ENERGY-SAVING TECHNOLOGIES

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Energy-saving technologies based on self-propagating high-temperature synthesis (SHS) are considered. Discussed are the classes of chemical reactions and synthesized products as well as the most popular technological types. The advantages and drawbacks of SHS as a challenge to conventional technologies were formulated. Fundamentals and concrete examples of energy saving due to implementation of SHS technologies were considered in brief. Research directions that characterize SHS as a technology-intensive process were enumerated. The prospects for energy saving in SHS technologies were outlined.

INTRODUCTION

Nowadays development of new efficient energy-saving technologies is of great importance for modern civilization. In this context, the following two energy-related principles (electrical and chemical) of high-temperature processes of chemical technology are worth mentioning.

The first one is conventional. Produced electric power is then used to obtain high temperature in reactors. Within this scheme, high temperature is attained twice: upon fuel combustion at an electric power station and then in a reactor. In this case, losses are unavoidable. But this is a universal principle applicable to any kind of technological processes.

The applicability of the second principle is confined to the class of exothermic reactions. In this case, high temperature is attained due to internal release of chemical energy rather than external heat supply, heat losses being minimal. For this reason, chemical technologies utilizing the second principle are termed energy-saving.

It is clear that the higher is the processing temperature, the more efficient is the chemical-energy approach and the higher is energy saving.

Combustion is the best way to utilize chemical energy for self-heating of substance for technological purposes. High rate of chemical reaction, no need for preheating, and simple facilities - all this makes the process highly convenient. It was termed "technological combustion".

The following are some widely known processes of technological combustion in metallurgy and chemical industry: production of pig iron in blast furnaces, of ferroalloys and alloying agents by out-of-furnace aluminothermy, of process gases and carbon black upon incomplete combustion of hydrocarbons, of inorganic acids by technological combustion of gases.

A method that allows us to use technological combustion for the synthesis of ceramics and ceramic materials was developed in 1967 at the Research Center of the USSR Academy of Sciences in Chernogolovka. It was termed self-propagating high-temperature synthesis (SHS) (see also review papers).
SHS is a special kind of combustion (in the mixture of powder reagents) that yields solid products with valuable properties. The photo and schematic of SHS process are presented in Fig. 1.

![Fig. 1. Photo (a) and Schematic (b) of SHS Process.](image)

SHS process involves the following stages typical of any kind of SHS processes: ignition of a starting sample, front propagation, and sample cooling after combustion. Typical parameters of SHS process are presented in Table 1. High burning velocities in the condensed phase, high combustion temperatures, and high heating rates allow us to regard SHS as an extreme chemical process.

This paper deals with the application of SHS to manufacturing ceramics. An incomplete list of ceramics that have already been prepared by SHS is presented in Table 2. These are non-oxide refractory compounds (both metallic and nonmetallic), complex (mixed) oxides, and other ceramic materials of different composition and destination.

**CHEMICAL ASPECTS**

The chemistry of SHS process differs from that of conventional ceramic processing. Necessary condition for SHS is the availability of exothermic reactions or stages that would sustain the propagation of combustion wave in the system. A general scheme of SHS process can be represented in the form:

$$\sum_{i} k_i (s, l, g) \rightarrow \sum_{j} P_j (s, l, g) + Q,$$

where $R_i$ is a reactant, $P_j$ is a product, $Q$ is the heat release. $s, l, g$ stand for solid, liquid, and gas, respectively.

<table>
<thead>
<tr>
<th>Table 1: Typical SHS Parameters</th>
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<tbody>
<tr>
<td>Particle size, $r$</td>
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<tr>
<td>Relative sample density</td>
</tr>
<tr>
<td>Sample diameter, $d$</td>
</tr>
<tr>
<td>Laboratory, industrial scale</td>
</tr>
<tr>
<td>Burning velocity, $U$</td>
</tr>
<tr>
<td>Peak temperature, $T_p$</td>
</tr>
<tr>
<td>Heating rate in the wave, $R$</td>
</tr>
<tr>
<td>Heat release in reaction, $Q$</td>
</tr>
<tr>
<td>Ignition power, $q$</td>
</tr>
<tr>
<td>Ignition delay time, $t_d$</td>
</tr>
</tbody>
</table>

As a rule, SHS systems contain a complex of components that normally are not combustible, while some of the compounds are used as oxidizers. This is the case with SHS:

(i) synthesis from elements (solid flux):  
- $Zr + 2B \rightarrow ZrB_2$
- $Ti + C \rightarrow TiC$
- $Mo + 2Si \rightarrow MoSi_2$

(ii) synthesis from elements (infiltration or spraying):  
- $Ti + 1/2 N_2 \rightarrow TiN$
- $3Si + 2N_2 \rightarrow Si_3N_4$

(iii) synthesis with a reducing stage (metallic):  
- $TiO_2 + B_2O_3 + 5Mg \rightarrow TiB_2 + 5MgO$
- $B_2O_3 + 3Mg + N_2 \rightarrow 2BN + 3MgO$
- $3Cr_2O_3 + 6Al + 4C \rightarrow 2Cr_3C_2 + 3Al_2O_3$
Table 1. Typical Parameters of SHS Process

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size, ( r )</td>
<td>( 0.1 \text{ - } 50 \mu m )</td>
</tr>
<tr>
<td>Relative sample density, ( \Delta )</td>
<td>from the bulk one to ( \Delta = 0.6 )</td>
</tr>
<tr>
<td>Sample diameter, ( d )</td>
<td>( 0.5 \text{ - } 1.5 \text{ cm} )</td>
</tr>
<tr>
<td></td>
<td>laboratory ( 0.2 \text{ - } 0.4 \text{ m} )</td>
</tr>
<tr>
<td></td>
<td>industrial-scale production</td>
</tr>
<tr>
<td>Burning velocity, ( U )</td>
<td>( 0.1 \text{ - } 10 \text{ cm/s} )</td>
</tr>
<tr>
<td>Peak temperature, ( T_m )</td>
<td>( 1500\text{ - }3500 \text{ K} )</td>
</tr>
<tr>
<td>Heating rate in the wave, ( W )</td>
<td>( 10^6 \text{ - } 10^8 \text{ K/s} )</td>
</tr>
<tr>
<td>Heat release in reaction, ( Q )</td>
<td>( 200 \text{ - } 1500 \text{ cal/g} )</td>
</tr>
<tr>
<td>Ignition power, ( q )</td>
<td>( 10\text{ - }200 \text{ cal/cm}^2\text{s} )</td>
</tr>
<tr>
<td>Ignition delay time, ( t_{ign} )</td>
<td>( 0.1 \text{ - } 1.0 \text{ s} )</td>
</tr>
</tbody>
</table>

As a rule, SHS systems contain a combustible and an oxidizer. Metals and nonmetallic elements normally act as combustibles, while boron, carbon, silicon, nitrogen, oxygen, and some of their compounds are used as oxidizers. The following are examples of chemical reactions in ceramic SHS:

(i) synthesis from elements (solid flames)

\[ \text{Zr} + 2\text{B} \rightarrow \text{ZrB}_2 \]
\[ \text{Ti} + \text{C} \rightarrow \text{TiC} \]
\[ \text{Mo} + 2\text{Si} \rightarrow \text{MoSi}_2 \]

(ii) synthesis from elements (infiltration flames)

\[ \text{Ti} + 1.2\text{N}_2 \rightarrow \text{TiN} \]
\[ 3\text{Si} + 2\text{N}_2 \rightarrow \text{Si}_3\text{N}_4 \]

(iii) synthesis with a reducing stage (metallothermic SHS)

\[ \text{Ti}_2\text{O}_3 + 2\text{B}_2\text{O}_3 + 5\text{Mg} \rightarrow 2\text{TiB}_2 + 5\text{MgO} \]
\[ \text{B}_2\text{O}_3 + 3\text{Mg} + \text{N}_2 \rightarrow 2\text{BN} + 3\text{MgO} \]
\[ 3\text{Cr}_2\text{O}_7 + 6\text{Al} + 4\text{C} \rightarrow 2\text{Cr}_3\text{C}_2 + 3\text{Al}_2\text{O}_3 \]

(vi) synthesis of complex oxides

\[ 3\text{Cu} + 2\text{BaO}_3 + \frac{1}{2}\text{Y}_2\text{O}_3 \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x+4} \]

Note that the presence of oxygen is unnecessary for combustion. In SHS, the examples of oxygen-free combustion are numerous. One of the most prominent is the synthesis of hydrides, where hydrogen, the well-known combustible, acts as oxidizer.

Discussing the chemistry of SHS processes, we considered only the overall reaction schemes. In reality, SHS reactions involve numerous intermediate stages. Their identification is one of objectives of SHS chemistry.

The chemical mechanism of the synthesis of yttrium barium cuprate, the well-known high-Tc superconductor, is presented below as an example: \(^{11}\)

**overall reaction scheme**

\[ 3\text{Cu} + 2\text{BaO}_3 + \frac{1}{2}\text{Y}_2\text{O}_3 \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x+4} \]

**actual reaction mechanism**

during preheating and in the zone of main heat release (up to \( \approx 850^\circ\text{C} \))

\[ 2\text{Cu} + \text{O}_2 \rightarrow \text{Cu}_2\text{O} + 1/2\text{O}_2 \]
\[ \text{BaO}_3 \rightarrow \text{BaO} + 1/2\text{O}_2 \]
\[ (\text{BaO} + \text{BaO}_{2})_{\text{init}} + 2\text{Cu}_2\text{O} \rightarrow 2\text{BaCu}_2\text{O}_5 \]
\[ (\text{BaO} + \text{BaO}_{2})_{\text{init}} + 2\text{Cu}_2\text{O} \rightarrow 2\text{BaCu}_2\text{O}_5 \]

in the after-burning zone (\(T_m \approx 950^\circ\text{C} \))

\[ 2\text{BaCu}_2\text{O}_5 + \text{CuO} + \frac{1}{2}\text{Y}_2\text{O}_3 \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x+4} + \text{Cu}_2\text{O} \]
\[ \text{BaCu}_2\text{O}_5 + \text{CuO} \rightarrow \text{BaCu}_2\text{O}_5 + 1/2\text{O}_2 \]
\[ 2\text{BaCu}_2\text{O}_5 + \text{CuO} + 1/2\text{Y}_2\text{O}_3 \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x+5} \]

in the cooling zone

\[ \text{YBa}_2\text{Cu}_3\text{O}_{x+4}\text{(tetra)} \rightarrow \text{YBa}_2\text{Cu}_3\text{O}_{x+4}\text{(ortho)} \]

This product is extremely capricious. To prepare high-quality product, one has to know the mechanism of SHS reaction in detail.

**CERAMIC SHS TECHNOLOGIES**

SHS technology has three types of objective. One is conventional chemical synthesis, when only the product composition should meet strict requirements. In this case, a typical objective is preparation of single-phase compounds. Another is direct synthesis of ceramic material with additional requirements to micro- and macrostructure of the product. Here, widespread task is direct synthesis of hard alloys. All these tasks should meet strict requirements to shape, size, and service parameters, as well as functionally-graded armor plates.

It is clear that, going from the first to the third, demands are markedly increased.

To resolve these problems, more versatile methods have been developed and are described below. These can be classified as:

- **TT-1** chemical synthesis,
- **TT-2** SHS sintering,
- **TT-3** forced SHS compaction,
- **TT-4** SHS recrystallization,
- **TT-5** SHS welding,
- **TT-6** gas-transport SHS deposition,

The first three are the most applicable for raw materials at the present detail below.

The scheme of simplest SHS production processes involves ignition of reactants to obtain intermediate porous or semi-porous compacts, and blanks which are then densified by conventional sintering methods. Three types of SHS powders should be distinguished:

- **Compact** powders,
- **Composite** powders,
- **Sintered** powders.

Applications of SHS powders vary with the particle size. SHS powders are used for compacted powders, driven sintering (20-40 \(\mu\text{m} \)), and plate compaction (20-40 \(\mu\text{m} \)).

The most popular SHS powders are those for:

- SiN, SiC, BN, HfC, MoSi₂, NAI,
- SrO-Al₂O₃, YBa₂Cu₃Oₓ.

Synthesis is conducted either in air or in inert gases, an open reactor that allows additional fuel during combustion, and a flow reactor (inert hydrogen, etc.) became most widely used.

SHS sintering is a technology used in the SHS process, yielding desired items. This step is conducted so that its initial shape and size is maintained. It must be conducted under specific conditions: (i) synthesis of all reactions in the gas phase in pressurized, evacuated reactors. However, complete sintering and this technological type was applied in their specific service parameters. By these...
Combustion in SHS, the examples of prominent is the synthesis of hydrides, nitrides, carbonitrides, and metal matrix composites. The overall reaction scheme of the SHS process involves the following steps:

1. Formation of reaction products
2. Reaction propagation
3. Solidification and product formation

The reaction scheme is as follows:

\[ \text{Yb}_{2}C_{6}O_{7} \rightarrow \text{Yb}_{2}C_{6}O_{7} \] (up to \(-30^\circ\text{C}\))

The quality product, one has to know the chemical composition, when it is not a conventional chemical synthesis, when it is a reaction in a reactor, in this case, a typical objective is direct synthesis of ceramic material with the product. Here, widespread task is direct synthesis of hard alloys. At last, direct (net-shape) production of items. In this case, the end product should meet strict requirements not only to its composition and structure but also to its shape, size, and service parameters. The example of resolved problem is direct synthesis of functionally-graded armor plates.

It is clear that, on going from the first to the third objective, actual difficulties increase markedly.

To resolve these problems, more than thirty modifications of SHS technology has been developed so far. These can be classified into the following six principal technological types:

1. **TT-1** chemical synthesis,
2. **TT-2** SHS sintering,
3. **TT-3** SHS compaction,
4. **TT-4** SHS metalurgy,
5. **TT-5** SHS welding,
6. **TT-6** gas-transport SHS deposition.

The first three are the most applicable to producing ceramics. They are considered in more detail below.

The scheme of simplest SHS production is as follows. It is based on the combustion of powder reactants to obtain intermediate products for further processing. These are cakes, shapeless compacts, and blanks which are used as raw materials for preparing powders. Their comminution is carried out by conventional mechanical disintegration or by chemical means. Three types of SHS powders should be mentioned: single-crystal grains, agglomerates, and composite powders.

Applications of SHS powders are versatile, depending on both their chemical composition and particle size. SHS powders are used for: sintering (<3μm), hot pressing (1-10μm), detonation-driven spattering (20-40μm), and plasma sputtering (40-100μm).

The most popular SHS powders are TiC, TiN, TiC+TiN, TiB2, TiC+H2, TiN, AlN, Si3N4, SiC+SiC, BN, BC, MoSi2, NiAl, TiNi5, Cr2C3, (TiC-Cr2C3)+Ni, LiNbO3, Mn2Zn1Fe2O4, SrO·6Fe2O3, Yb2Cu3O7.

Synthesis is conducted either in air or in special reactors. A universal reactor for various syntheses, an open reactor that allows self-purification of reactants from gasifying impurities during combustion, and a flow reactor for synthesis involving gaseous reactants (nitrogen, hydrogen, etc.) became most widely spread.

SHS sintering is a technology used to perform direct sintering of a combustible product during SHS process, yielding desired item. The charge is compacted in the form of an item, and SHS is conducted so that its initial shape and size be retained. Progress was made in the following two directions: (i) synthesis of nitride ceramics under high nitrogen pressure in high-pressure gasostat and (ii) synthesis of ceramics on the basis of carbides, borides, and carbonitrides in evacuated reactors. However, complete sintering is difficult to achieve under these conditions; and this technological type was applied to prepare items with high or low porosity, or retention of their service parameters. By these methods, the following SHS products were manufactured:
ceramic filters, porous blanks for filters, ceramic insulators, crucibles for metals, blanks of boron nitride, special refractories. These items are exemplified in Fig. 2.

Another very important technological type is the so-called forced SHS compaction. Its essence is fairly simple. Still hot combustion product is compacted to its pore-free state and, sometimes, shaped in special utilities. This can be achieved by (1) uniaxial pressing, (2) hot isostatic pressing (HIP), (3) extrusion, (4) rolling, (5) forging, and (6) explosive shock. Best results were obtained (see Fig. 3) in fabricating the STIM hard alloys (cutting inserts, dies, drawing dies, disks, press dies, rolls, etc.).

These and other technological types are applicable according to the overall scheme described below.

The process involves the following three stages:
(i) preparation of green mixture followed by quality control. This stage involves drying, weighing, mixing, pelletizing, and shaping;
(ii) SHS in air, reactors, gas stations, thermovacuum cameras, press dies, extruders, centrifugal machines, surface cameras, etc.;
(iii) processing combustion products by crushing, grinding, classification, polishing, cutting, sharpening, etc. of combustion product.

<table>
<thead>
<tr>
<th>Table 2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-oxide ceramic compounds</td>
</tr>
<tr>
<td>borides</td>
</tr>
<tr>
<td>carbides</td>
</tr>
<tr>
<td>nitrides</td>
</tr>
<tr>
<td>silicides</td>
</tr>
<tr>
<td>Metallic compounds (examples)</td>
</tr>
<tr>
<td>TiC, TiN, TiC-TiN, TiB₂, Ti₆Sn₃</td>
</tr>
<tr>
<td>Non-metallic compounds (examples)</td>
</tr>
<tr>
<td>AlN, Si₃N₄, SiC</td>
</tr>
<tr>
<td>B₂C, BN etc.</td>
</tr>
</tbody>
</table>


Table 2. Ceramic SHS Products.

<table>
<thead>
<tr>
<th>Non-oxide ceramic compounds</th>
<th>Complex oxide ceramic compounds</th>
<th>Ceramic materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>borides</td>
<td>nitrides</td>
<td>Silicon Nitride Ceramics</td>
</tr>
<tr>
<td>carbides</td>
<td>oxides</td>
<td>Boron Nitride Ceramics</td>
</tr>
<tr>
<td>nitrides</td>
<td>titanates</td>
<td>Hard Alloys (tungsten-free)</td>
</tr>
<tr>
<td>silicides</td>
<td>cuprates</td>
<td>Abrasives</td>
</tr>
<tr>
<td>Metal oxides (examples)</td>
<td>ferrites</td>
<td>Refractories</td>
</tr>
<tr>
<td>TiC, TiN, TiC/TiN, TiB₂, Ti₅S₃</td>
<td>examples</td>
<td></td>
</tr>
<tr>
<td>Non-metallic compounds (examples)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlN, Si₃N₄, SiC</td>
<td>Ba₃Ti₄O₁₂ (Ni-Mn)O-Fe₃O₃</td>
<td>High-Tc superconductors, etc.</td>
</tr>
<tr>
<td>B₂C, BN etc.</td>
<td>BaO₆F₆F₂O₃</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Photo of STIM hard alloys items.

3. Ceramic items

4. Milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, milling, 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Table 3. SHS as an Alternative Technology.

<table>
<thead>
<tr>
<th>Conventional technology</th>
<th>Alternative SHS technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>furnace synthesis, plasmochemical synthesis</td>
<td>simple SHS (TT-1)</td>
</tr>
<tr>
<td>sintering, hot pressing, isostatic pressing</td>
<td>SHS sintering (TT-2)</td>
</tr>
<tr>
<td>cast molding, centrifugal casting</td>
<td>SHS densification (TT-3)</td>
</tr>
<tr>
<td>plasma spray and detonation-driven sputtering</td>
<td>SHS casting (TT-4)</td>
</tr>
<tr>
<td>CVD processes</td>
<td>gas-transport SHS technology (TT-5)</td>
</tr>
<tr>
<td>electric-arc and induction surfacing</td>
<td>induction SHS surfacing (TT-6)</td>
</tr>
<tr>
<td>electric-arc welding</td>
<td>SHS welding (TT-5)</td>
</tr>
</tbody>
</table>

Among them, SHS is a fast stage. Although stages 1 and 3 are only indirectly related to SHS, their improvement is important for the SHS problem as a whole. Powders (metals, ceramics, oxides, hydrides, fillers, additives) and gases (NO, H2, O2, inert gases, gaseous compounds) can be used as reactants. This SHS technology is used for production of inorganic compounds (powders) such as nitrides, nitrides, silicides, hydrides, oxides, chloride, intermetallics, phosphides, etc. Multicomponent materials and items (abrasives, hard alloys, cermetics, refractories, superconductors, items for electrical engineering, surfaced items, joined items, etc.) can be manufactured as well.

SHS as a challenge to conventional processing can be used to solve similar tasks. In Table 3, SHS technology is compared to methods of conventional production methods.

Despite the need for the preparation of exothermic mixtures and some problems with raw materials, SHS technology possesses a number of advantages. The most important are (i) high burning velocity, (ii) lower cost of chemical energy, (iii) rapid layer-to-layer self-heating (instead of slow heating through the surface), and (iv) low number of processing steps (down to one-step production).

EFFICIENCY OF SHS PROCESS

Efficiency of SHS process stems from some physical features of the process. For instance, high combustion temperature ensures complete chemical conversion, self-purification from some impurities, and elevated rate of homogenization. As a result, this leads to high quality of end products. High burning velocity ensures high productivity. Internal (chemical) heat release ensures saving of resources and, accordingly, lower production cost. The overall efficiency of SHS originates from both lower production cost and enhanced service parameters of end products.

The technical level of SHS products is sufficient for resolving complicate technical problems. Some SHS products have no commercially available analogs (Table 4).

Table 4. Technical comparison (in comparison).

<table>
<thead>
<tr>
<th>1. Powders</th>
<th>2. Composite powders</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN, α-Si3N4, BN</td>
<td>TiC, α-Cr2O3, β-TiC, HfC2</td>
</tr>
<tr>
<td>3. TiC-based</td>
<td>4. Cutting inserts</td>
</tr>
<tr>
<td>Abrasive Pastes</td>
<td>STIM-5</td>
</tr>
<tr>
<td>5. Ceramic insulators for the furnace</td>
<td>6. Large-scale roll for copper rolling</td>
</tr>
</tbody>
</table>

The explanation for higher quality of SHS processes, it can be controlled by a low combination of parameters is found. For instance, SHS efficiency in the production of TiC powders by leading manufacturers: SHS powders are used in nitriding and oxygen contamination.

The characteristics of three different SHS technologies—plasmochemical—are compared in Table 4. The characteristics in all aspects. Difference in energy cost...
### Table 4. Technical Level of SHS Products: Examples.

(in Comparison with Commericially Available)

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Powders</td>
<td>higher nitrogen content&lt;br&gt;completeness of nitriding&lt;br&gt;lower content of impurity oxygen</td>
</tr>
<tr>
<td>2. Composite powders</td>
<td>no prototype</td>
</tr>
<tr>
<td>3. TiC-based abrasive pastes</td>
<td>grinding and polishing&lt;br&gt;simultaneously, higher labor productivity</td>
</tr>
<tr>
<td>4. Cutting inserts</td>
<td>higher wear resistance&lt;br&gt;during cutting</td>
</tr>
<tr>
<td>5. Ceramic insulators for the furnaces used in oriented crystalization</td>
<td>higher service life</td>
</tr>
<tr>
<td>6. Large-scale rolls for copper rolling</td>
<td>no prototype</td>
</tr>
</tbody>
</table>

The explanation for higher quality of SHS products is as follows: SHS is a multiparametric process, it can be controlled by a large number of parameters. Therefore, when the optimal combination of parameters is found, high quality of product is guaranteed.

SHS efficiency in the production of aluminum nitride powder is exemplified in Tables 5 and 6. In the former, the characteristics of SHS powders are compared with those of furnace-produced by leading manufacturers. SHS powders are superior over their furnace analogs in the degree of nitriding and oxygen contamination.

The characteristics of three different processing techniques—SHS, furnace, and plasmochemical—are compared in Table 6. The use was made of the data of pilot-scale production in the former Soviet Union. SHS products are superior over their analogs almost in all aspects. Difference in energy consumption and production cost is most impressive.
Table 5. Characterization of SHS Ceramic Powders (for AlN as an example).

<table>
<thead>
<tr>
<th>Impurity</th>
<th>SHS, ISMAN (high quality)</th>
<th>Furnace synthesis, trade companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N)</td>
<td>33.9</td>
<td>33.0-33.4</td>
</tr>
<tr>
<td>Impurity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oxygen (O)</td>
<td>0.3</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Specific</td>
<td></td>
<td></td>
</tr>
<tr>
<td>surface m²/g</td>
<td>2.0-20.0</td>
<td>1.0-8.0</td>
</tr>
</tbody>
</table>

Table 6. Characteristics of SHS, FS, and PCS Techniques.

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>SHS furnace synthesis (FS)</th>
<th>plasma-chemical synthesis (PCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>consumption</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>aluminum, kg/kg</td>
<td>0.9</td>
<td>1.65</td>
</tr>
<tr>
<td>nitrogen, m³/kg</td>
<td>3.3</td>
<td>31</td>
</tr>
<tr>
<td>Electric energy</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>requirements</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Labour input, arb.units</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Number of</td>
<td>4.0</td>
<td>0.75</td>
</tr>
<tr>
<td>processing steps</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Synthesis</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>installation</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>productivity, kg/hr</td>
<td>4.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Powder cost, arb.units</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Note. The data refer to pilot scale production in the former USSR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Considering energy-saving technologies, we should pay a little bit more attention to actual figures characterizing energy saving. The fact that SHS has no need for external energy supply is evident. Moreover, SHS is accompanied by energy release. In reality, energy is spent not only for synthesis but also for some auxiliary operations, and this should be kept in mind. Since different technologies require different raw materials, we should take into account energy consumption for preparation of these raw materials from the same starting products. Here, decisive arguments must come from calculations rather than from logic deductions.

In Table 7, the calculated energy saving upon the substitution of SHS for furnace production of powder titanium carbide is presented. In these calculations, we used the data obtained from one of the plants producing hard alloy grade carbide. Production data were taken from the Institute of Materials Science, Energy consumption in the Synthesis and Processing. In the Table 8, similar calculated data for implemented SHS-production of ferromagnesium alloys is presented. Design performed at the plant, in this case, is similar to that of the SHS-production of single crystal TiC.
Table 7. Calculation of Energy Saving Upon Substitution of SHS for Furnace Synthesis (for TiC as an example).

<table>
<thead>
<tr>
<th></th>
<th>Furnace synthesis</th>
<th>SHS-1</th>
<th>SHS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical reaction</td>
<td>TiO₂⁺3C → TiC+2CO↑</td>
<td>TiC → TiC</td>
<td>TiO₂⁺2Mg+Co → TiC+2MgO</td>
</tr>
<tr>
<td>Energy consumption per 1 kg powder, kWh/kg</td>
<td>≈ 35</td>
<td>≈ 2</td>
<td>≈ 3</td>
</tr>
<tr>
<td>Energy consumption per 1 kg powder Ti</td>
<td>≈ 11 kWh/kg</td>
<td>Mg ≈ 16 kWh/kg</td>
<td></td>
</tr>
</tbody>
</table>

Total energy saving, including energy consumption for manufacturing metal powder (but with no regard to energy release in reaction)

SHS-1: ≈ 24 kWh/kg
SHS-2: ≈ 19 kWh/kg

Table 8. Calculation of Energy Saving (Data of the Plant Producing Nickel-Zinc Ferrite).

<table>
<thead>
<tr>
<th></th>
<th>Furnace process</th>
<th>SHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical reaction</td>
<td>Fe₂O₃+0.73MnO+0.27ZnO → Mn₀.72Zn₀.27Fe₂O₄</td>
<td>0.8Fe⁺0.6Fe₂O₃+0.6O₂⁺ → Mn₀.72Zn₀.27Fe₂O₄</td>
</tr>
<tr>
<td>Energy consumption per 1 kg ferrite powder synthesis</td>
<td>12 kWh/kg</td>
<td>0.04 kWh/kg</td>
</tr>
<tr>
<td>Energy consumption per 1 kg ferrite powder processing</td>
<td>1 kWh/kg</td>
<td>1.2 kWh/kg</td>
</tr>
<tr>
<td>Energy saving at the plant</td>
<td></td>
<td>11.76 kWh/kg</td>
</tr>
<tr>
<td>Energy consumption per 1 kg Fe</td>
<td></td>
<td>1 kWh/kg</td>
</tr>
<tr>
<td>Total saving, including preparation of Fe powder</td>
<td></td>
<td>11.57 kWh/kg</td>
</tr>
</tbody>
</table>

Of the plants producing hard alloys in the former Soviet Union, while the data on SHS production were taken from the Institute of Structural Macromolecules, Russian Academy of Sciences. Energy consumption in the production of titanium and magnesium powders was taken from reported data.

In Tab. 8, similar calculated data for energy consumption at one of Russian plants that has implemented SHS-production of ferrites are presented. These data were taken from economic design performed at the plant. In this case, energy saving is also significant.
FUNDAMENTALS OF SHS

SHS production is technology-intensive. It can be controlled only with great understanding of combustion in the system, the mechanism of composition and structure formation in end product, and the means of their control. For this reason, basic research of SHS processes and their products developed extensively. The following are research directions that made fundamentals of SHS:

(i) combustion theory and experimental diagnostics for controlling SHS processes; nonlinear dynamics for selecting combustion modes;
(ii) thermodynamics of combustion for prediction and selection processing conditions;
(iii) kinetics of high-temperature reactions for understanding heat release modes;
(iv) high-temperature thermophysics for understanding heat-transfer processes;
(v) composition chemistry and structural macrokinetics for controlling the quality of SHS product composition, structure, and properties;
(vi) material science for characterization of end SHS product.

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Fig. 4. Chart of Research Work.

Progress in this research allowed formulating the efficient and substantiated means for controlling the burning velocity, combustion temperature, degree of conversion, as well as the composition and structure of combustion products [16-19].

Let us consider only one example how the combustion temperature—most important parameter of SHS process—can be controlled. For well-organized SHS, its maximum temperature (T_m) should be within the range (T_m - T_m). When T_m < T_m, combustion extincts, SHS does not occur. Otherwise, when T_m > T_m, product quality is unsatisfactory (dissociation, grain growth, macroinhomogeneity). An increase in the way to reduce the combustion temperature product.

Extensive research and development research work from an original idea studies ensure the fidelity of results.

FUTURE OF SHS AS ENERGY-SAVE TECHNOLOGIES

The principal objective of SHS is to develop technologies with the utilization of SHS twofold: joint production of material and energy. Fig. 5 shows two possible modifications of SHS:

(a) SHS-surface process.
(b) SHS and SHS-heating mixed process.

The latter is essentially a thermally released heat is possible.

The essence of the idea of SHS electrical SHS is used not for direct heating thermostimulator of electric power.

The first variant is more efficient and continuous SHS.
Fig. 5 Two Possible Methods of Released Energy Utilization, (a) SHS-Furnace Process, (b) SHS and SHS-Heating Mixed Process.

...macroinhomogeneity). An increase in temperature is achieved by external heat supply. The best way to reduce the combustion temperature is a dilution of charge with some amount of end product.

Extensive research and development of SHS allowed us to formulate an organization chart of research work from an original idea to industrial application. It is shown in Fig. 4. Intermediate studies ensure the fidelity of resultant solution.

**FUTURE OF SHS AS ENERGY-SAVING TECHNOLOGY**

The principal objective of SHS as an energy-saving technology is the development of technologies with the utilization of energy released in chemical reactions. Here the objective is twofold—joint production of materials and energy. Fig. 5 shows two possible modifications:

(a) SHS-furnace process,
(b) SHS and SHS-heating mixed processes.

The latter is essentially a thermally coupled SHS process. In this case, direct utilization of released heat is possible.

The essence of the idea of SHS electric power station is the following. The heat released during SHS is used not for direct heating but for the conversion to electric power by means of thermogenerator of electric power.

The first variant is more efficient for periodic SHS processes while the second one for continuous SHS.
CONCLUSIONS

The social significance of SHS is as follows: (i) saving of resources (energy, raw materials, and labor), (ii) development of new high-quality materials and products for application in engineering, technology, and industry, (iii) stimulation of new research in combustion theory, general and structural macrokinetics, and in materials science. Energy-saving SHS technologies are now fast developing, and we can expect for new interesting results in the future.

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References


