TECHNOLOGICAL BASIS OF SHS EXTRUSION

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The results of the development of the SHS extrusion process, including creation of the equipment, studies of the production conditions and product quality are presented. The concepts of the ability of different composite refractory materials to plastic deformation are formulated. Examples of practical applications of the method developed are given.

At present a new SHS extrusion method is used to obtain long articles from brittle not easily deformable refractory materials. As a process operation SHS extrusion is designed for shaping of synthesized combustion products by extruding them through a forming die. The structure formation occurs under high-temperature deformation. It is this peculiarity of the method which draws attention to SHS extrusion not only as an effective refractory material processing technique but also as a process in which its ability of plastic deformation in a high-temperature range and at relatively low pressures ($P < 500$ MPa), a property that is studied inadequately, is exhibited.

In this study much attention is given to aspects of the process. An attempt is made to explain the feasibility of extruding different objects at extrusion temperatures of about 1000°C (this temperature is only determined by operation conditions of the press equipment). Experimental material has been collected which shows the feasibility of plastic deformation in particular cases. Much attention is given to the development of specific SHS equipment. Mere enumeration of the numerous inventions and patents shows extensive activity in this field. Systematization of the experimental studies of the extrusion operating condition is made.

Equipment for SHS Extrusion. In the development of the first SHS extrusion installation [1] a serial hydraulic press was used; it was updated to extend the range of working speeds of its crosshead. The press had an automatic control unit setting time parameters of the process: the initiation time, the extrusion delay, and the extrusion time. To determine the optimal power and speed of extrusion, registration of the process parameters is needed. Therefore, the installation is equipped with a system measuring the press crosshead travel and pressure to be recorded by a mirror galvanometer oscillograph.

Designing of the moulding equipment which should provide the removal of impurity gases released in combustion and the effective pressure transfer from the press to the material at a combustion temperature of 1500-3000 K was most difficult. After some preliminary studies the following experimental scheme was suggested. A blank thermally insulated with asbestos cloth is placed into the molding die container. An initiation device is placed preliminarily into the die opening. The blank is ignited through filling in the conical part of the die. The filling is of the same composition as that of the blank. After the blank burns, the press is switched on, and the material synthesized is first compacted and then extruded through the die into the inner punch channel. The installation works following the reverse compaction principle: the punch is motionless, and the case is moved by the press along the punch.

The ignition from below provides a more homogeneous temperature field in deforming the burned blank; however, it did not appear to be adaptable to streamline production because it was labor-consuming; moreover, the wiring interfered with the normal material extrusion. Therefore other process schemes were used, in particular, ignition from above and a plug. In the case of ignition from above, the lead-in wires of the initiation device were built into the die cover and screened from the burned blank with a special washer. The plug was used to eliminate increased porosity of the initial part of the articles.

To prevent the axial curvature of the extruted rods, guiding gauges were pressed into the inner punch channel. In this case the material to be extruded moved along the gauge with a clearance not more than 1 mm, ensuring rectilinearity of the articles.

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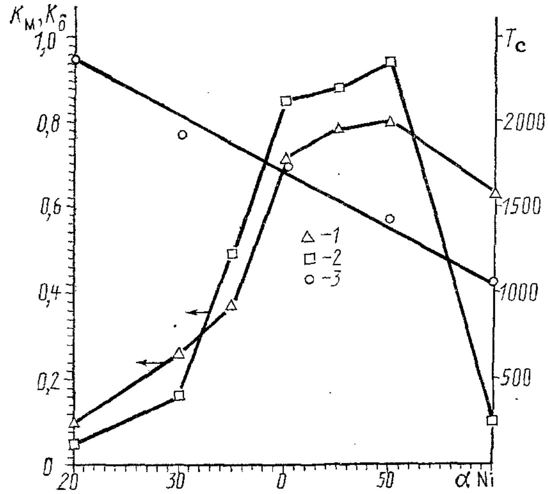


Fig. 1. Plot of the extrusion completeness (1), surface quality criterion (2), and the combustion temperature of compositions (3) versus the Ni content; T_c°C; α_{Ni}, mass %.

The development and updating of SHS extrusion equipment have been carried out to increase its output and functional capacity and to improve the product quality. Devices have been created which control the heating of the blank, die, and gauge. This extends the assortment of the SHS-extruded material due to weakly exothermic and slightly plastic compositions, improves the surface quality, and controls the material grain size.

A process scheme has been tested which employs complex material shear by combining translational and rotary motions. This improves the mechanical properties of the articles and decreases the porosity. This method produces complex profile articles, including the screwed hard alloy blanks of cutting tools (drills, milling cutters, etc.).

For commercial production of electrodes an installation was developed whose design increased its output substantially. The container of the installation is composed of two chambers (power and combustion) mounted coaxially. The blend blank is placed into the combustion chamber with a clearance for the gas discharge. Absence of contact between the blank and the chamber decreases the heat transfer into the walls, and no thermal insulation of the blank by asbestos fabric is therefore needed.

A more homogeneous temperature field in the blank is provided by placing the initiation device at the blank half-height level; this decreases the combustion time by a factor of two. After the blank burns, the punch forces it into the power chamber, where it is compacted and then extruded through the die into the gauge. After the punch is returned to the initial position, and the container is lifted by the ejector, a box die containing the die and gauge with the electrode produced is withdrawn from the installation. The box is replaced, and the cycle is repeated.

The SHS production of particular materials requires pressures of an inert or reacting gas or vacuum in the working space. These are cast materials, in the production of which pressure prevents the reaction mixture from spreading; nitride systems are produced under the nitrogen pressure.

For SHS production of articles from such materials an installation was designed which combines the press and reactor functions. It consists of a high-pressure chamber that also serves as a press frame. It has a standard hydraulic unit and a control board. One of the strengths of the installation is its leak-proofness, which prevents fumes from getting into the atmosphere.

Studies of the synthesis of cast products followed by hot hydrodynamic extrusion (HHDE) of the alloy are in progress. The material synthesis is carried out in special molds, and it is subsequently deformed together with its shell. The favorable scheme of the stressed state, used with HHDE [2], gives articles of high surface quality, in particular, articles from heavy tungsten-based alloys.

Work on the production of complex-shaped articles from SHS materials is under way. The SHS products are subjected to subsequent processing, for instance, by cross-wedge rolling or induction melting, which gives articles with a variable cross-section along its length.

SHS Extrusion Objects. At present a large number of different SHS-extruded materials and articles has been obtained. The most important of them will be discussed in what follows.

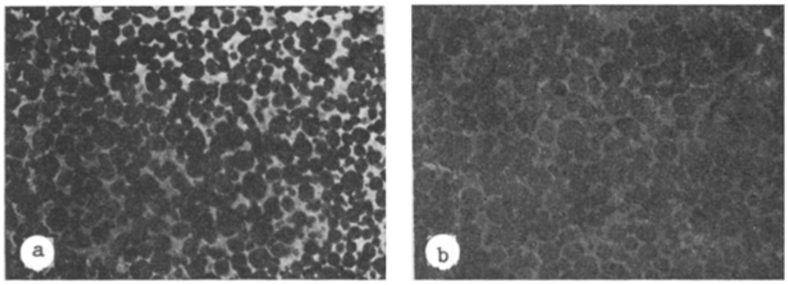


Fig. 2. A typical SHTM-2/30N (a, ×2000) and SHTM-2/40N (b, ×3000) microstructure.

One of the main problems in the development of a method is choice of the object of the investigation. Can all SHS materials be extruded and what are their suitability criteria? On the basis of the available experimental data the main condition of material extrusibility was found. This condition can be defined as follows: at the extrusion temperature the material should contain a sufficient amount of the phase providing for plastic deformation of the whole material volume. The necessary amount of the phase may be different for different materials.

As is known, plasticity is function of many parameters, among which pressure and temperature are the most important [3]. Therefore, to ensure that after synthesis the material remain in a plastic state, its temperature must be sufficiently high.

The most common objects of SHS extrusion are synthetic hard tool materials (SHTM) [4], containing a wear-resistant component (TiC, Cr_3C_2, TaC, TiB) and a binding metal or alloy (Ni, Co, Ti, steel). It is the binder which provides for plasticity of such materials. At sufficiently high temperatures the binding serves as a lubricant facilitating the slip of hard particles. The material can be deformed as a viscous plastic body, and articles can be formed from it. Special studies show that the ability of the composites to plastic deformation appears at temperatures of up to 0.7-0.9T_m of the metal component (but not of the hard base).

All the above-said may be illustrated by experimental results on extrusion of the TiC–Ni system materials. Figure 1 shows the dependence of the extrusion completeness (which may be a measure of material plasticity) on the nickel binding content. At a low binding content (20%) the material plasticity is low despite a high combustion temperature. The extrusion completeness of this composition did not exceed 10%. A binder content of 20% may be considered as a conventional limit above which the material extrusion can take place. It should be noted, however, that at different extrusion conditions (higher initial temperature of the blank, heating of the compaction equipment) the compositions with a 10% binder content may be extruded.

As the binder content increases from 20 to 50%, the composition plasticity grows, which is indicated by a continuous increase of the extrusion completeness. A decrease of the latter as the binding content rises (to 60%) may be explained by purely thermal factors, namely, an abrupt decrease of the combustion temperature and consequent underreacting of the components. The surface quality criterion K_δ, which also characterizes the material plasticity level, behaves in a similar way.

That the material plasticity rises substantially in the range of the binding content of 30-40% is remarkable. This phenomena may be explained in terms of the structure binding capacity [5]. A statistical quantity, the average contact number per particle N_{con}, may be used for a description of the binding capacity. A critical estimate of the minimal contact number $N_{con} \sim 2$ was obtained, at which a structure may be still considered as completely bound.

It is clear that the higher the structure binding capacity, the less plastic is the alloy due to the resistance of the carbide frame to the deforming force. Figure 2 shows photographs of the SHTM-2 alloy microstructure with nickel binding contents of 30 and 40%. Their structure binding capacity is 1.8 and 0.8, respectively, that is, the SHTM-2/30N structure is almost completely bound, whereas the binding capacity of the SHTM-2/40N structure is minimal, which explains the higher plasticity of the latter. The conclusion that the plasticity of hard-alloy materials is determined by the binding presence is confirmed by the fact that carbide grains preserve their shape during extrusion (no deformation) [6].

There are some differences in the SHS extrusion of hard-alloy materials containing intermetallic compounds (TiNi, NiAl, Ni_3Al) as a binding. The deformation of such a composition also occurs due to the binding plasticity (for instance, in the intermetallic compound NiAl the brittle–ductile transition is observed at ~700°C). However, in the synthesis of intermetallic phases in the combustion mode a sufficient amount of heat is released to obtain materials with a large binding content (up to 100%), which is impossible with an inert binding.

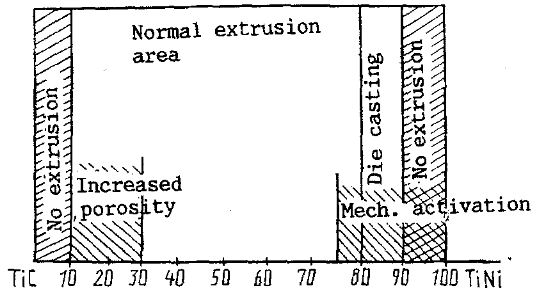


Fig. 3. SHS extrusion modes of TiC–TiNi, %.

Let us consider the peculiarities of the extrusion of such materials with the TiC–TiNi system as an example (Fig. 3). At a low content (<10%) the extrusion is unfeasible because of insufficient material plasticity. At 10-80% TiNi the extrusion is normal, i.e. the product is rod-shaped. At a binding content of 10% to 30% a higher porosity of electrodes is observed, which may be explained by the low material plasticity. At ~85% TiNi the material after the synthesis becomes a low-viscosity liquid. When even a low pressure is applied, the product flows out of the die and solidifies on the gauge walls as a tube.

At >80% TiNi in the material and at the initial room temperature the synthesis is only possible with preliminary mechanical activation of the charge. As the TiNi content increases up to 100%, the extrusion ceases because of insufficient composition temperature, which appears lower than the brittle-ductile transition temperature of intermetalloid (T_c = 630°C for the Ti + Ni composition at an activation time of 10 min). Thus, the use of a reacting binding substantially increases the range of its content in the material.

A different picture is observed in SHS extrusion of tungsten-based cast alloys. The alloys consist of tungsten crystallites surrounded by a solid Ni–Fe–W solution. Both phases (the grain and binding) are metal systems, and their plasticity is sufficient. Therefore, in extrusion of such compounds plastic deformation of tungsten grains, whose shape becomes an extended oval and which are oriented in the extrusion direction, is observed [6]. Thus, the high plasticity of all alloy phases results in a clearly expressed deformation texture of the articles.

A more complicated situation takes place at the production of heating elements based on molybdenum disilicide. The main difference is that those mixtures do not contain fusible metal bindings which are needed to perform the deformation process of the SHTM group. Moreover, the assortment of additives improving the properties of silicide systems and the ability to be processed (including moldability) is rather limited. The silicon activity in molybdenum disilicide is as high as that of metallic silicon. Therefore it is very difficult to obtain cermet type materials based on silicides. As binding metals for such materials only 15 fusible transitional metals may be used, including gold and silver, which do not react practically with molybdenum silicides and form eutectic systems with silicon [7]. However, because of the low operation characteristics of the systems formed and the high cost of the reactants, their use is limited.

At the Institute for Structural Macrokinetics, Russian Academy of Sciences, a group of materials based on molybdenum disilicide and a method of producing heating elements from them have been developed. The work was a success mainly due to the use of a complex oxide based on aluminum, silicon, and oxygen, referred to as mullite, as a filling agent and dielectric component of the system. We suggest on the following grounds that it is the oxide phase (but not the silicide phase) which carries out the molding process. Though the silicide phase of the product consisting of molybdenum disilicide and the oxide phase consisting of mullite have approximately the same melting temperatures of 2050 and 1950°C, respectively, the brittle–ductile transition ranges of these phases are substantially different. For molybdenum disilicide this range is between 1950 and 2050°C [8] and for mullite it is ~1650-1950°C. Since extrusion occurs at temperatures of 1700-1900°C it is clear that at the moment of molding only the oxide phase is in the viscoplastic state. This is confirmed by the experimental results: for small delay times before molding the oxide phase may exist on the rod surface as drops and rolls which may be visually observed [9].

Another proof of the low silicide phase mobility in the product being extruded was obtained in a study of the article structure. It was found that the microstructures of the transverse and longitudinal sections of rolls were identical, no grain deformation in the silicide phase or grain texturing occurs in an explicit form. The grain sinters form a continuous three-dimensional frame of molybdenum disilicide particles with the volume filled with the oxide phase.

Studies of SHS Extrusion Operation Mode. In the development of the SHS extrusion process, the primary objective was to investigate the influence of different technological parameters on the process and to distinguish the most important ones. In so doing a stable reproducibility of the process was pursued. In this part of the study the SHTM-2 alloys consisting of titanium carbide and nickel binding of 30 and 40% were used. The choice was determined by the fact that the problems involved in the synthesis of such systems had been studied quite well, and there were numerous data on the properties and structure of similar materials obtained by different methods.

It was found that the SHS extrusion process depended on many process parameters, of which delay time, preset pressure, degree of deformation, extrusion rate, and die geometry were the main ones. For stable process reproducibility their optimal value ranges to should be found.

The effect of these parameters on such characteristics of the articles as the length and mass of the extruded part, the surface defect depth, mechanical properties (strength and hardness), and product microstructure was investigated. A criterion approach appeared to be effective for finding the methods of controlling the product quality. The geometrical, structural and mechanical quality criteria were formulated. Let us consider two of them.

In SHS extrusion the material part cooled below the survivability temperature usually produces a compaction residue. As a criterion characterizing the product output it is convenient to take the extrusion completeness defined as the ratio of the extruded shaped material to the charge blank mass: $K_M = m/m_0$.

The surface defect pattern is an important aspect of the article quality. "Crow's feet" type defects are characteristic of articles from not easily deformable materials including the SHTM compounds. As a measure of the surface condition the flow layer dimension δ, equal to the double crack depth, may be taken. However, since the relative defective flow layer dimension is more significant than the absolute one, the corresponding criterion may be defined as $K_\delta = (d - \delta)^2/d^2$.

The criterion K_δ has a clear physical meaning of the relationship between the defective and defectless parts of the specimen cross-section. Its value should be considered as that part of the specimen which remains after the defective layer was removed, that is, the finite dimensions of the article.

Let us consider now the influence of every process parameter enumerated above. One of the most important operation factors is the delay time, the interval between the combustion initiation and initial pressure application. The physical meaning of this characteristic is the time interval needed for the rheological material properties to attain the optimal level for the shear deformation under compaction and extrusion conditions.

The numerical studies of the SHS extrusion process based on the thermal model [10] showed that the die configuration largely determined the heat-transfer and shear deformation processes during the extrusion. Therefore, experiments with dies of different configurations can estimate the extent to which the article characteristics are affected by these processes. From the parameters of the die configuration the conical part angle γ and the die parallel length L were selected.

The curves $m(\tau_d)$ for dies with different γ are presented in Fig. 4. The nonmonotonic shape of these curves is characteristic of a wide class of SHS materials and may be explained by the following considerations. Let us introduce some characteristic times: reaction time τ_r, material structure formation time τ_f, and material plasticity loss time (survivability time) τ_s. The times τ_r and τ_f are essentially the effective parameters of the chemical reaction process (the final product development) and the structure formation process (the compact material formation), and the time τ_s characterizes the rheological factors. Depending on the relation between the delay time τ_d and characteristic times τ_r, τ_f, τ_s, different limiting cases of SHS extrusion are realized.

At small delay times (the dotted part of the curves) the material is extruded as a hard base powder and initial components which did not react. This is accompanied by extruding under load drops of the metallic binding. All this takes place at $\tau_d < \tau_r$ because the final product formation reaction in the whole volume is not completed, the alloy structure is not formed, and the binding is in a liquid state.

As the delay time (the rising branch of the curves) exceeds τ_r the formed compound fragments start to appear; however, a part of the material is extruded as a hard base powder. This specimen region is characterized by an inhomogeneous temperature field, and three-dimensional zones with the formed structure and liquid binding zones. As τ_d and τ_f get closer, the formed material proportion increases (the extrusion completeness rises accordingly) and reaches a maximum at $\tau_d = \tau_f$. Thus, τ_f may be conventionally evaluated from the curve $m(\tau_d)$ extremum.

As the delay time increases further, the extrusion completeness decreases gradually (the descending branch of the curves), because cooling of the formed material results in expansion of the three-dimensional specimen zones which lost their deforming ability. Finally, at $\tau_d > \tau_s$, the output die section is completely clogged, and the extrusion ceases due to survivability loss of the near-die areas. Because of that τ_s can be found experimentally in real conditions.

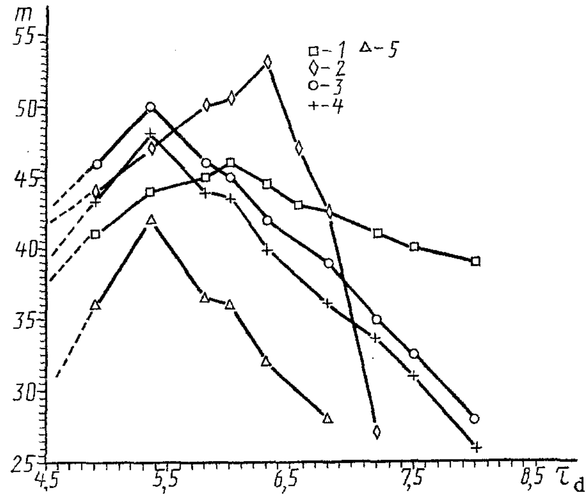


Fig. 4. Plot of molded material mass versus delay time for dies with different γ: 1) γ = 180; 2) 150; 3) 120; 4) 90; 5) 60°. m, g; τ_d, sec.

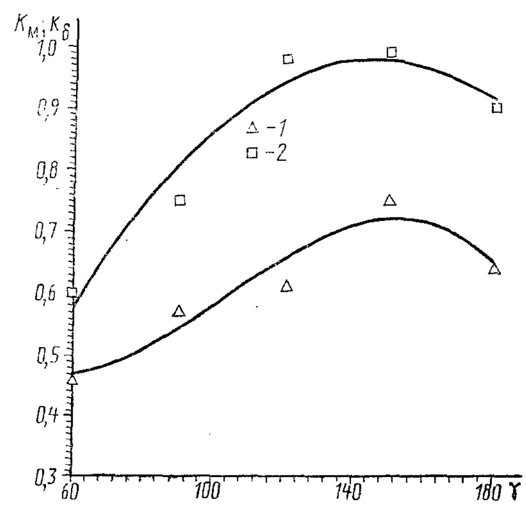


Fig. 5. Plot of the extrusion completeness (1) and the surface quality criterion (2) versus the angle of the conical die part at τ_d = 6.30 sec. γ, degree.

Thus, from the material condition by the initial moment of pressure application four cases of the SHS extrusion process may be distinguished, and their time ranges experimentally determined in each case.

As can be seen from Fig. 4, the cone angle of the conical part of the die determines mutual location of curves 1-5, having no effect on their shape. The nonmonotonic behavior of $K_M(\gamma)$ (Fig. 5) may be explained by the fact that the influence of the variable γ is ambiguous. On the one hand, γ determines the material flow behavior, and with this in mind, a smaller angle is useful because it provides a smoother variation of the profile and a lower extrusion resistance. On the other hand, the conical die part is an intensive heat-transfer surface where the material cools quickly especially at acute angles, which results in clogging of the die and extrusion cessation. Such competitive interaction of the hydrodynamic and thermal factors gives rise to the extremum in the curve $K_M(\gamma)$ and, consequently, to an optimal region of γ values. The optimal angle value of the conical part of the die depends on the set of chemical, thermophysical, and rheodynamic properties of the concrete material. In our case γ_{opt} is 150°, which is in good agreement with the results of [10].

As the experiments showed, the die parallel length L has a substantial effect on the mechanical stability of the material flow in the article extrusion and shaping. At L ~ 0-2 mm, the material flow is extremely unstable and the article cannot be molded actually. Moreover, the effect of elastic "swelling" of the rods is observed (the article diameter is larger than the die opening diameter). The experiment reproducibility is low.

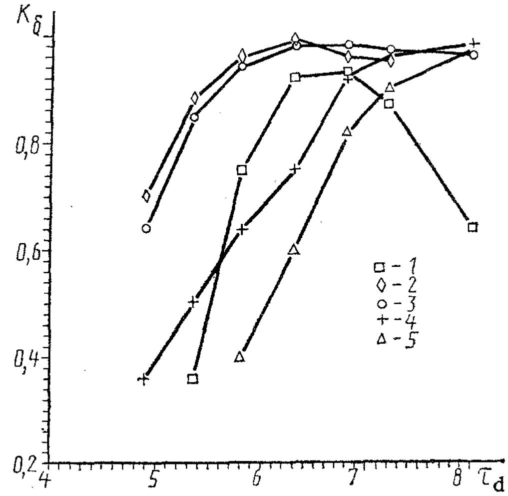


Fig. 6. Plot of the surface quality criterion versus the delay time at different γ: 1) g = 180; 2) 150; 3) 120; 4) 90; 5) 60°.

As the die parallel length increases, the extrusion instability decreases gradually, and the surface quality and reproducibility are improved. After a certain optimal value is achieved a further increase of L has no substantial effect.

Completeness of the material extrusion in the studied range of L = 0-35 mm was nearly constant. No effects associated with the thermal die clogging were observed. Probably, this may be explained by a sufficiently high speed of the material passing though the shaping opening at which the heat removal is not significant.

Data on the completeness of the material SHS extrusion must be considered together with the surface quality data of the produced articles (Fig. 6). It is seen that the curves $K_\delta(\tau_d)$ have different shapes for different γ. At γ of 150° and 120° the values of K_δ are maximal and the optimal delay time for the quality is close to that for the extrusion completeness, which is an important technological factor. Moreover, a high surface quality is obtained at γ of 60° and 90° but with times close to the survivability time that is, at the expense of a substantial reduction of the extrusion completeness. The curve $K_\delta(\gamma)$ (see Fig. 5), as well as $K_M(\gamma)$, is not monotonic; however, coincidence of the optimal regions is not necessary. The nonmonotonic shape of the curve may be explained by the considerations given above.

The analysis of the curves $K_M(\tau_d)$ and $K_\delta(\tau_d)$ gives an approach to the SHS extrusion reproducibility which is of crucial importance for every method. The approach proposed in this article consists in the investigation of the form of the relations between the process and article characteristics and the main process parameters. If the form of the relation shows that the best characteristics can be attained when the parameters vary in very narrow ranges, the process may be defined as "severe" in respect to these process parameters. For instance, curve 1 has a clear extremum, the delay time range where K_δ values are high is relatively narrow (about 0.5 sec), and outside this range K_δ drops abruptly. In practice this means a low process reproducibility and severe process requirements for the equipment, charge, etc.

One of the most important extrusion parameters is the deformation degree defined by

$$\psi = (S_0 - S)/S_0,$$

where S_0 is the initial blank cross-sectional area; S is the article cross-sectional area. Increase of the degree of deformation improves the quality of the article; the articles have no deep cracks, the article surface becomes cleaner. Figure 7 shows the dependence of the value of the defective layer on the article diameter and the dependence of the surface quality criterion K_δ on the degree of deformation, the latter curve is nonmonotonic with a maximum at $\psi = 0.96$. This indicates the practically important value of the optimal degree of deformation that gives the minimal relative defective layer. Moreover, as the deformation degree rises, the article porosity decreases substantially and, as a result, the article strength becomes higher [6].

Another process parameter of key importance for the process is the extrusion speed. As the speed increases, the extrusion completeness increases (Fig. 8). After the speed exceeds a certain critical value, the normal extrusion is disturbed, and the product is extruded as separate, poorly compacted lumps or powder. The critical speed value depends on other process parameters and is usually in the range of 40-60 mm/sec. For the dies with large angle γ the criterion K_δ is found to drop as the extrusion speed increases.

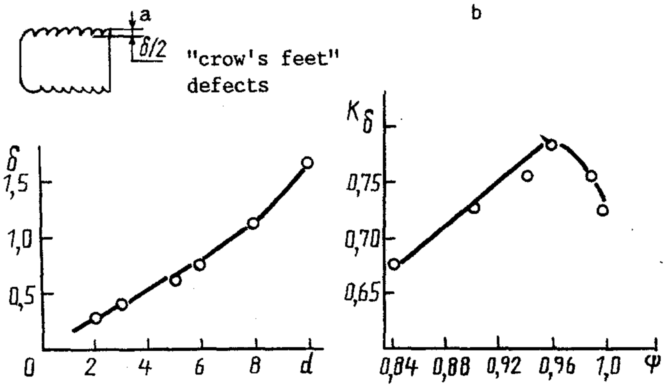
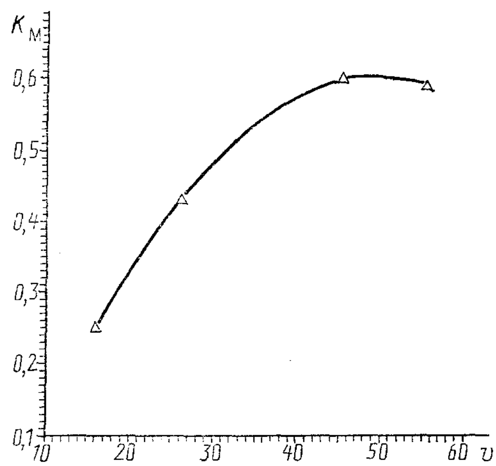


Fig. 7. Dependences of the defective layer on the article diameter (a) and of the surface quality criterion on the deformation degree (b). d, mm.



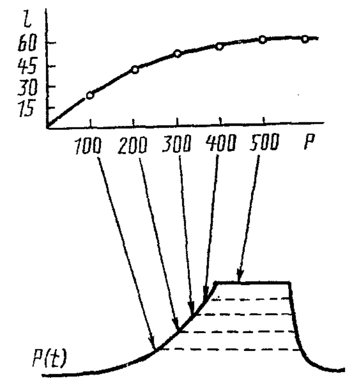


Fig. 8 Fig. 9

Fig. 8. Plot of the extrusion completeness versus the press plunger speed. v, mm/sec.

Fig. 9. Dependence of the specimen length on pressure. l, mm; P, MPa.

To determine the optimal value of the preset value pressure, the effect of this parameter on the specimen length was investigated. Figure 9 shows this relationship together with the pressure oscillogram. Their analysis suggests that the extrusion process occurs only at a pressure growth because of continuous material cooling. By stopping the pressure rise we interrupt the process at different stages. Saturation of the relation l(P) at an incomplete extrusion may be explained by the material survivability loss in the press equipment. The optimal pressure value corresponding to saturation is 500 MPa.

Thus, the study of the effect of the main process parameters on SHS extrusion allowed us to find the region of their optimal values. As a result, stable process reproducibility was achieved and such harmful effects as the die clogging and different extrusion instabilities were excluded.

Practical Application of SHS Extrusion. SHS extrusion is used employed to produce slender articles (h/d >> 1) which cannot be obtained by other power compaction methods. As examples of practical application of the method, only such articles from powder refractory materials were selected whose production process is already being implemented, whose operation characteristics have been investigated and some experience of their usage has been gained. It is worth noting that every application required solution of the problems not only directly connected with the production process, but also those lying outside.

The best developed SHS extrusion application is the production of electrodes for electric spark alloying. The results are reported in [11].

Because at present numerous technological and scientific problems are to be solved, creation of heaters designed for long operation in a corrosive medium at temperatures above 1600°C is very urgent. Most of the studies aimed at developing new materials for the heater are carried out along the line of updating the heaters based on molybdenum disilicide in order to obtain stable thermal, electrophysical, and operational characteristics. The industrial method of producing these heaters includes more than 50 operations; it is complicated, power- and time-consuming. Furthermore, such components of conventional heaters as bentonite clay and other plasticizers, needed at the cold nozzle extrusion and sintering stages, decrease substantially the heater working temperature and bring about high-temperature creep.

Application of SHS extrusion to obtain the heating elements is promising because of the ability to perform the material synthesis from the initial component powders for tens of seconds (instead of hours) and of molding articles of a given size and shape [12]. Moreover, its use substantially simplifies the heater production process, decreases the energy consumption and eliminates the use of complex and expensive equipment. In addition, the molybdenum disilicide synthesis and SHS extrusion production of articles do not require a plasticizer (bentonite clay), because of which the limiting working temperature can be increased substantially.

Tests of the heaters produced carried out at a special facility showed their serviceability up to a temperature of 1830°C, where no higher temperature creep was observed, and the specimen size and shape remained practically unchanged in short-term heating up to the melting temperature of the components (~2000°C). Extremely severe operation tests (fast thermal cycling with heating up to the limiting working temperature) showed a higher resistance of SHS heaters in comparison with the industrial specimens. During the tests electrophysical characteristics were measured with the electric resistivity method. The specific electrical resistances obtained in the temperature range of 20-1500°C exceed the values of the industrial heaters, including the heaters produced by Cantal Company, the world leader in the field. Slight variation of the SHS heater electric resistance under high temperature operation conditions indicates the absence of fast processes, which make the heater inoperative, and the specimen stability against large power loads [9].

Among other practical applications of SHS extrusion we may distinguish the production of hard-alloy electrodes for facing, the screw blanks of cutting tools (drills, cutters), tools for treatment of stone, microrolls. The work on using different steel grinding wastes for production of materials based on hard alloys and articles from them is under way. Microcutters for glass engraving were produced with a resistance not lower than that of conventional diamond cutters. Bars from magnetic abrasive materials were produced which may be successfully used as grains in roughing tools. The grains may be oriented in the grinding wheel by applying a magnetic field which increases the tool output.

The advantages of SHS extrusion as a method of producing slender articles from refractory materials are obvious. However, apart from purely technological aspects, this article has revealed the strengths of SHS extrusion as a method for investigating synthesis, structure formation, and high-temperature plastic deformation. At present it is difficult to follow all the feasibilities of SHS extrusion as a research tool; it is clear that a combination of theoretical and experimental methods will be effective here.

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NOTATION

L, die parallel length; γ, angle of the conical part of the die; τ_d, τ_r, τ_f, τ_s, delay time, reaction time, structure formation time, and survivability time, respectively; m, shaped, extruded material mass (article mass); m_0, initial charge blank mass; $K_M = m/m_0$, extrusion completeness criterion; d, article diameter; δ, surface defect depth; $K_\delta = (d - \delta)^2/d^2$, surface quality criterion; N_c, the average contact number per particle; ψ, deformation degree.

LITERATURE CITED

1. A. G. Merzhanov et al., "A method of producing articles from powder materials and a device for its implementation," International Application WO 90/07015, June 28, 1990. U.S. Patent W5053192.
2. V. P. Severdenko, V. S. Muras, and E. Sh. Sukhodrev, Hot Hydrodynamic Extrusion of Cutting Tool [in Russian], Minsk (1974).
3. B. I. Bersenev, K. I. Ezerskii, and E. V. Trushin, Physical Fundamentals and Practical Application of Hydroextrusion [in Russian], Moscow (1981).
4. A. G. Merzhanov, Self-Propagating High-Temperature Synthesis: Two Decades of Search and Findings (Preprint, Inst. Struct. Macrokinetics), Chernogolovka (1989).
5. K. S. Chernyavskii, Stereology in Metal Science [in Russian], Moscow (1977).

6. T. N. Shishkina, V. V. Podlesov, and A. M. Stolin, Inzh.-Fiz. Zh., **66**, No. 5, 547-557 (1992).
7. E. Fitzer and O. Rubisch, Elektrowarne, No. 5, 163-169 (1958).
8. G. V. Samsonov, L. A. Dvorina, and B. M. Rud, Silicides [in Russian], Moscow (1979).
9. S. V. Vedeneev and A. M. Bulaev, in: Production, Properties of Superhard Materials and Their Promising Commercial Applications [in Russian], Kiev (1991), pp. 79-84.
10. L. S. Stelmakh, in: Heat and Mass Transfer in Chemically Reacting Systems [in Russian], Vol. 2, Minsk (1989), pp. 21-30.
11. V. V. Podlesov, A. M. Stolin, and A. G. Merzhanov, Inzh.-Fiz. Zh., **63**, No. 5, 636-647 (1992).
12. A. G. Merzhanov et al., Ceramic composite material and its production method, International Application WO 91/0025, Jan. 10, 1991.