., Lukyanov V.V., Astanin V.V. Manufacturing technology of protective edge for polymer composite products. *News of Tula State University. Technical sciences*. 2024; 8:197–203.

ADDITIONAL INFORMATION

The authors declare that the preparation of the article did not use technologies of generative artificial intelligence and technologies based on artificial intelligence.

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N.Yu. Stepanenko – modeling and finite element analysis, work with the MSCMarc software package. Interpretation of the obtained data.

S.V. Chertovskikh – scientific management of the project, development of the general structure of the article, quality control of all stages of the study, scientific editing and revision of the text, formation of conclusions and recommendations for practical use. Participation in the formulation of the purpose and objectives of the study, writing the introduction and conclusion, justification of the practical significance of the work.

I.V. Kandarov – methodological support of the study, control over the correctness of the experimental design, participation in writing and editing the text of the article.

A.V. Rubtsov – participation in writing and editing the text of the article.

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