Contribution on Fundamentals of SHS and the Implementation of SHS Technology in Industry

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The paper considers the main results of the authors’ investigations in the field of the scientific backgrounds of the processes of self-propagating high-temperature synthesis (SHS) and their practical realization.


The first part of the paper considers the results connected with the elaboration of the methods of SHS experimental diagnostics, investigations of gasless and filtration combustion regularities, discovery of new interesting phenomena, processes, modes, and development of the process mechanism concept.

Great attention is paid to the formation of solid products in self-propagating processes (it’s the main difference of SHS from fuel combustion). The concepts of phase and structure formation mechanisms in final combustion products, equilibrium and non-equilibrium SHS products and processes are stated.

The method of kinetic electrothermography as a new direction of investigations of high-temperature metal interaction with gases and dynamic X-ray analysis for studying dynamics of phase transformations in the SHS wave are discussed.

The lecture describes the discovered phenomenon of structure non-uniqueness in binary systems and application of this phenomenon for structural regulation of combustion product characteristics, some interesting data in polymorphism of silicon nitride structure and dynamics of recrystallization in combustion products.

The second part, which is set out rather sparingly in spite of a great number of results, describes various SHS applications (chemical synthesis of inorganic compounds, elaboration of powders with particular properties, net-shape synthesis).

Interesting examples of self-propagating high-temperature synthesis of yttrium-barium cuprate (high-temperature superconductor), abrasive pastes for simultaneous grinding and polishing, complex titanium-chromium carbide possessing heat and wear resistance at high temperatures and used as an excellent material for protective coatings, unusual characteristics of multicomponent ceramics containing various combinations of nitrides, borides and silicides, etc. are given.

The paper contains brief information of alternative principles of the technology of inorganic materials, science-intensive production and various directions of material application, which are developed in the SHS field.

As the main result of their 40-year activity, the authors consider the creation of the boundary area between the combustion theory and materials science, the formation of a bridge between the combustion techniques and inorganic material technology, the spontaneous formation under the influence of the authors’ activity of the World community of the specialists who turned SHS into the advanced field of scientific and technical progress.

1. Introduction

In 1967 in the Branch of the Institute of Chemical Physics of the USSR Academy of Sciences in the scientific school of the Nobel-Prize Winner Nickolay Semenov, the authors of this paper and a young researcher Valentin Shkuro were lucky to make a significant scientific discovery [1] which was officially called “The phenomenon of wave localization of auto-braking solid-phase reactions”. It should be explained in the following way: in the reactions which occur between solid components with formation of solid products and a decrease in the reaction velocity a phenomenon was observed in which the reaction was localized in a layer propagating along the components mixture spontaneously with a constant velocity.

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Figure 1 shows typical shots of this process.
Shot 1. Initiation of the process by a heat pulse brought to the sample surface (ignition).
Shot 2. Formation of the flat reaction front in the zone of high temperature where the reaction started.
Shot 3. The reaction front propagation along the sample.
Shot 4. Sample cooling after the reaction front propagation.

We can see that the front appeared after the ignition moves along the sample made of powder reagents, converts them into the reaction products, and leaves the hot solid product behind. This picture looks like a flame propagation and that’s why that process was also called “Solid-flame combustion” (SFC) and the discovery acquired the second name “The phenomenon of solid flame”.

Why was the phenomenon considered a scientific discovery? Actually solid flames could be regarded as a discovery because they hadn’t been known before and couldn’t be predicted. It wasn’t clear at that time how such solid-phase reactions, auto-braking ones indeed, could occur in so fast modes as flame propagation.

Solid flames (SF) are material-forming combustion processes in the wide sense of the words without any connection to specific
Almost each scientific discovery has its own portent. From this point of view the SFP is not an exception. The authors consider that such portents of the discovery were metal-reduction of Beketov-Goldscmidt and modern combustion theory of Semenov-Zeldovich. Figure 2 shows the authors’ path to their scientific discovery.

In comparison with other processes the solid flame combustion has three characteristic features (Figure 3):

- Uncommonness of the combustion processes mainly forming solids couldn't help leading their investigation to the further development of the combustion process;
- Obtaining of valuable substances and materials during SFC, which could not be produced by well-known methods, couldn't help leading to the development of novel synthesis methods;
- Significant heat release and self-heating without gas evolution for the processes resulting in condensed products; it allowed solving some complicated tasks of specific pyrotechnics by means of SFC.

These features attracted the scientists’ attention. The investigation of the solid flame phenomenon was being developed. It was not lost among other scientific discoveries. The interest to it was continuously growing (and goes on growing now).

Such interest resulted in appearance of a method for obtaining inorganic substances and materials which was called “self-propagating high-temperature synthesis (SHS)” [2]. At first the phenomenon of solid flame and “its child” - the SHS process - were being developed together. The SHS method was used to synthesize refractory compounds and called a synthesis in solid flame processes. But when the child grew up a bit and began to look around, a conflict occurred (as it happens among people), and the SHS tore itself away from the solid flame and began to interest in any combustion processes which resulted in substances and materials valuable for science and technology.

And then the problem was being developed under the banner of SHS.

The discovery of the SFP and the development of the SHS method were made in the Scientific Center of the USSR Academy of Sciences in Chernogolovka which turned into the World Center of SHS processes. From the point of view of history and geography, it is possible to emphasize three stages in the development of SHS: the first one is connected with Chernogolovka when the investigations were carried out only in this town; the second can be called the Soviet period when other Soviet Republics and towns joint Chernogolovka, and at last, the world stage when other countries showed their interest to the problem (Figure 4).

This development resulted in the formation of the friendly world community of SHS specialists whose joint efforts led to the outstanding scientific and practical achievements.

This lecture shows some results of the authors’ activity which exerted helpful influence on the development of the problem.

## 2. Some Ideas on Mechanism and Regularities of SHS Processes

The SHS processes can be realized in all chemically active systems in which the reaction evolves heat and forms a solid product being of scientific and practical interest.

There are many varieties of SHS from the viewpoint of the state of the reacting medium (i.e. initial components and final products) (Table 1). It is not necessary to enumerate all of them but it should be mentioned that two types of the systems are widely used now: mixed systems (either powder mixtures
The most common variety of systems and combustion processes in different media.

### 1. Solid – solid systems (powder mixtures)

<table>
<thead>
<tr>
<th>System</th>
<th>Combustion process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractory metals (Nb, W, Ta, etc) and refractory non-metals (B, C)</td>
<td>Solid flame combustion</td>
</tr>
<tr>
<td>Metal – metal</td>
<td>Gasless combustion</td>
</tr>
<tr>
<td>Metal – non-metal</td>
<td>Gasless combustion</td>
</tr>
<tr>
<td>Non-metal - non-metal, without gas release</td>
<td>Gasless combustion</td>
</tr>
<tr>
<td>Metals and non-volatile non-metal (S, P)</td>
<td>Combustion with little gas release</td>
</tr>
<tr>
<td>Volatile metals (Mg) and non-metals (S)</td>
<td>Chemical-condensation combustion</td>
</tr>
<tr>
<td>Metal-reduced mixtures</td>
<td>Liquid flame combustion</td>
</tr>
<tr>
<td>• Low-temperature</td>
<td>Liquid flame combustion</td>
</tr>
<tr>
<td>• High-temperature</td>
<td>Liquid flame combustion</td>
</tr>
<tr>
<td>Multilayer nano-sized films</td>
<td>Combustion in thin films</td>
</tr>
</tbody>
</table>

### 2. Solid + gas systems

<table>
<thead>
<tr>
<th>System</th>
<th>Combustion process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal, non-metal powders and their non-stoichiometric mixtures in nitrogen, oxygen, hydrogen and complex gases:</td>
<td>Self-regulating filtration combustion</td>
</tr>
<tr>
<td>• pressed powders or in bulk in still gas</td>
<td>Forced filtration combustion</td>
</tr>
<tr>
<td>• expulsion through a porous reagent</td>
<td>Combustion of dispersed systems in a flow</td>
</tr>
<tr>
<td>• gas suspensions</td>
<td>Combustion in “boiling” layer</td>
</tr>
<tr>
<td>• pseudo liqueation</td>
<td></td>
</tr>
</tbody>
</table>

### 3. Solid + liquid systems

<table>
<thead>
<tr>
<th>System</th>
<th>Combustion process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal and non-metal powders in bulk in nitrogen</td>
<td>Cryogenic combustion</td>
</tr>
</tbody>
</table>

### 4. Multi component systems

<table>
<thead>
<tr>
<th>System</th>
<th>Combustion process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems with components of different aggregative state</td>
<td>Multi-phase combustion</td>
</tr>
</tbody>
</table>

In the combustion wave the temperature grows form its initial value (usually it’s the temperature of the environment) up to the maximum one, then it drops to the environment value again. The temperature growth is stimulated by the exothermic combustion reaction, and its drop behind the temperature maximum is connected with heat losses into the environment (cooling of the combustion product). Thus, a significant non-isothermity is observed in the wave (Figure 5). The combustion front has an important place on the temperature profile. It is a conditional point in which the highest temperature gradient exists. Before the front there is a pre-flame zone which is often called a warming-up one. In this zone there are no chemical reactions yet. It is a kind of preparation of the system for the fast chemical reaction. The heat transfer in this zone is rather active. From the other side of the front there is a reaction zone with intensive heat release and weak heat exchange. According to the modern theory of combustion wave propagation (its fundamentals were formulated in the work of Ya.B. Zeldovich and D.A. Frank-Kamenetsky [31]), the reaction velocity in the heat exchange zone and the heat release (for gas flames, heat and mass exchange) determine the velocity and mode of the combustion front propagation. Usually the width of the reaction zone is a bit less than the length of the warmed-up layer.

As to SHS systems, besides these classical concepts there are some peculiarities revealed during SFC investigation [4-10]. One of them means that the combustion zone can have a wide afterburning subzone in which the processes do not influence the front velocity. The other peculiarity is the existence of the post-process zone in condensed products of the reaction, where the product structure and composition are formed. This zone is usually rich of various phases and secondary reaction transformations which do not influence the combustion front velocity but appear to be very important from the viewpoint of structure and composition of the forming materials and substances. The zone of the post-processes can be very long – much longer than the burning SHS system. In this case the matter concerns not a zone but a combustion stage. In this zone (stage) the combustion product gets cold due to heat emission into the environment (Table 2).

Usually the combustion wave has a flat (to be more exact, almost flat) front moving with the constant velocity. It’s a steady-state mode of SHS system combustion. The main characteristics of this mode are the front velocity, combustion temperature, and final product composition (chemical, phase, and sometimes impurity). This stationary movement with a flat front can lose its stability in some cases. If the heat capacity (density) of the combustion product is lower than that of the initial reagents, the process goes out. Such situation can appear at combustion of explosives, gun powders, solid propellants, i.e. at combustion of condensed systems with gaseous reaction products. In SHS processes, for which the condensed product formation is one of the main characteristic features, the extinction does not occur but some new unknown types of combustion appear [11] (Figure 6).

If such instability appears due to longitudinal minor perturbations, the flat combustion front remains but the steady-state movement of the front is broken. It is a self-oscillating combustion mode in which the instantaneous values of the combustion rate are not constant in time, they fluctuate about an average value; moreover,
Table 2. Combustion temperatures and velocities for some gasless reactions.

<table>
<thead>
<tr>
<th>SHS-reaction</th>
<th>Melting temperature of a product, $T_m$, K</th>
<th>Combustion temperature at adiabatic conditions, $T_{ad}$, K</th>
<th>Combustion velocities, $U$, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti+C $\rightarrow$ TiC</td>
<td>3290</td>
<td>3290</td>
<td>0.5 - 2.5</td>
</tr>
<tr>
<td>Ta+C $\rightarrow$ TaC</td>
<td>4270</td>
<td>2570</td>
<td>0.4 - 0.5</td>
</tr>
<tr>
<td>Ti+B $\rightarrow$ TiB</td>
<td>2500</td>
<td>2470</td>
<td>3.0 - 10</td>
</tr>
<tr>
<td>Mo + 2B $\rightarrow$ Mo</td>
<td>3270</td>
<td>2270</td>
<td>0.2 - 2</td>
</tr>
<tr>
<td>Ta + B $\rightarrow$ TaB</td>
<td>3370</td>
<td>2570</td>
<td>0.2 - 2</td>
</tr>
<tr>
<td>Ta + 2B $\rightarrow$ TaB$_2$</td>
<td>3370</td>
<td>2280</td>
<td>0.2 - 1</td>
</tr>
<tr>
<td>5Ti + 3Si $\rightarrow$ Ti$_5$</td>
<td>2390</td>
<td>2300</td>
<td>2 - 5</td>
</tr>
<tr>
<td>Ti + Si $\rightarrow$ TiSi</td>
<td>2190</td>
<td>1900</td>
<td>0.5 - 3</td>
</tr>
<tr>
<td>2Zr + Si $\rightarrow$ Zr$_2$Si</td>
<td>2490</td>
<td>1850</td>
<td>0.1 - 1</td>
</tr>
</tbody>
</table>

The utility of unstable modes for synthesis is not revealed (though there are some ideas) and such regimes are avoided in the SHS practice. The described phenomena were observed at combustion of both types of SHS systems but the combustion pattern of the system "porous reagent – gaseous reagent – solid reagent" is much richer. The most attractive for the researchers was the possibility of combustion of porous samples in a quiescent gas of a low pressure. The gas amount in pores is not sufficient to ensure the above mentioned self-propagating process and the missing part of nitrogen is supported from the surroundings by means of filtration which occurs spontaneously at combustion initiation due to the pressure gradient (in the combustion zone the pressure is lower than that of the surroundings due to the gas absorption by the reaction). In this case the combustion front acts like a pump injecting gas into pores. If "the pump" works well, the filtration combustion occurs by the layer-by-layer regime (with a practically flat wave), if "the pump" doesn't manage the front requirements, the deficiency of the gaseous reagent in the internal parts of the sample results in a significant curvature of the combustion front surface, and at extreme conditions the surface combustion arises. At higher pressures the combustion can occur due to the gas in pores. The filtration is also observed in this case but it has a back action leading to the gas withdrawal from the combustion front because due to high temperatures the gas pressure at the combustion front is higher than that of the environment. Also the SHS processes with forced filtration are very interesting (gas purging through a porous sample). Different variations of gas purging are possible here: toward the combustion front (counter filtration), after the combustion front (troubled filtration), and along the combustion front (transverse filtration). Each variant of the filtration combustion is rich of different effects and attractive for researchers (Figure 7). It should be mentioned that in most cases SHS reagents form heterogeneous systems. However, in many cases the processes can be considered in quasi-homogeneous approximation and then the specificity of heterogeneity does not result in new phenomena appear. They propagate unstationary along more complicated paths having radial and spiral parts. They can collide, merge and split. However, the pattern of such movement is determined, i.e. the process is periodic – in some distance covered by the wave (or some time) the described complicated pattern of the spin wave repeats itself. Such a regime is a degenerate spin wave in its essence or a determined mode of multi-spot combustion. And at last, with the further deepening into the instability zone the periodicity disappears in the process of degenerate spin wave propagation, and undetermined chaotic movements of the spots ensue (chaos in combustion).

The spontaneous filtration can be considered in quasi-homogeneous approximation and then the specificity of heterogeneity does not result in new phenomena...
and effects. But there are some situations when the heterogeneity scope exceeds the characteristic dimensions of “quasi-homogeneous” combustion and new heterogeneous aspects appear. Thus, the combustion in SHS systems differ greatly from that studied before. It can be controlled by changing the green mixture parameters (reagent particle size, density, reagent ratio, nature and concentration of the reactive impurities and fillers), shape, dimensions and initial temperature of the system, composition and pressure of the ambient gas.

The following approaches are widely used now: dilution of a green mixture with the final product (for decreasing the combustion temperature and velocity), in-furnace or Joule heating (for increasing the combustion temperature and velocity), introduction of regulating additives into the green mixture (influence on the mechanism of the final product formation), realization of the process in centrifugal devices and special moulds in which the process and the products are subjected to force actions.

SHS is a multi-parameter process and there are many “control sticks” of its regulation which allow solving the tasks of modern materials science and getting a required result.

We’d like to underline that within our investigation of the chemical reaction wave propagation in SHS systems we discovered new (unknown before) types of combustion processes (filtration combustion, unsteady propagation of flames with condensed reaction products, etc.) that are of interest for SHS research field and adjacent disciplines.

One of the most important peculiarities of SHS processes is formation of valuable materials in combustion waves. The science of combustion was developed under the influence of energetic problems and interested in burning of different fuels (gaseous, liquid and solid) used in heat-and-power engines and devices. Also the combustion processes were studied and developed for solving the tasks of ecology and fire and explosion safety.

There were only few technological applications before SHS (see review [12]). The closest processes to SHS are out-of-furnace metallothermy (thermite combustion). They have been known for a long time but they were not studied from the viewpoint of combustion science (only within SHS investigations this problem got its second wind).

Below the formation and peculiarities of SHS solid-phase products will be considered.

Two product formation mechanisms are possible in SHS processes:

a) Equilibrium mechanism by Khaikin-Aldushin-Merzhanov [5, 6, 8-10]. This mechanism is realized when the component interaction leading to the final product formation occurs under the mode of reaction diffusion in the zone of the main heat release close to the combustion front.

It is called equilibrium because in most of the cases the reagent interaction is described by the parabolic law for which the kinetic auto-braking is insignificant and the front velocity, just as in the classical combustion theory, is connected with the equilibrium state of the substance (i.e. the processes in that section of the wave where the combustion reaction is being completed).

In the case of significant auto-braking, e.g. at exponential laws of the component interaction, the zone of afterburning appears and these processes mustn’t be considered equilibrium ones.

b) Non-equilibrium mechanism by Borovinskaya [13-15]. This mechanism takes place when the reaction of the final product formation does not affect the front velocity; the combustion reaction* does not form the final product, it forms a substance in the non-equilibrium intermediate state which dissociates and forms the final product.

Figure 8 shows the scheme of both mechanisms of product formation. The equilibrium mechanism is often met in slow, completely solid-phase SHS processes, and non-equilibrium – in fast reactions (the experiments which led us to the concept of the non-equilibrium mechanism will be described later).

When we speak about a combustion product formation, we mean all the components of the material composition and structures, i.e. chemical, phase and impurity compositions, crystal, microscopic and macroscopic structure.

If the product composition and structure are completely formed during the process, the mechanism is equilibrium; if the formation is not completed we deal with the non-equilibrium mechanism. Different structure and composition components achieve the equilibrium state at different velocities; it often occurs that after the process some components are already at the equilibrium state

*When the matter concerns a chemical mechanism of the combustion reaction, that stage of chemical transformation is named which defines the front velocity.

Figure 8. Scheme of equilibrium and non-equilibrium mechanism.

![Figure 8](image.png)

Figure 9. Width of the main diffraction peak on the half-height as a function of cooling time.

![Figure 9](image.png)
and the others are not. As to SHS processes with their multizone combustion wave, the formation of any product characteristics can be completed in any zone behind the front. (Unfortunately, there is no information about it in literature). Realizing the necessity of research in this direction, one of the authors expressed a simple idea of a dependence of the peak width in the diffraction pattern on the product cooling time and organized some experiments with the colleagues [16]. In Figure 9 you can see such dependence for the combustion product of non-stoichiometric mixture Ti±0.5C. The width of $\Delta \theta$ peak was measured at its half-height, the cooling time $t_c$ was determined by the combustion thermogram, the dependence $\Delta \theta$ (t_c) was a drooping curve with saturation. Since the peak width is an indirect characteristic of the crystal lattice order, it is obvious that the points on the drooping branch corresponds to the formation of its non-equilibrium state and on the saturation section – to that of the equilibrium state. This result leads us to the important conclusion that during the combustion cooling its auto-annealing occurs (it is usually carried out at a constant temperature but not at its decreasing value as in SHS processes). It is possible to obtain either equilibrium or non-equilibrium combustion products by regulating the cooling time [17].

We’d like to underline that the SHS method is considered to be an efficient synthetic approach for obtaining both equilibrium and weakly studied non-equilibrium materials. The formation of chemical composition is determined by the chemical reaction velocity in the wave. Paper [18] was the first to give the information about the chemical mechanism of the SHS process. The work studied the combustion of a tantalum sample in nitrogen. At different stages of combustion the sample was thrown into the vessel with liquid argon. The data of chemical and X-ray analyses allowed establishing the following reaction scheme:

$$\text{TaN}_{\text{brutto}} \rightarrow \text{TaN}_{\text{exp}} \text{(at pressure of N}_2 \leq 4 \text{ MPa)} \rightarrow \text{TaN}_{\text{stab}} \text{(at pressure of N}_2 > 4 \text{ MPa)}$$

More thorough examination of the experimental results proved that the intermediate product Ta$_2$N was formed in the reaction zone and defined the front velocity while the further nitriding occurred in the afterburning zone and defined the final product phase composition.

This direction was being developed slowly. But when dynamic XRD analysis with synchrotron radiation or dynamic diffractometry was applied for these purposes, the investigation of the chemical mechanism of SHS processes got its further development (see below).

In connection with chemical and phase composition formation in the combustion wave, it is necessary to mention the impurity composition. Impurities as well as slight amounts of special doping elements introduced into the material can play a significant role in development of some properties. The formation of impurity composition of the combustion product greatly depends on the effect of self-purification from impurities [19]. This problem was studied in details in [20-21]. The SHS process appeared to be rather convenient for obtaining purer substances and materials in comparison with other methods. It is possible to obtain either equilibrium or non-equilibrium combustion products regard them as new substances and materials and allow discovering new interesting structures in combustion products (see below).

It is necessary to know material properties for its practical application. They depend on various values characterizing the combustion product composition and structure. However, it is difficult to obtain all the required information about any material, and there is no theory which could allow predicting the product properties surely. Perhaps, specialists in materials science do not go beyond the investigation of some problems connecting the properties of a specific product with some of its characteristics.

The authors of this lecture think that the absence of such “global” link as “composition and structure $\rightarrow$ properties” leads to the customary perception of dependence of solid product properties on their production method. Indeed, if we compare the materials of the same chemical composition but of different production methods, we can observe a wide spread of properties even in the case of compounds, let alone multicomponent materials.

The above consideration is given to explain why the consumers of SHS products regard them as new substances and materials and require attestation of their properties revealed for the analogues products before. The fact that the SHS method greatly differs from other ones in the conditions of the product formation intensifies the necessity of these investigations.

Below you will find some interesting results of the work (as examples of specific directions in this field).

3. Original Directions of Investigation

3.1. Kinetic electrothermography

Investigation of SHS reaction kinetics, i.e. chemical reactions in the combustion wave of SHS systems is a very complicated task because of:

• high temperatures developed in SHS processes and, correspondingly, high reaction velocities;
• a significant temperature gradient in the wave.

The first circumstance results in difficulties in measurement, the second one in necessity of studying the reaction mechanism at first and then defining kinetics of different stages. It is very important because in different plots of the wave due to a wide range of temperature, different stages can define the reaction kinetics; it can result in mishmash at interpretation of experimental data.

The well-known methods of evaluation of efficient constants of brutto-reaction by the equations of the combustion theory as well as experimental data processing are widely used know. They are also used in studying SHS processes, and though the obtained information is useful, it is not exact because of inexact conformity of experimental and theoretical models.

But it isn’t so bad. For the reactions of metal interaction with gas, an excellent electrothermograph method has been developed; it allows studying kinetics under high temperatures (up to 3000 K) at isothermal conditions (!). A special electrothermograph was made [22-24]. The scheme of its operation can be seen in Figure 10. It lies in blowing the gaseous reagent on the metal thread which is the other reagent. The power of electric heat evolution is measured during the experiments. The “heart” of the device...
and its original part is the follow-up system developed by L.N. Galperin and L.B. Mashkinov. It keeps the temperature of the thread constant. In order to achieve it the system automatically changes the electric power evolved on the thread. And the decrease in the electric power is equal to the rate of the heat evolution due to the chemical reaction.

Hence, the electrothermograph issues the same information as kinetic calorimeters but at high temperatures. There is one more peculiarity. When the current is off, the thread gets cold sooner, and the thread high-temperature state is quenched at the moment of switching off. After making cross-sections of the thread, the researcher gets the opportunity to realize metallographic studies of switching off. After making cross-sections of the thread, the thread high-temperature state is quenched at the moment

![](image)

**Figure 10. Electrographic method: experimental setup.**

with precipitation of the solid element (C, Si) on the thread. Within the second stage the reagents are transferred deep into the thread by the laws of reaction diffusion. Analysis of both stages allows describing the kinetics of the reaction diffusion in the systems Me-C and Me-Si [25-26].

### 3.2. Dynamic XRD analysis

Formation of combustion product phase composition appeared to be a subject of investigation after synchrotron radiation was used for taking X-ray patterns in different points of the stationary combustion wave. In this case an X-ray is directed to an arbitrary point on the sample lateral surface, against which the combustion runs, and the continuous shooting of X-ray patterns is made. It allows determining the time variations of the substance phase composition including those of the green mixture and transition to the cold combustion product. Then the phase composition profiles are plotted by using space-time relations of stationary combustion. It is possible to understand the phase formation mechanism by analyzing them.

One of the important parameters in this investigation is the time of X-ray patterns collection \( t_s \). It allows determining the distance of the combustion wave shift during the time of one X-ray pattern. The lower the \( t_s \), the more exact information can be obtained by this method. It is obvious that for correct measurements it is necessary to satisfy the inequality \( t_s < \Delta t \) (where \( \Delta t \) is the time of the process under study).

It should be mentioned that \( t_s \) is a device (method) characteristic while \( \Delta t \) depends on the front propagation velocity. The higher the velocity, the lower the \( \Delta t \). Therefore, it is easier to study slow processes than fast ones. Also we’d like to underline that the penetration depth of X-ray radiation into the sample is not significant and it allows taking the information from a thin near-surface layer. The temperature of which depends on the terms of heat exchange on the sample surface. Nobody has analyzed this situation from the makrokinetic point of view, and it is impossible to judge if this information is true though there is no doubt that the approach supplies rather valuable data. The first who used synchrotron radiation for dynamic XRD analysis of a combustion way was V.V. Boldyrev with co-authors in 1981 [27]. They studied phase formation at combustion of nickel and aluminum powders. The source of X-ray radiation was a synchrotron in Novosibirsk (Russia). That work demonstrated the possibilities of the method and attracted new researchers (American researchers Vong and Larsen Holt [28-29] who carried out analogous experiments using a synchrotron in Stanford (USA). Recently, French researchers have become very active [30]. Also Russian scientists continue their work in this field (A.S. Rogachev, A.E. Grigoryan, B.P. Tolochko, M.R. Sharafutdinov) [31]. However, the work is very expensive; it does not allow realizing perfect investigations.

The activity in this direction became brighter when V.I. Ponomarev with the authors of this article as well as other scientists combined a standard diffractometer with a fast-acting detector made in the Institute of Nuclear Inve-stigations (Dubna). It appeared to be very attractive for many scientists [32-33]. The idea of measurement using a dynamic diffractometer is the same as in synchrotron-assisted analysis. Let’s consider one of recent results [34]. In Figure 12 you can see 3D images of the sequence of dynamic diffraction patterns at combustion of Zr in air. The formation and disappearance of the intermediate product can be seen with a naked eye, so we can suppose the reaction mechanism as initial information for thorough investigations.

The installation of dynamic XRD analysis has become a convenient...
device for fast determination of intermediate products in SHS processes. Table 3 taken from [35] presents the information about the intermediate products discovered in preliminary SHS experiments carried out using the method of TRXRD.

In work [36] a successful attempt was made to connect dynamic curves with the mechanism of combustion product formation. It suggests introducing dimensionless distance from the combustion front as a spatial value on the abscissa axis. According to the general concepts of the combustion theory, when the afterburning subzone is absent (i.e., for the cases when kinetic braking is not high) there is a narrow reaction zone in the combustion wave of \( \Delta \xi \sim 1 \) in width. If the dynamic curve of phase formation is within this interval, it means that we deal with the equilibrium mechanism of the product formation. For the non-equilibrium mechanism the phase formation curves are far from the beginning, \( \Delta \xi >> 1 \) (Figure 13).

In conclusion of this part of our lecture we’d like to underline that both ways of the same method – synchrotron radiation and radiation of X-ray tube – supplement each other. The method of synchrotron radiation has \( t_d \sim 0.001 \) s, and dynamic diffractometry operates with \( t_d \sim 0.1 \) s. It means that for studying fast SHS processes a synchrotron should be used, and for slow ones it is more profitable to have a device of dynamic XRD.

### 3.3. Origin of the concept of non-equilibrium mechanism of combustion product formation

At the beginning of the work in the theory of SHS processes, the concept of reaction diffusion as the only mechanism of final product formation was prevailing. The reason can be easily realized. SHS as a synthesis method was unambiguously connected with the idea of solid flame and the scientific discovery which was officially called “The phenomenon of wave localization of solid-phase auto-braking reactions”.

The approach developed in [13-15] allowed creating simple models of the flame propagation. They were described by the classical equations of the combustion theory in which the kinetic functions were expressed by the laws of metal oxidation – parabolic and exponential.

In spite of its simplicity, the approach played an important role in the combustion theory.

Computerization of the equations describing the combustion models of SHS systems led to a new result formulated as a conception of weak and strong braking of heat evolution, narrow and wide reaction zones, combustion and afterburning subzones. Later this conception was used in various works of the combustion theory and took its special significance.

However, in 1975 the concept acquired a powerful competitor. When studying combustion of titanium and zirconium in nitrogen of various pressures, I.P. Borovinskaya [37] and her student under wardship V.E. Loryan paid attention to an unusual result of the product analysis. It proved that non-stoichiometric nitrides

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Final product</th>
<th>Registered intermediate phases</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>( \alpha )-Ti + O(_2) + Ar (50% vol.)</td>
<td>TiO(_2) (rutile)</td>
<td>( \beta ) Ti; solid solution of oxygen in ( \alpha ) Ti</td>
<td>Khomenko, Mukasyan, Ponomarev, Borovinskaya, Merzhanov</td>
</tr>
<tr>
<td>1992</td>
<td>( \alpha )-Ti + N(_2)</td>
<td>TiN</td>
<td>( \beta ) Ti; solid solution of nitrogen in ( \alpha ) Ti</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>( \alpha )-Ti + ( \alpha )</td>
<td>TiO(_2) - TiN, rutile low temperature modification, ( x = 0.02 )</td>
<td>( \beta ) Ti; TiN(<em>x); solid solution of O (N) in Ti; Ti(</em>{75})O(<em>{25}); Ti(</em>{30})O(_{5}); TiO(_2) (high temperature modification)</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Ta + ( x )C; ( 0.4 \leq x \leq 1.2 ) Ta + 1.2 C</td>
<td>Ta(_x)C, TaC</td>
<td>-</td>
<td>Borovinskaya, Merzhanov, Ponomarev, Mukasyan, Shkiro</td>
</tr>
<tr>
<td>1993</td>
<td>0.57Ti + 0.43Cr + 0.86C</td>
<td>Complex carbide</td>
<td>Titanium carbide; liquid (melt) Cr</td>
<td>Khomenko, Shkiro</td>
</tr>
<tr>
<td>1993</td>
<td>( \alpha )-Ti + 0.37 C</td>
<td>TiC(_x) + ( \alpha )Ti</td>
<td>( \beta ) Ti; TiC; liquid (melt) ( \beta )Ti</td>
<td>Borovinskaya, Merzhanov, Ponomarev, Khomenko, Shkiro, Mukasyan, Rogachev</td>
</tr>
<tr>
<td>1994</td>
<td>Ni + Al</td>
<td>NiAl</td>
<td>-</td>
<td>Rogachev, Khomenko, Varma, Merzhanov, Ponomarev</td>
</tr>
<tr>
<td>1994</td>
<td>2Ni + 3Al</td>
<td>Ni(_3)Al(_3)</td>
<td>NiAl</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Nb + B</td>
<td>NbB</td>
<td>NbB(_2); Nb(_3)B(_4)</td>
<td>Borovinskaya, Merzhanov, Ponomarev, Khomenko, Shkiro, Mukasyan, Rogachev</td>
</tr>
<tr>
<td>1994</td>
<td>5Ti + 3Si</td>
<td>Ti(_5)Si(_3)</td>
<td>Ti(_5)Si(_4)</td>
<td>Borovinskaya, Merzhanov, Ponomarev, Khomenko, Shkiro, Mukasyan, Rogachev, Shugaev, Kachelmeger</td>
</tr>
</tbody>
</table>

Figure 12. Diffraction still frames for Zr combustion in air.
of MeN\(_x\) composition (where x < 0.75) were formed under the experimental conditions. The researchers hardened the combustion product by throwing the samples into liquid argon in order to understand the mechanism of the product formation. They were very surprised not to observe any nitride phases in the product. According to the analysis, the combustion products were solid solutions – unsaturated, saturated and oversaturated subject to the experimental conditions. After annealing the solid solutions in nitrogen, the researchers obtained nitrides of almost the same composition as those obtained without annealing. The most interesting was the formation of oversaturated solid solutions. While analyzing the results, I.P. Borovinskaya made a conclusion that during the combustion nonequilibrium products were formed, then under high pressures they turned into equilibrium ones by afterburning (unsaturated solid solutions) or by reorganization of their crystal lattice (oversaturated solid solutions). Later on I.P. Borovinskaya [15] came out with a suggestion that the reaction products could be not only solid solutions but other types of nonequilibrium state of the substance. In this way the nonequilibrium conception of final product formation appeared. The lecture of I.P. Borovinskaya at the IV All-Union Symposium on Combustion and Explosion, 1977, Leningrad, aroused great interest. The nonequilibrium conception of combustion product formation in SHS processes was called later the conception (or mechanism) of Borovinskaya; it led to the foundation of the nonequilibrium theory of the flame propagation (Merzhanov, [4]) and was developed in the works of A.S. Rogachev and A.S. Mukasyan [38-40] (the conception of stage processes with equilibrium and nonequilibrium stages, of preliminary and secondary structure formation, etc.).

3.4. Neutron diffraction analysis of SHS compounds

Since SHS compounds differ greatly from their in-furnace analogs, the investigation of SHS products is of great interest. These investigations were not systematic. They were carried out by specialists in crystal chemistry and substance structure if the results appeared to be attractive for them.

At the beginning of the 70-s specialists in neutron diffraction analysis became interested in the structure of tantalum nitride obtained by SHS [18]. Being specialists in synthesis, the authors measured nitrogen content in the product and discovered that it was superstoichiometric with a large excess of nitrogen (they demonstrated the excess by the formula TaN\(_{1.2}\)) and a cubic lattice (of the type NaCl). The specialists in neutron diffraction analysis from the Institute of Nuclear Physics of the Uzbek Academy of Sciences – Irkin Karimov and his colleagues – paid attention to the stability of the crystal lattice in the case of a large nitrogen excess and became interested in the compound superstructure. They wanted to ascertain its arrangement – either the excess nitrogen atoms were located in the interpoints of tantalum sublattice or this sublattice was defective and had a lot of vacancies. Neutron diffraction analysis supported by measurements of pycnometric density proved that it was not matter of the excess of nitrogen atoms, the point was a lack of tantalum ones [41]. From the structural viewpoint, the formula of the synthesized compound must not be written as TaN\(_{1.2}\), it should be presented as Ta\(_{0.823}\)N. It is interesting that the ratio of tantalum and nitrogen atoms in this compound (5:6) corresponds to the stoichiometric compound Ta\(_{5}\)N\(_6\). However, this formula must not be used either because this compound has a cubic but not hexagonal lattice (evidently, we deal with a random coincidence) [41].

Cooperation of the specialists in SHS and their colleagues in neutron diffraction analysis allowed them to characterize the degree of disarray of the nonmetal lattice in nonstoichiometric carbides, nitrides, hydrides, and after the process of annealing they could find and study the regularities of lattice ordering and conditions of superstructure formation [42].

3.5. Non-uniqueness of structures in binary materials

Structure formation in combustion products is a very important and interesting but insufficiently studied direction of SHS investigation. Let’s consider two examples to realize the outlook of this direction.

The first example

It was necessary to obtain a ceramic material with low thermal conductivity and electrical resistivity for solving a practical task. Two-phase ceramics BN+TiB\(_2\) was chosen for this purpose; the synthesis was carried out by the equation:

\[ B + TiB_2 \rightarrow TiB_2 + BN \]

However, it was impossible to solve the problem because of its low electrical resistivity the synthesized TiB\(_2\) did not conduct current. The researchers carried out another synthesis reaction, which preserved the material composition,

\[ Ti + 2B + BN \rightarrow BN + TiB_2 \]

and got an excellent result: the material electric conductivity was very high (~17 order of magnitude higher that that in the first case). The paradox was solved when the researchers studied the structures of both materials. Figure 14 demonstrates the obtained results. The structures of both materials of the same composition appeared to differ drastically. On the left you can see the structure which can be called quasi-homogeneous. It consists of BN matrix with uniformly distributed TiB\(_2\) particles. The electrical resistivity of the material with such a structure is high and close to that of BN.
On the right there is a structure which can be called framed. It proves the fact that TiB₂ particles form a group and also contacts with each other providing a through path for electrons. The electrical resistivity of the material with such a structure is low and close to that of TiB₂ [43-44]. Within the transition from one structure to the other the electrical resistance changes by 10¹⁷ times. The synchronous existence of two structures at the same composition I.P. Borovinskaya called “The phenomenon of non-unique structures in binary materials” and application of a property was called “Structural regulation of material properties”.

In further investigations in this field some new results were obtained [45] (Figure 15).

The second example
Not long ago when chemical-condensation combustion processes in SHS systems were being studied, a possibility of synthesis of a large amount of various non-equilibrium structures (including nano-sized ones) of one and the same compound was shown [46]. Figure 16 demonstrates the variety of silicon nitride structures which were formed at silicon combustion in nitrogen. The properties of such structures are being studied, and probably, it will be possible to synthesize new ceramic materials with high operation characteristics.

4. On SHS Backgrounds

Investigation of SHS processes and products have a fundamental character with basic results which compose SHS scientific backgrounds. It would be wrong to think that the SHS scientific backgrounds are a simple sum of the above-mentioned tasks and results. There are direct and inverse relations between all the parts. For instance, the interest which arose to nano-materials has led to foundation of a new class of chemical-condensation SHS processes [47]. Their combustion mechanism is more complicated in comparison with the conventional processes of SFC and consists of the following stages:

- Reagent interaction with regulating additives leading to formation of active gaseous intermediate products;
- Passing of main combustion reactions in the gas phase (gas-phase SHS) with final product formation,
- Condensation of final products with formation of low-sintered cakes consisting of nano-sized particles.

It required organizing a wide search of systems (reagents and additives) which could react by chemical and condensation mechanism, carrying out experimental diagnostics and studying combustion and structure formation regularities, investigating possible application of the existing analysis methods, and “turning back” – formulating additional requirements to the system selection and process organization including application of nano-sized reagents.

The interaction of all these parts resulted in the formation of a new direction of our investigations which was called “Structural Macrokinetics” (SMK) [47]. It unites macrokinetic investigations of the processes with structural study of the materials. According to N.N. Semenov and D.A. Frank-Kamenetsky macroscopic kinetics (macrokinetics) deals with direct and inverse relations between chemical reactions and heat- and mass-exchange, thus SMK also concerns phase and structural transformations. As appears from the above, SMK is a science about all material-forming processes. But now the word SMK is used only in the theory of SHS processes, and even on the level of the process ideology and methodology. The theory of structural macrokinetics of the processes of self-propagating high-temperature synthesis
should be created.

SMK rests on two approaches: static and dynamic [47]. Within the static approach (it is called structural statics) the process is not considered. The relationship is established between the final product composition and structure, from one hand, and between the initial mixture composition and structure and the process terms from the other. On the earliest stage of SHS when developing the methodology of syntheses and establishing the relationship between product characteristics and experimental terms for choosing proper conditions of syntheses, I.P. Borovinskaya did not know that she was dealing with structural statics. But structural statics studies not only so called dead relations between characteristics and parameters. It also describes some new interesting phenomena.

For instance, an Armenian scientist Petros Avakyan and his colleagues with participation of the authors of the article studied the combustion of the green mixtures forming ferrites [48-49]. They paid attention that the product was characterized by magnetization and was a permanent magnet (Figure 17). The structure investigation proved that the product consisted of elongated domains oriented along the combustion wave propagation. The scientists supposed that such a spontaneous orientation was connected with the axial temperature gradient appearing in the product at its cooling. But it’s interesting to mention that the sample magnetization does not depend only on its orientation in the magnetic field of the Earth, and the South Pole always appeared in the place of igniting. The dynamic approach (it was called structural dynamics) deals with the problems connected with the formation of composition and structure characteristics within the transformations in different zones of the combustion wave and at various process stages till the complete cooling of the product. It is a complicated problem. Its successful solution depends on the methods of continuous study of structure components like dynamic radiography used for analyzing phase composition. The following formula is rather popular in SMK: SHS = Combustion + Structure Formation. It reminds that SHS is not only a combustion process, not only destruction of a reagent initial structure but also creation of a new structure in the combustion product. The modern view on the SHS process can be represented as the diagram shown in Figure 18.

5. Chemical Synthesis Materials

Chemical synthesis of substances and materials is the major objective of SHS. The work in this direction has played an important role in the development of SHS as a significant area of R&D. It has been shown that SHS is a science-intensive process and requires deep knowledge of the specialists. It is rather complicated from the viewpoint of development but at the same time it is comparatively simple for realization. In some cases it is difficult for SHS specialists to make a choice since there are a lot of SHS process varieties and possibilities of achieving one and the same result.

5.1. SHS of chemical compounds

First of all two periods should be mentioned. Within the first one the possibility of SHS application for synthesizing various types of compounds was studied. Below you can see the chronology of the work [50].

1967 - SHS in metal-nonmetal powder mixtures with obtaining borides, carbides, silicides of transition metals of groups IV and V of the Periodic System: $\text{Me}_x\text{B}_{2x}$, $\text{Me}_x\text{C}_x$, $\text{Me}_x\text{Si}_x$ (where $\text{Me} = \text{Ti, Zr, Hf, Ne, Ta}$); also SHS in the systems of metal-nitrogen, nonmetal-nitrogen with obtaining metal nitrides $\text{TiN, ZrN, AlN, NbN, TaN, TaN and nonmetal nitrides BN, AlN, Si}_3\text{N}_4$.

1972 - SHS in metal powder mixtures with obtaining intermetallics: $\text{NiAl, TiAl, Ti-Ni}$, etc.

1975 - SHS in metal-hydrogen systems with obtaining hydrides $\text{MeH}_x$ (where $\text{Me}$ is a metal of groups IV and V of the Periodic System or a rare-earth metal).

1976 - Combustion in multi-component systems with obtaining complex compounds (solid solutions of binary compounds of the type “two metals-one nonmetal” (e.g. $\text{Ti}_x\text{Zr}_{1-x}\text{C}$) or “one metal-two nonmetals” (e.g. carbonitrides $\text{TiC}_x\text{N}_y$)).

1977 - Combustion of metal powders with sulfur, selenium, phosphorus with obtaining chalcogenides ($\text{MoS}_2$, $\text{NbSe}_2$, etc.) and phosphides ($\text{AlP}$, etc).

1979 - SHS in powder mixtures of oxides and peroxides with obtaining complex oxides ($\text{PbBaO}_3$).

1980 - SHS with aluminum reduction in high-caloric mixtures with formation of high-temperature melts with phase separation and crystallization at cooling and obtaining cast compounds ($\text{Cr}_3\text{C}_2$, $\text{MoB}$, $\text{W}_2\text{C}$, etc).)

1981 - SHS with magnesium reduction in the mixtures with producing cakes of inorganic compounds and magnesium oxide with the following removal of the latter.

1983 - SHS of nitrides in the systems “a chemical element – azide”,
The works carried out in 1967-1970 resulted in the conclusion that it is possible to solve any synthetic problems by the method of SHS (i.e. to find a reaction which can evolve heat and lead to the formation of the required product). But the application of this method can be restricted by a deficit or high prices of the reagents or difficulties in organization of original conditions of its occurrence.

However, in the 90-s the interest to possible application of the SHS method for synthesizing different compounds disappeared and the work was continued only in synthesizing the compounds of practical interest. For these years a great number of various high quality compounds have been synthesized. Previously, the major interest was given to the comparison of the characteristics of the compounds obtained by the SHS and furnace methods, now the characteristics of SHS compounds are compared with the ones required for specific applications. But the main thing in realization of SHS processes is providing the necessary chemical and phase composition (in most cases it regards chemical and phase purity of the compound).

Let’s consider two examples.

### 5.1.1. Synthesis of refractory compounds [2, 51-53]

This group of compounds is at the head of the above list. It was the synthesis of a refractory compound which resulted in the discovery of the phenomenon of “autowave localization...”. The first syntheses were restricted by the formula of discovery; they were necessary chemical and phase composition (in most cases it regards chemical and phase purity of the compound).

The minimum eutectic temperature is 3116 K.

The adiabatic temperature of combustion is 2734 K.

Here is the classical example:

\[ \text{Ta(s)} + \text{C(s)} \rightarrow \text{TaC(s)} + \text{Q} \]

The adiabatic temperature of combustion is 2734 K.

The minimum eutectic temperature is 3116 K.

Table 4. The first refractory compounds produced by SHS.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Metal content, mass.%</th>
<th>Non-metal content, mass.%</th>
<th>Crystal structure</th>
<th>Micro-hardness, kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC</td>
<td>80</td>
<td>&lt;10–3</td>
<td>19.8</td>
<td>9×10–2</td>
</tr>
<tr>
<td>ZrC</td>
<td>88.2</td>
<td>&lt;10–3</td>
<td>11.4</td>
<td>3×10–2</td>
</tr>
<tr>
<td>NbN</td>
<td>86.9</td>
<td>&lt;10–3</td>
<td>13.0</td>
<td>-- 10–2</td>
</tr>
<tr>
<td>TiN</td>
<td>77.6</td>
<td>&lt;10–3</td>
<td>21.4</td>
<td>-- 10–2</td>
</tr>
<tr>
<td>TaN</td>
<td>91.8</td>
<td>--</td>
<td>7.5</td>
<td>-- 10–2</td>
</tr>
<tr>
<td>BN</td>
<td>43.8</td>
<td>0.2</td>
<td>55.7</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>TiB₂</td>
<td>68.6</td>
<td>--</td>
<td>31.0</td>
<td>10–1</td>
</tr>
<tr>
<td>HfB₂</td>
<td>89.0</td>
<td>--</td>
<td>10.7</td>
<td>&lt;10–2</td>
</tr>
</tbody>
</table>

### 5.1.2. SHS of high-temperature superconductor - yttrium-barium cuprate YBa₂Cu₃Oₓ [54-56]

Obtaining of this compound is one of the most complicated tasks in combustion synthesis due to many reasons (complexity of the compound containing four elements, absence of combustion reaction concepts leading to the formation of this compound, technical and chemical instability resulting in oxygen loss, and, finally, superconducting properties of the product).

This complicated problem was solved by M.D. Nersesyan and his colleagues with participation of the authors [54]. The first result was connected with a successful combustion reaction:

\[ 3\text{Cu} + 2\text{BaO}_2 + 1/2\text{Y}_2\text{O}_3 \rightarrow 3\text{CuO} + 2\text{BaO} + 1/2\text{Y}_2\text{O}_3 \] (Y123)

In this case Cu is considered to be a fuel, BaO₂ - a condensed oxidizer, O₂ - a gaseous oxidizer, and Y₂O₃ - an active filler (Y₁₂₃ is the abbreviated name of this cuprate).

![Figure 19. SHS of yttrium-barium cuprate.](image)

The mechanism of this reaction is rather complicated and includes several stages. In order to obtain the required result, the researchers had to find out the main stages of the process using the methods of hardening and dynamic XRD. The sequence of these stages is presented in Figure 19.

\[ 3\text{Cu} + 2\text{BaO}_2 + 1/2\text{Y}_2\text{O}_3 \rightarrow 3\text{CuO} + 2\text{BaO} + 1/2\text{Y}_2\text{O}_3 \]

\[ 2\text{BaCuO}_3 + \text{CuO} + 1/2\text{Y}_2\text{O}_3 \]

\[ \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x} \]

\[ \text{Formation of precursor powder} \]

The researchers paid attention to the role of the last phase: it was the phase transition of the tetragonal phase to orthorhombic one which imparted superconducting characteristics to the product. So, the experimentators paid particular attention to the conversion degree of the substance at this stage, and the SHS process resulted in obtaining of an excellent superconducting powder of Y₁₂₃. The Table 5 demonstrates some characteristics of the SHS products in comparison with the best grades of Y₁₂₃ produced in the USA. It should be underlined that all the data in the table were obtained under the similar conditions (using the same installations, the same period of time by the same workers). The comparison proves that the SHS products (SHS-12) are the best. Having obtained these results, the Institute of Structural Macrokinetics, RAS, where Y₁₂₃ had been synthesized, supplied this powder to the American company SuperConco where it was used to make superdense items. The production of Y₁₂₃ by the SHS method impressed the chemists greatly and they believed in outstanding opportunities of SHS.

### 5.2. SHS of powders

When the SHS method was used for obtaining powders, some additional demands (in comparison with the synthesis of...
Table 5. Comparison of some characteristics of the best powders $\text{YBa}_2\text{Cu}_3\text{O}_x$ produced by SHS and in furnaces (1990).

<table>
<thead>
<tr>
<th>Grade</th>
<th>SSC 03-0065 (USA) furnace</th>
<th>SHS-J2 (USSR) SHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen content, (7-x)</td>
<td>6.89</td>
<td>6.92</td>
</tr>
<tr>
<td>Critical transition temperature to superconducting state, K</td>
<td>92.0</td>
<td>93.5</td>
</tr>
<tr>
<td>Ortho-phase content, mass. %</td>
<td>~99</td>
<td>~99</td>
</tr>
<tr>
<td>Average particle size, mm</td>
<td>6.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Impurity content</td>
<td>absent</td>
<td>absent</td>
</tr>
</tbody>
</table>

5.2.2. SHS powders of complex titanium-chromium carbide for wear and corrosion protection [36,56]

It is profitable to produce powders for plasma and detonation spraying by the SHS method because at grinding of cakes and ingots it is easy to provide the output of the required rather large fractions. Many SHS powders were tested as raw materials for applying coatings (TiC, TiN, TiC-TiN, TiB$_2$, W$_6$C-WC, Cr$_3$C$_2$, Al$_2$O$_3$-Cr$_7$O$_{12}$, etc.).

We'd like to consider only one example of the most efficient application of SHS powders for this purpose. The matter concerns the production of titanium-chromium carbide powders and application of plasma wear-and heat-resistant coatings using these powders. The complicated carbide was obtained by the scheme:

$$x\text{Ti} + (1-x)\text{Cr} + y\text{C} \rightarrow \text{Ti}_x\text{Cr}_{1-x}\text{C}_y$$

When $x\approx0.7$, $y\approx0.9$, the SHS product is single-phased, has a lattice similar to that of NaCl with $\alpha\approx 4260$ Å, and is characterized by a stable chemical composition (mass%):

$$\text{Cr} \approx 25-27$$

$$C_{\text{total}} \approx 17.0 \text{ min}$$

$$C_{\text{free}} \approx 0.5 \text{ max}$$

and high microhardness ($H\approx 4000 \pm 200$ kg/mm$^2$). The main fraction (40 - 80 µm) output at the product milling is 65% minimum. The analogous product was known before. It was synthesized by annealing of TiC and Cr$_3$C$_2$ powder mixtures. But the difficulties of the furnace synthesis of complex compounds with maintaining their mono-phased character did not allow this product to get its own start in life. Titanium-chromium carbide is a valuable material for the technology of plasma coatings and can be successfully used instead of Cr$_3$C$_2$ powder which is characterized by a lower microhardness (~2.2 times) but higher heat resistance (~3 times). Two types of SHS powders with a nickel binder were used: cladded (the particle is coated by Ni film) and composite ones. The latter were obtained by introducing Ni into the initial mixture of Ti, Cr and C; it excluded the necessity of a special cladding operation. All the SHS powders contained ~30% mass Ni. The Table 6 shows some specifications of plasma coatings.

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![Figure 20. General diagram of synthesis routes in SHS-technology.](image)

![Figure 21. Abrasives.](image)
The nearest tasks of the SHS specialists are to gain nano-sized powders are given in articles 62-64. Some results of SHS application for obtaining powders of various classes and application fields will be further developed. Doubt that the problem of producing nano-sized powder by the SHS method will be solved. Synthesis of other compounds is under study. No oxide nano-sized powders have been obtained by various methods. By the time, a lot of oxide nano-sized powders have been synthesized. This method allows obtaining various materials: sintered, compact and cast ones. The methodology of their synthesis was developed. It is based on the study of relations between the final product structure and the initial reagent selection, the green mixture composition and structure and the combustion terms. Such directions as syntheses of hard alloys, multifunctional and ceramic materials and various composites have been predominately developed. Within the activity in direct synthesis of SHS materials the researchers got a lot of interesting and significant results.

5.3. Compact SHS materials and items

Compact materials can be obtained:

- By processing a combustion product (thermal treatment);
- By using SHS powders (sintering, hot pressing);
- Directly from reagents during SHS (direct production).

In contrast to the powder synthesis the best way to produce materials is the direct synthesis. This method allows obtaining various materials: sintered, compact and cast ones. The methodology of their synthesis was developed. It is based on the study of relations between the final product structure and the initial reagent selection, the green mixture composition and structure and the combustion terms.

5.3.1. Tungsten-free hard alloys and STIM [65-68]

These SHS materials have been known for a long time. After achieving a success in the field of abrasive materials, the authors tried to organize the same work in creation of hard alloys. But they could not find a specialist who wanted to explore the possibility of hard alloy production from SHS powders. But it did not depress their wish and soon the authors with V.I. Ratnikov realized a new approach in creating hard alloys which was called SHS compaction. It is densification of a hot combustion product up to the non-porous state. The method allows obtaining hard alloys by SHS without using solid powders. As a result, new types of tungsten-free hard alloys were produced (Table 7). They were called synthetic hard tool materials (Russian acronym: STIM). It is obvious that STIM alloys have various properties. Among them are materials with high values of strength, hardness, wear resistance, stability to thermal loading, etc. The authors of the paper and the well-known specialists in SHS A.N. Pityulin, E.A. Levashov, A.S. Shteinberg worked at the problem. The most interesting are cutting STIM alloys. Non-reground plates made of STIM-5 alloy are characterized by excellent cutting properties for a wide range of materials to be machined and machining regimes. The development of cutting materials satisfying high requirements proves great possibilities of the SHS method. In Figure 23 you can see the photos of some hard-alloyed items.

Table 6. Characteristics of gas-thermal coatings.

<table>
<thead>
<tr>
<th>Coating-forming powder</th>
<th>Porosity, %</th>
<th>Adhesion strength, kg/mm²</th>
<th>Wear resistance, rel. un</th>
<th>Heat-resistance at 1200 °C, rel.un</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr₂C₂ (industrial product)</td>
<td>9</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cr₂C₂ + Ni</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>TiC-Cr₂C₂</td>
<td>8</td>
<td>3.6</td>
<td>7</td>
<td>0.35</td>
</tr>
<tr>
<td>TiC-Cr₂C₂ + Ni (cladded)</td>
<td>2-7</td>
<td>2-5</td>
<td>~50</td>
<td>0.32</td>
</tr>
<tr>
<td>TiC-Cr₂C₂ + Ni (composite)</td>
<td>-</td>
<td>3.1</td>
<td>75-85</td>
<td>0.48</td>
</tr>
</tbody>
</table>

5.2.3. SHS in the problem of nanopowders [60-61]

Earlier, SHS was thought to be incapable of yielding finely dispersed powders. From one hand it was a complicated task because at low temperatures recrystallization processes occurred rather actively, from the other hand it was not necessary since SHS powders had their own application fields. However, the problem of nanomaterials has aroused great interest among SHS specialists and several investigation directions have appeared:

- classical SHS with suppressed recrystallization (several approaches);
- gas-phase SHS (it has become more important in connection with SHS);
- SHS with a high-temperature solvent;
- SHS stimulated by carbon combustion;
- “solution” combustion;
- SHS in multilayer nano-sized films.

By the time, a lot of oxide nano-sized powders have been obtained by various methods. Synthesis of other compounds is under study. No doubt that the problem of producing nano-sized powders of various classes and application fields by the SHS method will be further developed. Some results of SHS application for obtaining nano-sized powders are given in articles 62-64.

The nearest tasks of the SHS specialists are to gain experience in analyzing nano-sized powders and to determine the efficient ways of their application.
Table 7. New grades of tungsten-free hard alloys.

<table>
<thead>
<tr>
<th>Alloy grade</th>
<th>Composition</th>
<th>Density, g/cm³</th>
<th>Average particle size</th>
<th>Hardness, HRA</th>
<th>Bending strength, MPa</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>STIM-1B/3</td>
<td>(TiC-TiB₂) + Cu</td>
<td>4.94</td>
<td>5-7</td>
<td>93.5</td>
<td>700-800</td>
<td>Cutting plates</td>
</tr>
<tr>
<td>STIM-2</td>
<td>TiC + Ni</td>
<td>5.50</td>
<td>5-7</td>
<td>90</td>
<td>1000-1100</td>
<td>Armored plates</td>
</tr>
<tr>
<td>STIM-2A</td>
<td>TiC + (Ni-Mo)</td>
<td>6.40</td>
<td>1-2</td>
<td>87</td>
<td>1600-1800</td>
<td>Stamp instrument</td>
</tr>
<tr>
<td>STIM-3B</td>
<td>(TiC-Cr₃C₂) + Ni</td>
<td>5.37</td>
<td>3-4</td>
<td>92.5</td>
<td>800-1000</td>
<td>Cutting plates</td>
</tr>
<tr>
<td>STIM-3B</td>
<td>(TiC-Cr₃C₂) + steel</td>
<td>5.40</td>
<td>2-4</td>
<td>92.5</td>
<td>700-800</td>
<td>Nonscaling items</td>
</tr>
<tr>
<td>STIM-4</td>
<td>TiB + Ti</td>
<td>4.20</td>
<td>1-2</td>
<td>86</td>
<td>1200</td>
<td>Items resistant to thermal shock</td>
</tr>
<tr>
<td>STIM-5</td>
<td>(TiC+TiN) + (Ni-Mo)</td>
<td>5.80</td>
<td>1-2</td>
<td>91.5</td>
<td>1200-1400</td>
<td>Cutting plates</td>
</tr>
</tbody>
</table>

Table 8. SHS ceramic materials.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Residual porosity</th>
<th>Product</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN</td>
<td>30 - 50</td>
<td>Rods, crucibles, bushings, bricks, plates, fixing items</td>
<td>Electric-insulating, corrosion-resistant bushings, crucibles for ferrous metal and amorphous alloy melting; lining of high-temperature heaters</td>
</tr>
<tr>
<td>B-BN</td>
<td>~15</td>
<td>Lining bricks</td>
<td>Biological protection</td>
</tr>
<tr>
<td>BN + SiO₂</td>
<td>~10</td>
<td>Lining bricks, bushings</td>
<td>Lining of MGD-generator channel; erosion-resistant bushing in the cutter of a device of air-plasma cutting of metals and alloys</td>
</tr>
<tr>
<td>BN + TiB₂</td>
<td>~10</td>
<td>Lining bricks and plates, metal lines, stop valves, steel-pouring nozzle</td>
<td>“Pouring” of amorphous bands; biological protection; obtaining of sprayed powders of tool and structural stainless steels</td>
</tr>
<tr>
<td>AlN</td>
<td>20 - 30</td>
<td>Cylinders, plates</td>
<td>Sintering fixture for heat-conducting boards of integrated circuits</td>
</tr>
<tr>
<td>AlN + TiB₂</td>
<td>&lt;5</td>
<td>Bricks, plates evaporation elements</td>
<td>Lining of electrolysis baths; application of aluminum coating</td>
</tr>
<tr>
<td>SiAlON</td>
<td>20</td>
<td>Items of a complicated shape: turbines, items with honeycomb structure, lining bricks and plates</td>
<td>Parts of internal combustion engine for turbo blowing; catalyst carriers for exhaust gas afterburning</td>
</tr>
<tr>
<td>SiAlON + SiC + BN</td>
<td>&lt;10</td>
<td>Turbines for internal combustion engines, lining bricks, steel-pouring nozzles</td>
<td>Parts of internal combustion engine, electrolysis bath protection (in Al production); metallurgical fixture</td>
</tr>
<tr>
<td>SiAlON + TiB₂</td>
<td>~15</td>
<td>Lining bricks and plates</td>
<td>Parts for metallurgical production; black ceramics</td>
</tr>
<tr>
<td>Si₃N₄ + SiC + TiN</td>
<td>&lt;5</td>
<td>Plates, rods, bushings, spherical items</td>
<td>Friction pairs, wear-resistant parts for internal combustion engines; ball bearings</td>
</tr>
<tr>
<td>Si₃N₄ + SiC + TiN + C</td>
<td>10 - 15</td>
<td>Bushings, plates</td>
<td>Parts operating at high temperatures</td>
</tr>
<tr>
<td>SiAlON-BN</td>
<td>20 - 30</td>
<td>Lining bricks and plates</td>
<td>Items for metallurgical production</td>
</tr>
</tbody>
</table>
5.3.2. Multicomponent SHS ceramics [69-73]

Here we’d like to concern ceramic materials based on nitrides (BN, AlN, Si₃N₄, Si₃AlON). The synthesis of these materials includes preparation of a green mixture which consists of chemical elements and active fillers. This mixture is placed into the gasostat (a constant pressure vessel) with nitrogen pressure of 50-350 MPa. SHS is initiated in the system, and during the process the components of the green mixture turn into nitrides.

Further, some homogeneous processes occur in the multicomponent combustion product. They can be entirely completed, and then the SHS process results in the formation of a single-phase ceramic material. Somehow or other, such a product is not a simple sum of components, even in the case of incomplete homogenization its composition differs from that of its furnace analog.

The bright example of the above-mentioned is SHS ceramics of BN+SiO₂ composition. This ceramics is characterized by high corrosion resistance and used in MHD-generators while the analogous material of the same composition can’t provide the sufficient operation time or be used for the same purposes. The sintered ceramics is useless in this case. In Figure 24 profiles of substance loss in the MGD generator channel are given in comparison with generic materials.

The synthesized ceramics is porous - either with the open porosity or closed but it always keeps its shape.

Some information about the most advanced ceramic materials with specific application fields is given in Table 8 and some photos are presented in Figure 25.

5.3.3. “Black ceramics” [73-74]

Among the ceramic materials synthesized directly from elements in the gasostat there is so called “black ceramics” remarkable due to its unusual properties. It consists of three components but they are not simply sintered. The components have partially reacted with each other. The ceramics strength does not depend on temperature up to 1500 °C. It is characterized by an anomalously low friction coefficient. It is much lower than that of bronze which is a widely used antifriction material. Also the conditions of its obtaining are unusual. The green mixture composition has its own “know-how”, non-observance of which would not allow reproducing its outstanding properties. The combustion product porosity is surprisingly low (less than 1%). The green item shape and dimensions are preserved to high precision. When being studied, the material seems to be a dispersion-hardened one.

For “black ceramics” such notions as “a combustion product” and a final “SHS product” coincide.

Figure 26 presents some characteristics of “black ceramics” and photos of some samples. The possibilities of a wider application of “black ceramics” are being studied.

5.3.4. SHS porous catalyst carriers

SHS products proved to be porous materials. They are used to make porous items to be impregnated with metals, filters for liquid and gas purification. SHS filters for drinkable water purification and apirogenic water preparation are well known now [75].
6. On SHS Product Technology, Manufacturing and Application

6.1. SHS technology [80]

The SHS technology is a large group of new technological processes united by a common feature – optimum use of heat evolved by exothermic reactions and organization of their spontaneous propagation. These processes differ from each other due to their secondary characteristics (chemical classes of raw materials and products, reaction conditions, combustion and structure formation modes, types and intensity of external effects, etc.).

The main peculiarities of the SHS technology are:

• Technological SHS processes do not include heating devices because the process warms-up the reagents itself up to required high temperatures. It simplifies the construction of SHS reactors.

• There is no significant difference between the processes occurring in small and large volumes. It allows predicting SHS processes in large installations; that is very important for production of large-sized items.

• For technological processes of the discontinuous type it is not necessary to use any follow-up arrangements as the process occurs rather fast as consistent with the predictions of the laboratory experiments.

• In the SHS problem the distinction between the investigators studying the SHS regularities and mechanism and the technologists realizing the processes under the production terms is eliminated. There are several examples when a researcher becomes a developer and then a technologist.

Essentially, the SHS technology is an alternative non-power-consuming technology of inorganic materials regarding the existing one which is connected with high power consumption.

By the present time six technological types (TT) of SHS processes have been developed:

• TT-1 - a technology of simple burning of SHS systems with obtaining an SHS semi-product as a cake or an ingot and its further processing into powders;

• TT-2 - a gasostat technology of porous and low-porous materials and items;

• TT-3 - forced SHS compaction (densification of a hot combustion product);

• TT-4 - a technology of high-temperature SHS melts (high-caloric, high-temperature SHS processes forming melt products) or SHS metallurgy*;

• TT-5 - SHS welding;

• TT-6 - gas-transport technologies of fine powders and coatings. Specific equipment has been created for realization of TT-1 – TT-6:

• SHS reactors of various volumes and application purposes (vacuum, open-type, pressure chambers);

• Thermovacuum chambers, high pressure vessels, special moulds, extruders, mills, centrifugal reactors, welding devices, etc.

The common scheme of the SHS technology is presented in Figure 27. It consists of three macrostages:

• Raw material preparation;

• SHS;

• Product machining or processing.

It differs from conventional processes only by the synthesis stage. Figure 28 presents the formula of the SHS technology efficiency. It consists of two parts:

• Engineering efficiency – it is found out at the customers and connected with a higher technical level of SHS products; it

• Economic efficiency (a decrease) of production costs; it results in a decrease in the prime cost (and an increase in the production profitability).

* It is still a perspective name; however, the rates of TT-4 development are high and we hope it will become basic soon.
6.2. Production [81]

Nowadays all TT are used under the terms of pilot-scale facility. As to semi-industrial and industrial-scale production, TT-1 – TT-4 have been developed up to this level. But the most widely used technology is TT-1. The available scheme of the SHS facility of the pilot-scale production meets the requirements of customers. Since the efficiency of pilot-scale and semi-industrial SHS facilities is high, they can compete with power-consuming industrial ones. For large-tonnage facilities automated technological lines have been created and the problems of continuous SHS technologies are under study. Nowadays some industrial high-standard facilities are well-known all over the world. Among them are:

- Production of molybdenum dilicide and high-temperature heating elements;
- Production of grinding-and-polishing titanium carbide powders;
- Production of ferrite powders (magnetically soft);
- Production of nitried ferro-alloys and materials - “Etalon” Company organized at Magnitogorsk Metallurgical Plant (Russia);
- Production of titanium diboride and composite powders of titanium diboride with alumina (USA);
- Production of large-sized pipes with internal wear-resistant coating for transporting abrasive media and pipe-lines thereof in China (a large output and a great number of the production facilities are very impressive);
- Production of carbide powders and ingots (Great Britain);
- Production of tungsten carbide (the plant is being built in Chernogolovka);

The authors continued working enthusiastically and is being developed purposefully.

The created facilities are characterized by a significant profitability which proves great opportunities of SHS not only from the scientific-and-technical point of view but from the production viewpoint as well.

6.3. Application [82-83]

SHS processes and products can be used in:

- Mechanical engineering (abrasives, tool and structural materials, ceramics, etc.)
- Metallurgy (ferro-alloys and alloying agents, including nitried and refractory ones; crucibles for non-ferrous metal melting, boats for vacuum metallization);
- Chemistry and chemical industry – boron-containing refractory compounds, phosphides and fumigants, pigments, filters for liquid and gas purification, catalysts;
- Electrical engineering and electronics – high-temperature heating elements, items of electro-conducting solid lubricants, oxide raw materials for single-crystal growth; superconducting ceramics, ferrites, sealing glue, heat-conducting aluminum nitride substrates;
- Mining industry – pipes with internal wear-resistant ceramic coating, processing of some mineral raw materials.

There are some other products. Among them are floor and wall tiles (building materials manufacturing), high-temperature heat insulators for furnaces of oriented crystallization (aviation engineering), shape-memory implants for operation on bones (medical industry), etc.

The number of application fields of SHS materials and items is constantly growing. It proves that SHS as a field of science and technology is rather young and can lead to outstanding unexpected achievements. Thus, the idea of SHS appeared to be rather attractive for many scientists all over the world; it resulted in the establishment of the World Community of SHS specialists and turned SHS from a modest discovery into a promising actively developing field of the scientific-and-technical progress.

7. Main Results of SHS Activity and their Significance

“The Phenomenon of Solid Flame” is appreciated as a significant scientific discovery. Why? It might seem there is nothing special. The discovery was really made – autowave processes of the combustion type in which the generation velocity of the agent responsible for self-propagation (in our case it is heat) sustains a remarkable auto-braking had not been known before. Moreover, it was not comprehended at once. It might be a private problem. But it was not the combustion phenomenon or combustion with completely condensed product formation that the authors discovered. Thermite combustion had been known before and exactly its investigation led the authors to the discovery. So they modestly appreciated it. Besides, specialists in metallurgy and materials science who did not sense self-propagating mechanisms of chemical reactions did not acknowledge the discovery; they considered the phenomenon not to differ from well-known metallurgical processes.

But years passed. The authors continued working enthusiastically and the method of self-propagating high-temperature synthesis based on the discovery was doing its serious work. As a result a boundary area between the combustion theory and materials science has been created and called structural macrokinetics. It has brought combustion and materials science together: the specialists in combustion became more interested in materials science and those in materials science got rid of their fear of combustion and accepted its creative role. A bridge between the combustion practice and materials technology has been made. New terms – “material-generating combustion processes” and “combustion product materials science” – have appeared. The World Community of specialists in structural macrokinetics and self-propagating high-temperature synthesis has been established and is being developed purposefully.

Below are enlisted the main results:

1. New investigation subjects and methods in chemistry, physics and mechanics have been proposed.
2. New phenomena, effects, modes, processes have been discovered, studied and described, new concepts have been developed, new theories and research directions have been established in combustion science, non-linear dynamics, macroscopic kinetics and materials science. A new scientific area called Structural Macrokinetics was originated.
3. Generation of weak physical fields (electric, magnetic) and radiations (electromagnetic, acoustic) has been found out at autowave processes occurring in chemically reacting media, it has given rise to new investigation problems of intimate mechanism of chemical reactions in combustion waves.
4. The approaches have been developed which allow regulating self-propagating chemical processes by means of intensive physical effects and inhibitory-promoting action of functional additions.
5. The method of self-propagating high-temperature synthesis (SHS) has been suggested; it allows obtaining novel materials and substances including porous ones with nano-sized pores, entirely compact materials with nano-sized pores. A huge number of inorganic substances and materials have been synthesized.
6. A concept of the alternative technology based on the principle of optimum utilization of chemical reaction heat has been developed. New high efficient technologies based on SHS processes (SHS technologies) have been created.
7. High profitability of high science-intensive facilities has been proved.

All the results are of great interest for:

- Chemistry (physical chemistry, inorganic chemistry, electrochemistry, crystallochemistry);
- Chemical physics (chemical kinetics, macroscopic kinetics, combustion science);
- Materials science (physical materials science, material technology);
- Non-linear dynamics,

and other fields of modern engineering as they have enriched them with new information and created new directions of R&D.

Within the development of this field of experience, the notion of SHS has changed. At first it was defined as a synthesis of refractory compounds at solid-flame combustion, now SHS is considered to be a high-temperature synthesis.

1. “Initial” SHS is a synthesis of refractory compounds during the processes of solid-flame combustion.

2. Modern SHS is a high-temperature process occurring:
   - at self-sustaining modes:
     - autowave (or self-propagating);
     - induction (or self-accelerating);
     - stabilized in space (for flowing systems);
   - in material-forming media (solid, liquid, gaseous, multiphase)
   - with obtaining
     - Powders of various particle shapes and sizes, including nanosized ones;
     - Porous materials and items including those with nano-sized pores;
     - Compact non-porous materials (sintered, compacted by external forces, cast and also those with nano-sized grains);
     - Films and coatings of different thickness including nano-sized ones,
   - which are characterized by various chemical, physical and mechanical properties,
   - can be produced under industrial terms by the science-intensive technology which is alternative to a conventional one, and
   - can be used in scientific investigations, medicine and various industries.

Acknowledgement

The authors of the lecture pay high tribute to the fact that the solid-flame ideas became very attractive for many scientists in different countries. As a result The World SHS Community was created. It united the specialists whose concentrated efforts provided the further consistent development of this scientific-and-technical direction. The SHS progress was also promoted by nine international symposia, publication of the specialized SHS journal, many bilateral workshops and meetings, realization of joint projects.

The authors are also grateful to:

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