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Computer Modeling of New Experimental Schemes of SHS-Extrusion

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Abstract

The paper discusses thermal and rheodynamic models of the processes of deformation of powder materials under SHS-extrusion for recommendations, prognosis and methods for the application of new experimental schemes. Numerical studies of the influence of rheododynamic and thermal factors on the process of compacting and molding of combustion products are carried out.

The most effective methods of obtaining long-length samples of large diameters (more than 5 mm) and a length of more than 100 mm were verified by the SHS-extrusion method, which involved increasing the height of the tablet, increasing the combustion temperature, improving thermal conditions of extrusion, using a heat insulator (3 mm thick asbestos) on the core matrix and in its hole, heating the caliber and the matrix. Recommendations on the influence of the scale factor (geometric dimensions of the incoming billet) on the features of obtaining long-length large-diameter samples by the SHS-extrusion method are given.

It is shown that the change in the scale factor has a significant effect on the length and quality of the extruded rods due to the uniformity of the temperature field. It was found that there is a limiting value of the diameter of the incoming billet above which the material is practically not extruded from the inner tire. It is noted that the recommendations and forecasts are made and established for TiC (70 %) + Ni(30 %) composition (30 %), but it can be expected that the qualitative nature of the features of obtaining large-sized products will not change for other compositions.

Keywords

Self-propagating high-temperature synthesis; long-length products; thermal and rheodynamic models; mathematical modeling; heat removal; compaction; extrusion.

Introduction

One of the promising and actively developing variants of self-propagating high-temperature synthesis (**SHS**) [1, 2] is the SHS-extrusion method for obtaining long components from brittle and hard-to-deformable powders of refractory inorganic compounds [3–6].

In this process, the synthesis of the material and the formation of the product takes place in a few seconds (instead of hours, as in powder metallurgy) in a single technological cycle, combining combustion processes and high-temperature deformation. The actual task is to achieve intensive plastic deformation of powders of inorganic compounds during the extrusion process itself because at this time the material is in a plastic state due to high temperatures.

One aspect of this method is to provide the most effective methods of obtaining large-sized elongated rods.

With the expansion of the technological capabilities of SHS-extrusion, it has become expedient to use modeling of this process to solve a number of problems related to hardening of the material, a high temperature gradient affecting the quality of the product, and, most importantly, to develop recommendations and forecasts for obtaining long-length products of large diameter.

In order to find additional ways of controlling the SHS-extrusion process and the quality of products, it seems promising to develop new technological schemes for this process by using matrices of various designs: multistage, screw, angular, etc. Essentially, it is the forecast of the influence of the form and size of matrices on the structure and properties of finished products. Experimental research causes difficulties, and methods of mathematical modeling allow exploring an object by simulating an experiment on a computer and thus eliminating or significantly reducing the volume of the experiment.

The feasibility and advantages of mathematical modeling in exploring the possibilities and practical applications of the technological process of SHS-extrusion are obvious [7, 8]. Earlier, thermal models describing the processes of cooling of combustion products and their heat exchange with the environment under real conditions of SHS-extrusion were formulated in [7, 9]. On the basis of these models, the temperature fields arising both in the sample material and in the elements of the press tooling were investigated. It is noteworthy that for each specific practical application it is necessary to solve the problems directly related to the technology of manufacturing the products in question and the technical characteristics of these products.

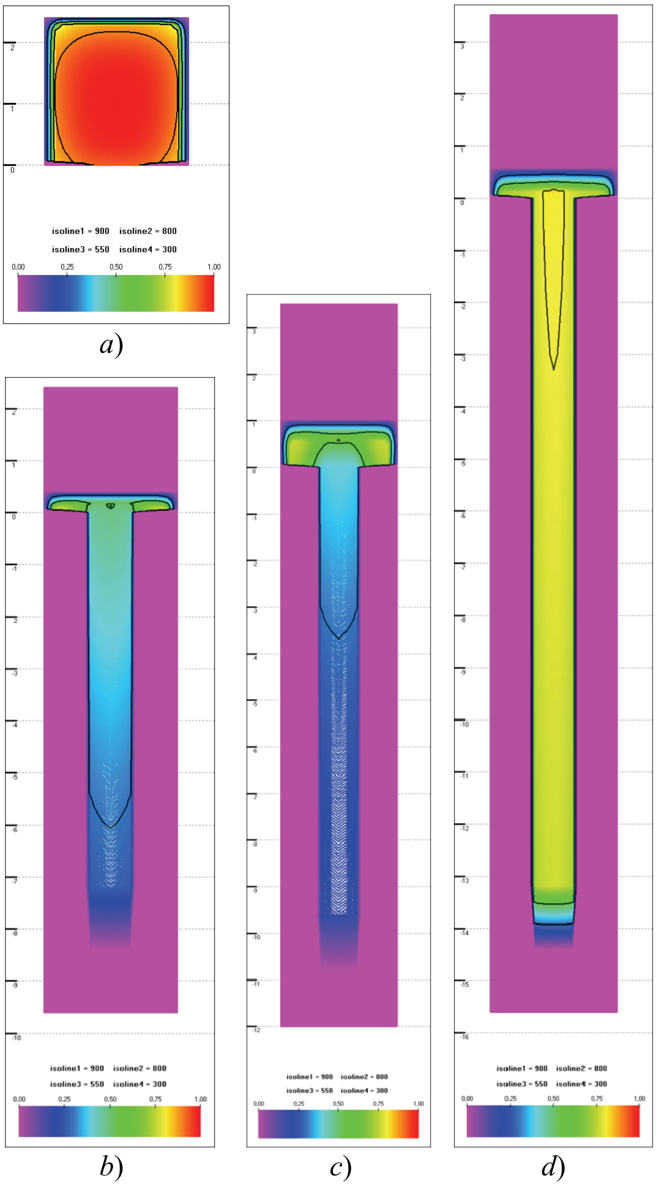


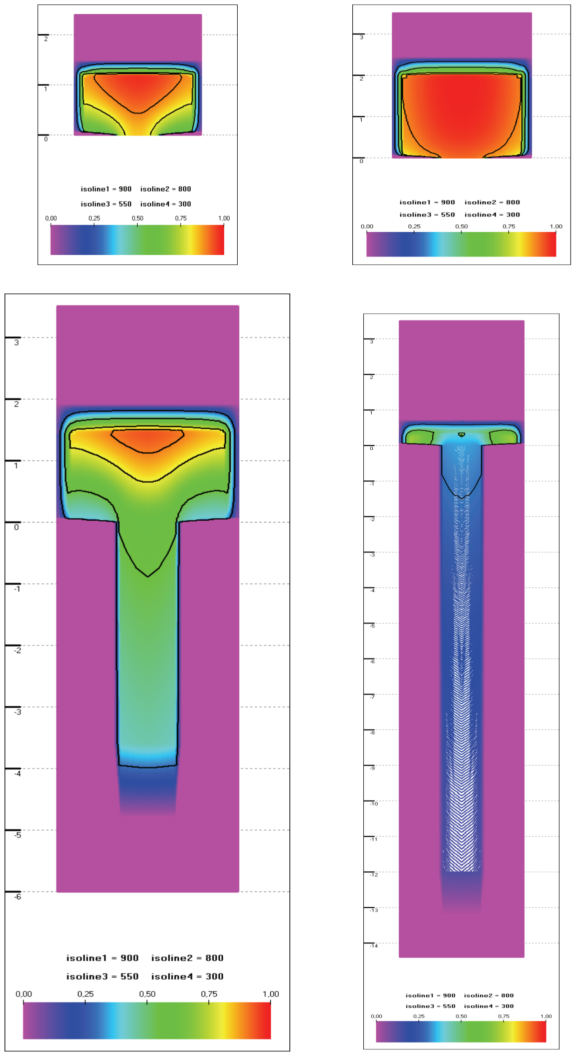
Fig. 1. The influence of preform height and thermal conditions on the length of the rods of large diameters (10 mm) (*a*):
b – rod length $L = 112$ mm (max), asbestos thickness 3 mm, initial height of the preform $H_0 = 30$ mm; *c* – rod length $L = 145$ mm (max), asbestos thickness 3 mm, the combustion temperature increased by 200 degrees ($T_{gor} = T_{gor} + 200$), the initial height of the preform $H_0 = 45$ mm; *d* – the length of the rod $L = 191$ mm (max), the asbestos thickness 3 mm, the initial height of the preform $H_0 = 45$ mm, adiabatic extrusion conditions

Production of long-length products of large diameters by SHS-extrusion

It has become necessary to produce long-length products of large diameters (more than 3 mm) and lengths over 100 mm by the method of SHS-extrusion. Examples of the practical use of such products are electrodes for surfacing and anodes used in the production of aluminum by the Hall–Héroult method, and used in the design of an electrolytic bath. Based on the thermal models of SHS-extrusion, after necessary modification, the temperature fields were studied in a sample of TiC+Ni composition, a heat insulator and an extruded rod depending on various process parameters, that is, different methods of experiment (presence or absence of thermal insulation on the profiling matrix, increase in temperature of combustion, heating of various zones of equipment, etc.) [9]. The studies [10] made it possible to give recommendations and forecasts on the use of new versions of experimental SHS-extrusion schemes.

As the numerical calculations showed, in the transition to production of the large-diameter rod (8–10 mm) by the SHS-extrusion the insulation became even more necessary. When extruded without asbestos of the initial preform of 30 mm in height, the length of the product was 57 mm (29 %), the use of asbestos and the increase in the burning temperature of the composition by 200 degrees led to an increase in the length by two times to 112 mm (58 %) (Fig. 1 *b*). Further improvement of extrusion conditions did not lead to a significant increase in the length of the rod, because at a tablet height of 30 mm that was almost the maximum length. To increase the length, it was necessary to increase the initial height (mass) of the preform.

When increasing the initial height of the preform (up to 45 mm), and using a heat insulator and increasing the combustion temperature by 200 degrees, the length increased up to 145 mm (76 %). Virtually, the entire sample was heated uniformly prior to extrusion, without cold masses at the matrix base (Fig. 1 *c*).



а) *б)*

Fig. 2. Thermal regimes of samples with a diameter of 10 mm: *a* – extrusion without a heat insulator (rod length 57 mm;) *b* – the presence of a heat insulator (3 mm thick asbestos) on the matrix, increasing the combustion temperature by 200 degrees, heating the caliber and matrix by 200 degrees (rod length 171 mm)

Additional heating of the caliber and matrix to 200 degrees gave an increase in length to 171 mm, and under adiabatic extrusion conditions, the length of the rod reached 191 mm (Fig. 1 *d*).

Numerical studies made it possible to give the following recommendations for obtaining long-length samples of large diameter (8–10 mm) by the SHS-extrusion method (Fig. 2):

1) increase in the height of the tablet (up to 45 mm);

2) increase in the combustion temperature (by 200–300 degrees);

3) improving the thermal conditions of extrusion, using a heat insulator (3 mm thick asbestos) on the profiling matrix and in its opening, heating the caliber and the matrix (up to 300–400 degrees).

The role of the scale factor in the process of obtaining long-length rods by the SHS-extrusion method

The role of the scale factor (the influence of the height and diameter of the initial cylindrical preform) on the temperature distribution in the material and the completeness of extrusion of long-length samples obtained by the SHS-extrusion method (SHS self-propagating high-temperature synthesis [13]) was theoretically investigated. Numerical studies were carried out using mathematical modeling of thermal regimes of the SHS-extrusion process. It is shown that the change in the scale factor has a significant effect on the length and quality of the extruded rods due to the uniformity of the temperature field. It was found that there is a limiting value of the diameter of the initial preform, above which the material is practically not extruded of the inner tire [2, 3].

Fig. 3 and 4 show the temperature fields of the extruded material with different values of the initial height of the initial preform (H_0) and radius of the hole of the matrix $r_1 = 4$ mm.

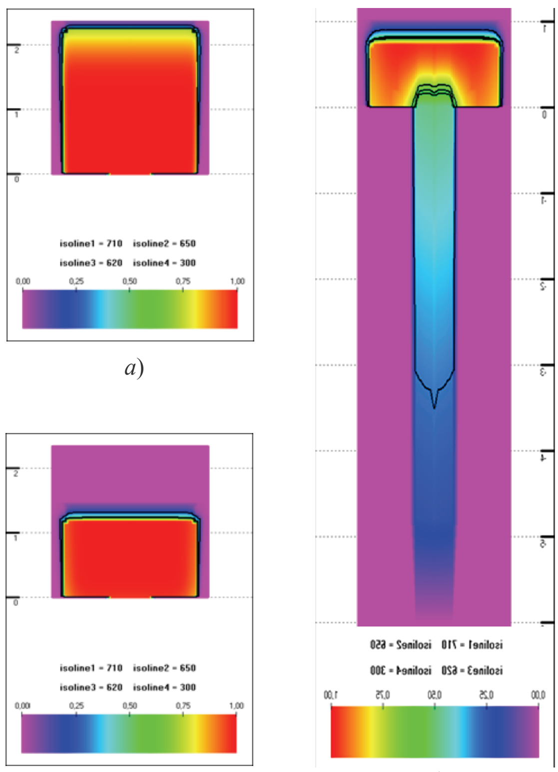


Fig. 3. Temperature distribution in the sample in the stages: *a* – burning-delay; *b* – pressing; *c* – extrusion. Parameters: radius of the hole of the profiling matrix $r_1 = 4$ mm (rod diameter $d_1 = 8$ mm), angle of the matrix 180 degrees, press plunger velocity $V = 40$ mm/s, thickness of the asbestos around the sample Asb = 1.5 mm. The initial height of the sample $H_0 = 30$ mm, the length of the extruded part $L = 75$ mm

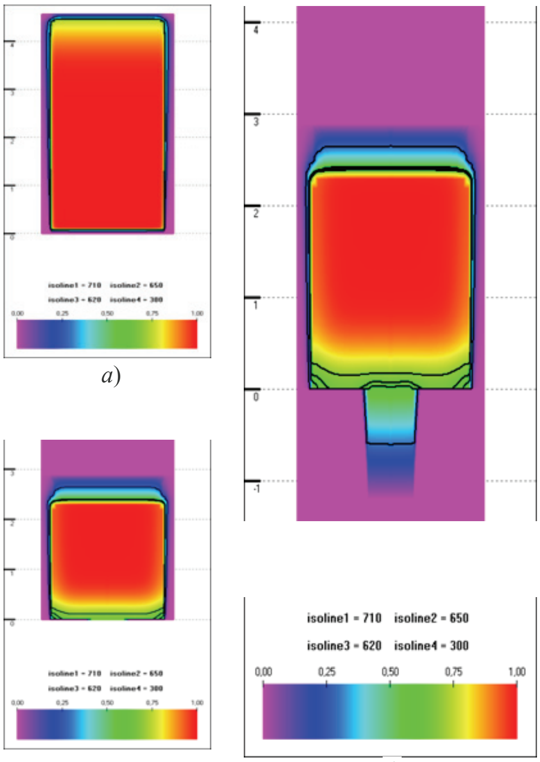


Fig. 4. Temperature distribution in the sample in the stages: *a* – burning-delay; *b* – pressing; *c* – extrusion. Parameters: radius of the hole of the profiling matrix $r_1 = 4$ mm (rod diameter $d_1 = 8$ mm), angle of the matrix 180 degrees, press plunger velocity $V = 40$ mm/s, thickness of the asbestos around the sample Asb = 1.5 mm. The initial height of the sample is $H_0 = 60$ mm, the length of the extruded part $L = 11$ mm

To explain the obtained results, we introduce the compaction time, which is determined by the relation: $(H_0 - H_k)/V$, where V is the velocity of the press plunger, H_0 and H_k are the initial and final (after pressing) sample height, respectively. There is a competition between the cooling processes of the sampling areas (due to an increase in the compaction time of large preforms) and an increase in the heat content (with an increase in the height of the preform). The decisive role is played by the initial conditions of temperature after pressing the material before it is extruded. At the time of extrusion, the temperature of the matrix region of the sample with a height of 30 mm (Fig. 3 *b*) was high, so the length of the rod and the extrusion volume (Fig. 3–5) were large. At a sample height of 60 mm, the matrix regions had time to cool down (Fig. 4 *b*) during the burning and pressing and to block the hole of the profiling matrix with cold masses – the material was not completely extruded – the length and completeness of extrusion were small.

Fig. 5 shows the dependence of the length of the extruded rod on the preform height for matrices with holes of 4 and 2 mm.

As can be seen from Fig. 5, the length of the rod decreased with the increasing sample height. The dependence of extrusion completeness (K) on the height of the preform had a similar form. For small tablet heights from 30 to 45 mm, the length did not change much, the extrusion completeness gradually decreased, and with a further increase in the height of the sample, not only the extrusion volume but also the length greatly decreased. Analyzing the obtained data, it can be argued that the height of the preform has a significant influence on the length of the extruded part. There is the most acceptable range for changing the height of the initial preform for profiling matrices with the radius of the hole of 2 and 4 mm, which is in the range of 30–45 mm.

The influence of the radius of the preform on the completeness of extrusion for matrices with the radii of the hole of 2 and 4 mm was investigated. In both cases, with an increase in the radius of the preform (with its height unchanged), the completeness of extrusion decreased even for a rod with a diameter of 8 mm (radius 4 mm) from 40 to 7 %.

Explaining this important fact, it is noteworthy that the completeness of extrusion depends on a number of factors. There is a competition of cooling processes in the matrix regions (due to an increase in the compaction time of large tablets) and an increase in the heat content. On the one hand, when the radius of the sample changes (with a constant value of the radius of the hole), the heat content of the sample increases, and on the other hand, the heat sink is enhanced by increasing the heat sink surface as the radius of the sample increases and so does the radius of the mold. However, the decisive role in this matter is the competition of the cooling time and the time of extrusion of the material. When the sample radius is increased and the radius of the matrix exit hole remains unchanged, the resistance to extrusion increases, therefore, there comes a time when the

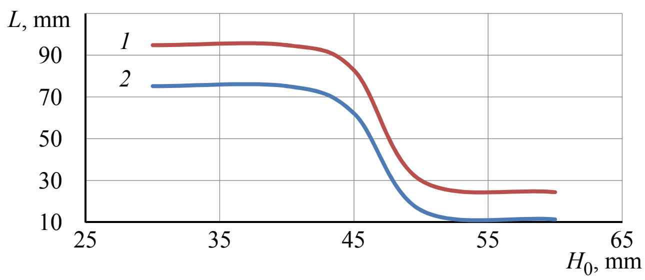


Fig. 5. The dependence of the length of the extruded rod (L) on the initial height of the sample (H_0) for the radii of the profiling matrix hole of 2 (*1*) and 4 mm (*2*) (parameters: the matrix angle 180 degrees, the press plunger velocity $V = 40$ mm/s, the thickness of the asbestos around the sample Asb = 1.5 mm)

material has time to cool down before extrusion begins. As can be seen in Fig. 6 *b*, *c*, practically the entire lower surface of the sample cooled down and a smaller amount of material was extruded.

Thus, the critical value of the radius of the mold (sample) is reached, when the material is not completely extruded because during the time of adjustment and advancement to the gap, it has time to cool down. There is a blockage of the matrix. This phenomenon is well known in the practice of SHS-extrusion. It has not been verified experimentally that this phenomenon can occur with an increase in the radius of the preform with an unchanged radius of the matrix outlet hole.

In this regard, it is interesting to note that an experimental study of the effect of the scale factor on the process of material formability was conducted in [14], i.e. its ability to high-temperature deformation. The authors of this work believe that an increase in the diameter of the original sample to 30 mm at a constant height leads to a general reduction in the degree of deformation by 10 %. This may be due to a decrease in the true load on the sample caused by an increase in the area of application of pressure during pressing.

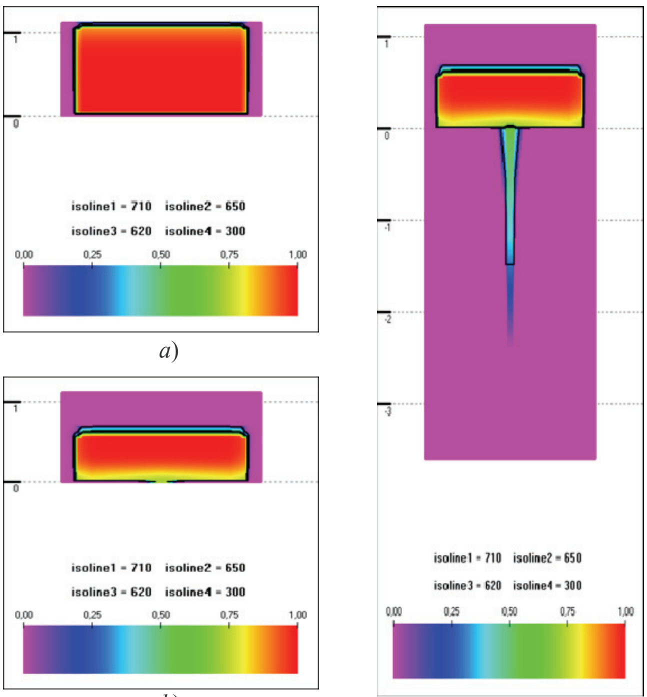


Fig. 6. Temperature distribution in the sample in the stages: *a* – burning-delay; *b* – pressing; *c* – extrusion. Parameters: the radius of the opening of the profiling matrix r_1 = mm (rod diameter d_1 = 8 mm), the radius of the sample r_0 = 28.5 mm, the matrix angle 180 degrees, the press plunger velocity V = 40 mm/s, the thickness of the asbestos around the sample Asb = 1.5 mm. The initial height of the sample H_0 = 30 mm, the length of the extruded part L = 21 mm

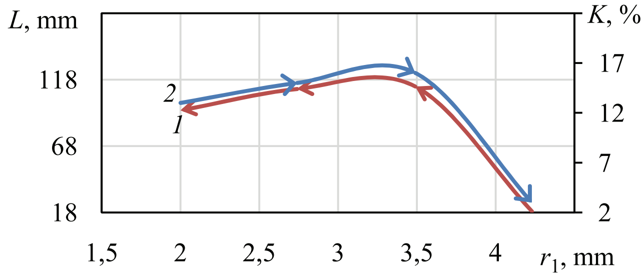


Fig. 7. The dependence of the length of the extruded rod *L* (*1*) and the completeness of extrusion *K*, %, (*2*) on the hole radius and the mold radius (r_1) (parameters: the matrix angle of 180 degrees, the press plunger velocity V = 40 mm/s, the thickness of asbestos around the sample Asb = 1.5 mm, the initial sample height H_0 = 30 mm, constant degree of deformation)

An interesting result was obtained by investigating the dependence of the length and completeness of extrusion on the simultaneous change in the radius of the hole and the radius of the mold, i.e. at a constant degree of deformation. The radius of the sample and the radius of the hole were changing simultaneously so that the degree of deformation could not change. The radius of the hole varied from 2 to 4.23 mm, and the radius of the sample (and mold) changed from 13.5 mm (mold – 15 mm) to 28.5 mm (mold – 30 mm). The initial height of the samples was 30 mm. The dependence of the length of the rod and the completeness of extrusion on the hole radius – the sample radius is non-monotonic (Fig. 7) and it is possible to select the range of optimal values of the matrix holes (and the corresponding sample radius): from 3 mm to 3.5 mm.

On the dependence curve of the length and completeness of extrusion on the radius of the matrix hole – radius of the mold, it is possible to isolate the limiting value of the radius of the sample and the mold, further increase of which leads to almost blockage of the matrix (extrusion yield less than 7 %).

The conducted studies show that there are optimal intervals for the height and diameter of the preform, as well as the diameter of the profiling matrix, under which there is a noticeable increase in the length and completeness of extrusion of the extruded rods. There are limiting values of the radius of the preform and the mold, the increase of which leads to almost a blockage of the matrix.

The numerical studies made it possible to give the following recommendations on the height and diameter of the preform, as well as on the degree of deformation to obtain long samples of large diameter (8–10 mm) by the method of SHS extrusion. It is expedient to use a tablet with a height of 30 to 45 mm and a rod with a diameter of 8–10 mm for the initial preform with a diameter of 30 mm.

SHS-extrusion with a two-stage reduction of the material

To study the possibilities of SHS-extrusion with a two-stage reduction of the material, mathematical modeling of the process was carried out. The results of the study presented below showed that such a technological scheme can have important practical consequences. When studying the SHS-extrusion process under conditions of a two-stage reduction, the following questions were discussed:

– Is there an effect of double compression on the density distribution in the extruded material and if so, in what qualitatively different modes does it appear?

– What are the optimum values of the radius of the intermediate matrix to achieve the greatest length of the extruded part of the material?

Mathematical modeling of SHS-extrusion in real technological conditions of multistage reduction [15] promotes the development of such poorly explored area as plastic deformation of powder refractory composite materials in the high temperature region.

To compare the single-stage and two-stage reduction of the material [15], there was used the known non-isothermal rheodynamic model of SHS-extrusion [7, 10–11] based on the concept of a high-temperature powder preform as a viscous body consisting of a chaotic incompressible phase and vacuum mixture. It is assumed that the compaction of the material occurs by the mechanism of a viscous flow of mass into the pores (according to the theory of Ya.I. Frenkel). The rheological properties of such a medium, i.e. the ability to deform and flow, are determined by the properties of the solid phase, the presence and degree of porosity. The main task of theoretical analysis within the framework of rheodynamic models is the analysis of the density, temperature and stress-strain state of the material during its pressing and extrusion, depending on the pressure and on the initial distribution of temperature and density over the sample volume. An important point of this description is the choice of rheological equations.

A feature of our approach to the modeling of SHS-extrusion with double reduction is the separation of two stages of the process, each of which is analyzed in detail given their specific features and tasks. The theoretical analysis of each subsequent stage takes into account the results of the analysis of the previous stage in the form of initial conditions.

It is assumed, that the process of plunger extrusion with a double reduction takes place in two stages: in the first stage, the material is filled with a transient profiling matrix, and in the second stage, the material is extruded into a caliber. Therefore, the initial conditions for the second stage are the values of density, temperature, stresses and velocities obtained in the first stage. With one reduction, the material is immediately extruded into the caliber. The profiling matrices are cone-shaped and the angle of the cone can vary from 60 degrees to 180 degrees (the so-called rectangular matrices). In this paper, we consider a matrix with a cone angle of 180 degrees [15].

Numerical calculations showed that, for large diameter rods (5 mm), a two-stage reduction with the chosen process parameters (the same with a single-stage reduction) makes it possible to obtain 97 % of the maximum possible rods (Fig. 8, boundary line *2*), and for a single-stage reduction at the same parameters it is possible to obtain only 72 % (Fig. 8, boundary line *1*).

An important question of applying a two-stage reduction is to choose the radius of the intermediate matrix. In some cases, it is possible to identify the optimal transition radius for obtaining higher quality extrudates. Fig. 9 shows the dependence of the

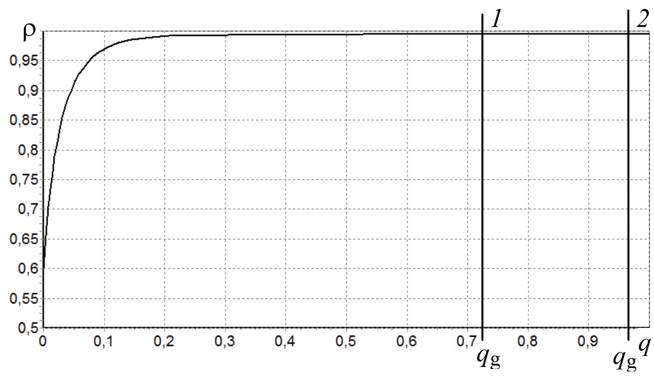


Fig. 8. Distribution of the density ρ of the mass coordinate *q* (along the length of the rod):
1 – one reduction, $q_g = 0.72$; *2* – two compressions, $q_g = 0.97$. The graph shows the location of the boundary (q_g), corresponding to the mass of the extruded part (the length of the extruded rod). Parameters: Pressure on the press plunger $P = 108$ Pa, viscosity $5 \cdot 10^8$ Pa·s, Bio criteria: bottom-Bin = 1.0, upper-Biv = 0.5, the caliber diameter d_2 = 5 mm, diameter of the transition matrix for double reduction d_3 = 8 mm, the delay time t_d = 3 s

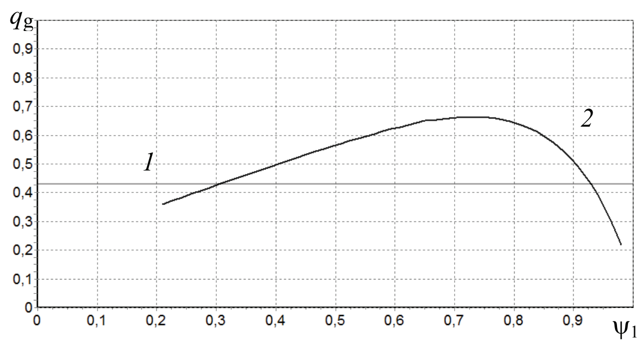


Fig. 9. Dependence of the mass of the extruded part q_g on the degree of deformation $\psi_1 = 1 - S_2/S_0$:
1 – single-stage reduction, *2* – two-stage reduction.
Parameters: Pressure on the press plunger $P = 108$ Pa, viscosity $5 \cdot 10^8$ Pa·s, Bio criteria: bottom-Bin = 1.0, Biv = 0.5, diameter d_2 = 2 mm, delay time t_d = 3 s

extrusion completeness on the degree of deformation $\psi_1 = 1 - S_2/S_0$ through the intermediate matrix. This dependence *2* has a non-monotonic character. The ascending branch of this dependence corresponds to the positive effect of the two-stage reduction. On the descending branch, the extrusion time is increased, and consequently, with intensive heat removal the material does not have time to extrude and the effect of the two-stage reduction becomes negative. Here, the competitive interaction of the processes of heat removal, compaction and extrusion is observed.

Conclusion

The undertaken research by a method of mathematical modeling gives the following answers to the questions posed in the introduction:

– the two-stage reduction increases the length of the extruded part of the material;

– there are optimal values of the radius of the intermediate matrix to achieve the greatest length of the extruded part of the material. These values should be determined given the competition of processes of heat removal, compaction and extrusion;

– the most favorable conditions for the SHS-extrusion to increase the completeness of extrusion (the ratio of the extruded length of the sample to the maximum possible length) are provided in the regime of sequential flow of compaction and extrusion processes.

Numerical studies made it possible to give the following recommendations for obtaining long-length samples of large diameter (8–10 mm) by a two-stage SHS-extrusion method:

1) for large diameter rods (5 mm), a two-stage reduction is more preferable than a single-stage reduction and at selected process parameters (similar to a single-stage reduction) allows obtaining rods 97 % in length from the maximum possible;

2) the optimum values of the radius of the intermediate matrix to achieve the greatest length of the extruded part of the material must be found using numerical calculations based on the proposed model.

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