Thermally coupled combustion synthesis of composite ferroalloys

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The results of a study of thermally coupled processes of self-propagating high-temperature synthesis (SHS) of composite ferroalloys are presented. It is shown that activation of the synthesis process by burning weakly exothermic systems based on ferroalloys is possible using various techniques. Namely, it can be realized by physical heating of the SHS charge in an electric furnace; mechanical activation of the exothermic charge; recovery of heat energy of synthesis; chemical heating of the SHS charge with termite additives and the use of a chemical oven. Various options of thermal stimulation for gas-free and filtration combustion synthesis with participation of ferroalloys, known as the metallurgical SHS process, are considered on the base of specific examples. Thermal activation of the gasless procedure of the metallurgical SHS process is considered on the example of the combustion of the ferroboron-titanium system, and the filtration procedure – on the example of nitriding of low-carbon ferrochromium. The combustion products of ferroboron-titanium mixtures are considered as promising materials for steel microalloying with boron and titanium, and nitrided ferrochrome with low carbon content is one of the most demanded materials in melting of nitrogen-containing steels. The results of the studies carried out in this work have shown that the low exothermicity of the synthesis reactions of composite ferroalloys is not an obstacle to their implementation in the combustion mode. Well-known and new stimulation techniques for combustion synthesis allow to significantly expand the range of synthesized materials. Technological techniques such as heat energy recovery, mechanical activation of the exothermic charge, physical heating of the SHS charge in an electric furnace, chemical heating of the SHS charge with termite additives and the use of a chemical oven ensure the involvement of new raw materials with less exothermicity in the SHS process and carrying out of the process in milder conditions.

Key words: composite ferroalloys, self-propagating high-temperature synthesis, nitrides, borides, nitrided ferroalloys, thermal coupling, filtration combustion, gasless combustion.

DOI: 10.17580/cisisr.2024.02.05

Introduction

A lot of chemical reactions for synthesis of inorganic compounds are known, which are accompanied by release and forming of condensed products. Part of them (most exothermic) are used in conventional processes of self-propagating high-temperature synthesis (SHS) and metallothermic processes [1–6]. At the same time, we know many chemically reacting systems, which are prospective from practical point of view and which are characterized by insufficient heat release for realization of self-sustaining combustion processes in conventional conditions in these systems.

We can activate the process in such cases via introduction of additional energy in the SHS system, or by recovery of existing energy. Conventional process of combustion synthesis can use various activation methods:

– physical heating of SHS charge in an electric furnace;
– mechanical activation of exothermic charge;
– recovery of heat energy of synthesis;
– chemical heating of SHS charge by termite additives;
– use of a chemical oven.

Physical heating of SHS charge in an electric resistance furnace was the first answer on compensation of insufficient energy in a gasless exothermic mixture. Such variant of combustion synthesis can be realized both in layer-by-layer and in volumetric (thermal explosion) mode. Increase of initial temperature of reacting SHS charge with use of external physical heat was firstly applied in fabrication of intermetallics [7]. Increase of initial temperature of a mix of metallic powders up to 50–500 °Chelped to synthesize aluminides of Ni, Co, Ti, Cr, Mo, Nb and other compounds in the mode of layer-by-layer gasless combustion. However, practical use of such furnace SHS technology is characterized by losing its main advantages (minimal energy consumption, simplicity of equipment and short processing time). Preliminary heating of exothermic charge or its part is also widely used in metallothermic production [8].

Mechanical activation of SHS charge occurs usually in planetary mills. This processing provides combustion synthesis in low exothermic mixtures and increase of transformation degree in them [9].

Recovery of heat energy during SHS processes is realized in the mode of coflow gas filtration. SHS blowing during gasless synthesis is implemented by inert gas (usually by argon or helium). In hybrid systems, e.g. during synthesis of nitrides, forced filtration is realized by nitrogen or its mixture with argon [10–12]. Recovery of heat energy during gasless synthesis war firstly applied for fabrication of composite ferroalloys on the base of titanium borides [13]. Forced filtration of inert gas allowed to provide combustion synthesis in the system ferroboron-titanium and in other low caloric mixtures using commercial alloys with boron. Conventional SHS process without forced argon filtration can be realized in these mixtures only after significant rise of their initial temperature.

Process activation by chemical energy is widely used for aluminothermic fabrication of refractory metals and complex ferroalloys. Vacant missing heat is introduced in metallothermic charge in the form of termite additives [1, 2, 8]. Such technique can be hardly realized in conventional SHS synthesis from elements, owing to complication of consequent separation of combustion products. The attempt of release of an aimed product via preliminary separate granulation of donor charge and acceptor charge is described in [14].

Introduction of additional chemical heat using so-called “chemical oven” is another variant of increase of SHS charge exothermicity. In this case chemical reaction pass independently from each other, while heat from more exothermic reaction promotes implementation of another one, which is less exothermic [15]. E.g., gasless equiatomic mixture of Ni powders with Al, with combustion temperature 1640 °C, was used in synthesis of intermetallics of Nb–Al and Nb–Ge systems for a material of chemical oven in the mode of gasless combustion [16]. In the above-mentioned variants of thermally coupled synthesis, a charge of an aimed product (energy donor) and a charge of chemical oven (energy acceptor) are separated spacely and can be classified as gasless compositions.

There was no information about examples of chemical oven use in hybrid systems until development of the SHS process, where ferroalloy is one of a charge components [17–19]. As a result of SHS processing of conventional ferroalloys, the complex alloying compositions on the base of nitrides, borides, silicides and other refractory compounds with composite structure are formed. Such ferroalloys provide higher absorption degree of microalloying elements by steel melt. SHS mixtures on the base of ferroalloys are evidently less exothermic in comparison with mixtures on the base of metals. Thereby thermal activation of these mixtures is often required for realization of combustion synthesis in them.

The aim of this research is consideration of various techniques for thermal stimulation of gasless and filtration combustion synthesis in the mixtures containing ferroalloys. Such synthesis is known as metallurgical SHS process. Thermal activation of such gasless SHS and filtration processes is examined on the example of combustion of ferroboron-titanium system and nitriding of low carbon ferrochromium, respectively. Combustion products of the mixtures of ferroboron-titanium are considered as prospective materials for steel microalloying by boron and titanium [20–23], while nitrided ferrochromium with low carbon content is one of the most demanded materials in melting of nitrogen-containing steels [24–31].

Initial materials and experiment technique

Commercial grades of ferroboron can contain 6.0–25.0 % of boron [32, 33]. That’s why influence of physical heating on combustion in the mixture ferroboron-titanium was examined with use of specially obtained model alloys with three compositions. Two of them correspond to semiboride (Fe_2B, 8.8 % B, $T_{smel.} \approx 1410$ °C) and mono-boride (FeB, 16.2 % B, $T_{smel.} \approx 1650$ °C), while the third alloy – to eutectic composition ($FeB–FeB_n$) with 25.6 % B, $T_{smel.} \approx 1500$ °C. Such model alloys were produced via sintering of Fe powders (PZhV grade, GOST 9849-86) and amorphous boron (B-99A grade, TU 1-92-154-90) in a vacuum furnace. Composition of sintering products was controlled by X-ray phase and chemical analyses. SHS experiments used titanium powder with dispersity less than 0.05 mm, which was extracted from the powder of PTS grade according to TU 14-22-57-92. Exothermic mixtures, corresponding to the reaction of forming of a dual-phase alloy, were prepared from ferroboron and titanium powders (**Table 1**). Cylinder samples with diameter 25 mm and height ~30 mm were formed from the mixtures; then they were subjected to combustion in argon atmosphere with pressure 0.15 MPa (gaseous argon of especial purity, according to the GOST 10157-2016) via conventional technique [3]. The experiments on recovery of heat energy in gasless combustion used calcium hydride titanium powder of PTS grade according to TU 14-22-57-92 and powder obtained from commercial ferroboron of FB20 grade according to the GOST 14848-69 with boron content 21.4 %. Mixtures of powders with dispersity 100–160 μm and atomic correlation Ti/B = 0.7 were used in this research.

The powders for filtration synthesis were obtained via additional comminution-activation of initial alloy with size of particles less than 0.315 mm (powder of low carbon ferrochromium, PFN grade, from Klyuchevskiy ferroalloys plant) in a planetary mill. Then these powders we subjected to combustion without compacting in gas-permeable shells with various diameters. Porosity of initial samples was ~ 60 %.

Table 1. Calculated composition of combustion products for the powder mixture (Fe–B) + Ti

Ferroboron phase composition	Boron content in ferroboron, % (mass.)	Calculated reaction							
		Variant 1				Variant 2			
		$(Fe–B) + Ti \rightarrow TiB_2 + Fe$				$(Fe–B) + Ti \rightarrow TiB_2 + FeTi$			
		T_{ad}, °C	Composition of combustion products			T_{ad}, °C	Composition of combustion products		
			B	Ti	Fe		B	Ti	Fe
Fe_2B	8.8	1230	7.3	16.3	76.3	1780	5.4	38.1	56.4
FeB	16.2	1640	11.6	28.0	60.3	2190	7.7	52.5	39.8
$FeB–FeB_n$	25.6	2110	16.3	36.8	47.5	2310	11.6	54.6	33.7

T_{ad} – calculated adiabatic combustion temperature [3].

Experimental results and discussion

1. Heating of initial mixture

Gasless synthesis. It was found out, that in the first case synthesis can be implemented only for the alloy with maximal boron content (25.6 % B) (Table 1, **Fig. 1**).

For the second variant of the initial charge, synthesis becomes possible also when using mono-boride alloy (16.2 % B). Combustion in the mixtures consisting of Fe_2B and Ti powders could not be realized without their temperature rise.

Fig. 2 presents relationships demonstrating the influence of initial temperature on combustion rate for the charge with ferroboron, with various composition. It can be seen, that synthesis is possible in very narrow range of relation of the components (T_0 = 500 °C) for the alloy with lower boron content (16.2 % B), but increase of boron concentration enlarges charge combustion ability. As for the mixture containing ferroboron with 25.6 % B, synthesis is realized without increase of initial charge temperature. Increase of initial mixture temperature essentially expands its combustion ability. It is possible to obtain the product with ~ 7.8–16.3 % B and ~36.2–69.4 % Ti without use of preliminary heating, while increase of initial temperature rise up to 500 °C leads it expanding of this range to ~ 5.8–18.2 % B and ~ 29.0–77.3 % Ti.

In the case of minimal boron content in the initial alloy (8.8 % B), it is possible to initiate combustion only after heating up to 700 °C. Combustion rate increases with temperature rise for all examined compositions.

Thus, preliminary heating of the initial exothermic mixture during gasless synthesis in the system ferroboron-titanium allows to intensify the process and to obtain products with more wide range of composition variation.

Filtration synthesis. Nitrided ferrochromium with low carbon content is one of the most demanded materials in melting of nitrogen-containing steels [25, 29]. In this case, it is difficult to implement combustion synthesis in the system with low carbon ferrochromium and nitrogen due to its low exothermicity [33] and complication in obtaining a powder with required dispersity [34]. It was shown in [35, 36] that nitriding of low carbon ferrochromium in the conditions of self-sustaining filtration combustion is possible only with use of fine-dispersed powder at high nitrogen pressure. However, high strength of low carbon alloys does not allow to provide economically efficient production of ferrochromium powders with dispersity required for nitriding in combustion conditions in commercial volumes.

The relationship between combustion rate and nitriding degree for powders of low carbon ferrochromium with various dispersity (from one side) and nitrogen pressure (from other side) is presented in the **Fig. 3**. Combustion rate in all cases increases with pressure rise owing to improvement of conditions for nitrogen filtration. The melting temperature of low carbon ferrochromium with 75.6 % Cr is located within the range 1550–1670 °C. The value of combustion temperature measured by thermocouples within the range of pressures from 2.0 to 10.0 MPa was 1220–1300 °C. Respectively, nitriding of low carbon ferrochromium powders, which were obtained via mechanical activation, is realized in solid phase procedure. Due to long-term additional nitriding, high degree of chromium transformation in nitrides is achieved.

Increase of initial charge temperature expands possibilities of combustion synthesis during filtration procedure. It was revealed that heating of initial low carbon ferrochromium powder is accompanied by intensification of combustion process, and nitriding of more coarse alloy powder becomes possible (**Fig. 4**).

Metallographic analysis of combustion products confirmed absence of melting tracks for any phase in these products. Solid phase mechanism usually promotes achievement of high nitriding degree both for metals and ferroalloys. Most part of nitrogen is absorbed by the alloy directly in a synthesis wave, including the process of layer-by-layer combustion. The part of the alloy which did not react, interacts with nitrogen just via the procedure of volumetric additional combustion. This process is supported by high material porosity, which is observed behind a combustion front. So, nitrogen content in the product can increase by 10–14 % (depending on process conditions and initial alloy com-

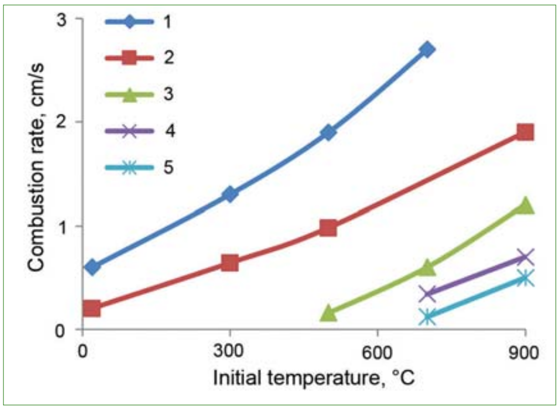

Fig. 1. Influence of initial temperature on combustion rates for ferroboron and titanium mixtures: 1 – 25.6 % B; 2, 3 – 16.2 % B; 4, 5 – 8.8 % B; 1, 3, 5 – Ti/B = 0.5; 2, 4 – Ti/B = 0.86

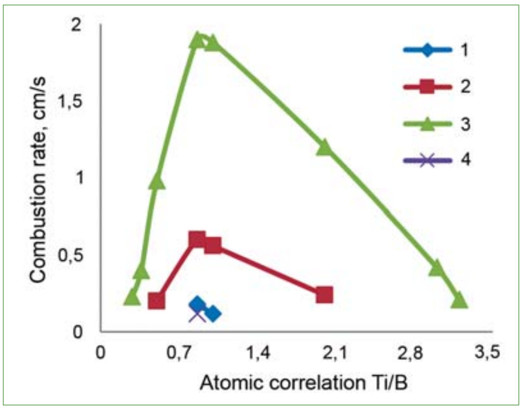

Fig. 2. Influence of the components correlation on combustion rate for the mixtures with ferroboron and titanium: 1 – FeB; 2, 3 – ($FeB–FeB_n$); 4 – Fe_2B; 2 – T_0 = 20 °C; 1, 3 – T_0 = 500 °C; 4 – T_0 = 700 °C

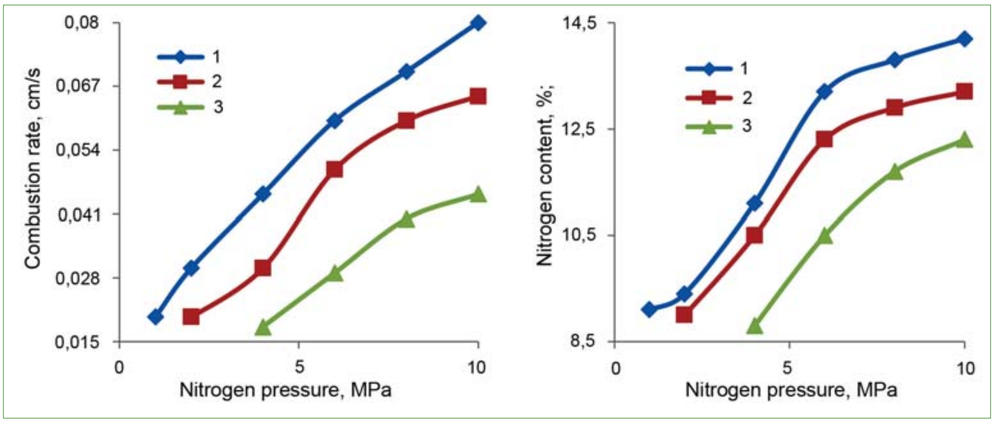

Fig. 3. Influence of nitrogen pressure on combustion rate and nitriding degree for mechanically activated low carbon ferrochromium: 1 – δ_{90} ~0.02 mm; 2 – δ_{90} ~0.04 mm; 3 – δ_{90} ~0.08 mm

position) due to such additional reacting and combustion. However, it should be noted, that maximal value of nitriding degree was not achieved even in the optimal conditions for nitriding of low carbon ferrochromium powder.

From practical point of view, preliminary heating of initial low carbon ferrochromium powder for nitriding via combustion can be hardly realized. To implement such process in the industrial scale, it is necessary to create SHS reacting furnaces with high production capacity, which will be able to operate with increase pressure. Production of comparatively cheap nitrided ferroalloys in such furnaces will be evidently economically inefficient.

NTPF "Etalon" (Magnitogorsk) implemented pilot-industrial experiments for nitriding of low carbon ferrochromium via increase of the initial temperature of a nitrogen as a gas component of exothermic charge. To provide introduction of heated nitrogen in the SHS reactor, the special has burner was mounted at its entrance. When passing through this burner, gas was heated up to ~ 500 °C. In such way it was possible to provide nitriding of low carbon ferrochromium powder in delivery state with dispersity -0.315 µm. However, this process was not practically developed in the industrial scale owing to technical complications in its organization and rather lo nitrogen content in product.

2. Recovery of heat energy

Gasless synthesis. The experiments on research of heat energy recovery during gasless combustion were carried out according to the technique described in the work [11]. The relationship between combustion rate of the mixture of titanium powders with ferroboron and specific argon consumption are presented in the **Fig. 5**. As soon as the amount of gas, which is blown-up through charge, increases, combustion rate rises essentially. When argon consumption is less than 500 $cm^3/s \cdot sm^2$, combustion becomes impossible. Increase of combustion rate during blowing of the mixture of titanium powders with ferroboron by inert gas is stipulated by convective redistribution of heat from the high-temperature area, where exothermic reaction already passed, to initial charge.

To realize combustion of titanium powders with ferroboron without forced filtration, it is required to use more fine powders (**Fig. 6**). The curves 1 and 2 correspond to synthesis in argon atmosphere with pressure 0.15 MPa, while the curves 3 and 4 correspond to synthesis with argon blowing and specific consumption 1330 $cm^3/s \cdot cm^2$.

Thus, forced filtration allows to realize gasless synthesis with use of more coarse powders in a charge. The process rate increase essentially in this case.

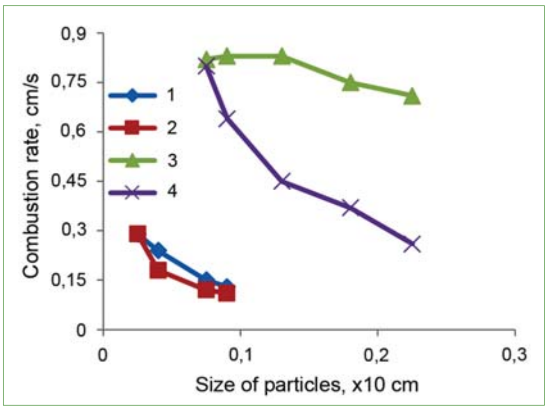

Fig. 4. Influence of initial temperature (T0) on combustion rate of low carbon ferrochromium: 1 and 2 – less than 0.04 mm; 3 and 4 – less than 0.2 mm; 1 and 3 – 6 MPa; 2 and 4 – 2 MPa

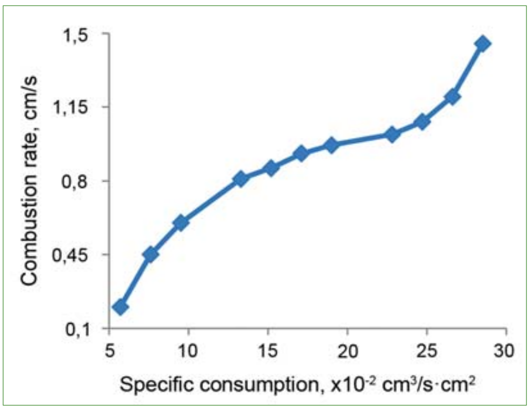

Fig. 5. Influence of specific argon consumption on combustion rate of titanium and ferroboron powders

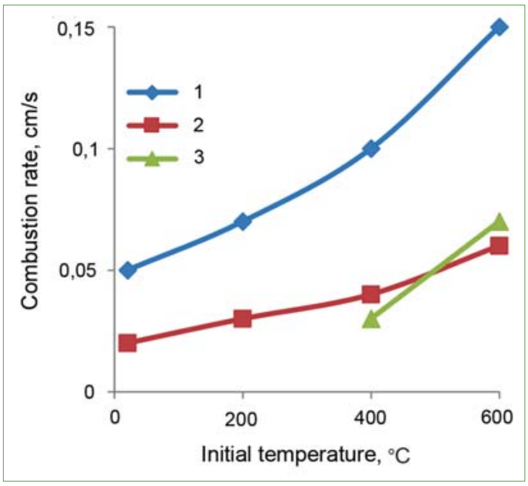

Fig. 6. Influence of dispersity on combustion rate of titanium and ferroboron powders: 1 –Ti less than 50 μm, (Fe–B) – var.; 2 – (Fe–B) less than 50 μm,Ti – var.; 3 – (Fe–B) 50–100 μm, Ti – var.; 4 – Ti 50–100 μm, (Fe–B) – var.

Filtration synthesis. The relationship between combustion rate and nitriding degree of low carbon ferrochromium powder (75.6 % Cr) with various dispersity (from one side) and nitrogen consumption during the process in laboratorial coflow SHS reactor [11] (from other side) is presented in the **Fig. 7**. Ferrochromium starts to burn in coflow at larger values of specific gas consumption due to lower exothermicity (in comparison with metallic chromium). In this case, combustion rate of ferrochromium and chromium increases with rise of nitrogen consumption.

Thus, the higher is nitrogen consumption, the smaller its amount is observed in combustion products. Additionally, nitriding degree of low carbon ferrochromium powder during forced filtration (4.7–7.5 % N) is rather less than its nitriding degree during natural filtration (8.8–14.2 % N) within the examined range of technological parameters (see Fig. 3). It is caused by absence of an additional reacting stage during forced blowing by nitrogen, as it was demonstrated on the example of pure chromium combustion. Quenching of nitriding products by oncoming gas flow fixed such nitrogen amount in synthesis products, which was absorbed by an alloy powder directly in the combustion area.

Thereby, transition to a forced filtration of a reacting gas allows to implement combustion synthesis of nitrided low carbon ferrochromium powder practically at the atmospheric pressure of nitrogen, using comparatively coarse powders of an initial alloy.

3. Chemical heating of SHS charge by termite additives

Filtration synthesis. Applying to SHS synthesis of nitrided ferroalloys, the principle of thermal conjugation via introduction of termite additives in initial charge was firstly used during fabrication of complex nitrogen-containing alloying compositions on the base of chromium and manganese [19]. Heat release during forming of nitrides of these metals is rather less than in the process of synthesis of nitrides of metals from III–V groups in the Periodical system table.

Self-supporting combustion process of chromium and manganese powders in nitrogen can be hardly realized in usual conditions. Exothermicity of the systems is lowered additionally when using the alloys of these metals with ferrum for nitriding. Thereby, it was suggested to add the powders of Al, Ti, V and other metals or alloys on their base in the powders of ferrochromium and ferromanganese to increase thermal effect; their interaction with nitrogen occurs in the way (**Fig. 8**), which is usually used for gasless systems [16] and which are characterized by significantly larger thermal effect [37]. Unlike an external chemical oven, termite additives can be identified as so-called internal chemical oven. Charge of the aimed product and charge of the chemical oven are not separated in their spaces. Practical realization of such combustion synthesis includes mixing of the powders of the main weak exothermic ferroalloy and the powder of the strong exothermic metal or ferroalloy.

Nitriding of these powders passes in parallel way (**Table 2**). Such way for manufacture of nitrogen-containing alloying compositions becomes acceptable, if combustion products of the chemical oven are compatible with composition of molten steel during their consequent use. Nitrides of aluminium, vanadium, silicon and other metals, which are donors of chemical heat, are considered as the same nitrogen sources for steel, as nitrides of chromium and manganese are metallic acceptors for thermal energy. Introduction of termite additives is the most efficient remedy for synthesis of complex

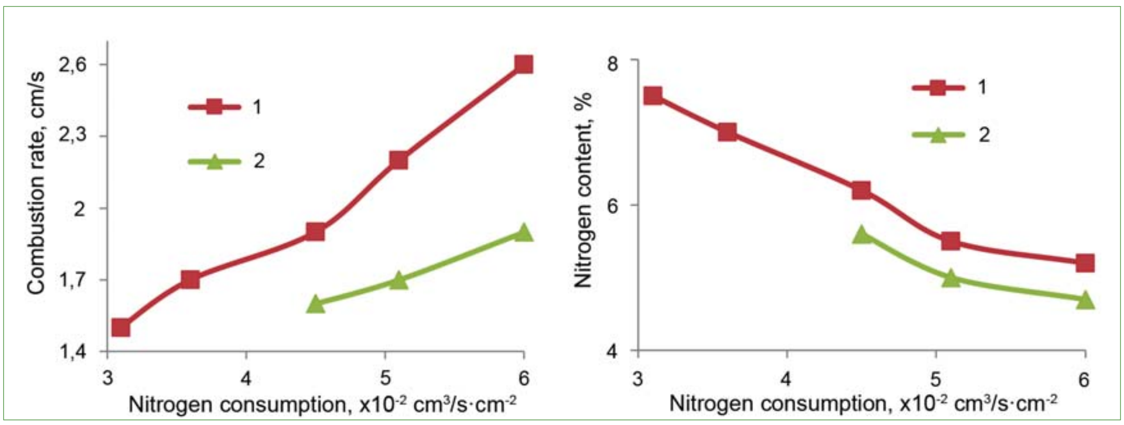

Fig. 7. Influence of specific nitrogen consumption on combustion rate and nitriding degree for ferrochromium: 1 – 63–80 μm, 2 – 63–200 μm.

Table 2. Examples of synthesis in the chemical oven

SHS variants	Variants of chemical oven	
	Internal chemical heating. Termite additives	External chemical heating.Chemical oven
Synthesis from elements	$(\mathrm{W} + \mathrm{C}) + (Ti + C) \rightarrow \mathrm{WC} + \mathrm{TiC}$	$[Ti + B \rightarrow TiB_2] + [\mathrm{B} + \mathrm{C} \rightarrow \mathrm{B_4C}]$ $[Ti + C \rightarrow TiC] + [\mathrm{Nb} + \mathrm{C} \rightarrow \mathrm{NbC}]$
Synthesis from alloys	Gasless synthesis	
	$(FeTi + FeB) + (Ti + FeSi_2) \rightarrow \mathrm{TiB_2} + \mathrm{Ti_5Si_3} + \mathrm{Fe}$	$[Fe{-}Ti + C \rightarrow TiC + Fe]$ $[\mathrm{FeTi} + \mathrm{FeB} \rightarrow \mathrm{TiB_2} + \mathrm{Fe}]$ $(Ti + FeSi_2) \rightarrow Ti_5Si_3 + Fe$ $[\mathrm{FeNb} + \mathrm{FeB} \rightarrow \mathrm{NbB_2} + \mathrm{Fe}]$
	Filtration synthesis	
	$Fe{-}Ti + \mathrm{FeMn} + \mathrm{N_2} \rightarrow \mathrm{TiN} + \mathrm{Mn_4N} + \mathrm{Fe}$	$[FeSi_2 + N_2 \rightarrow Si_3N_4 + Fe] + [\mathrm{FeCr} + \mathrm{N_2} \rightarrow \mathrm{CrN} + \mathrm{Fe}]$

Composition in the chemical oven is displayed by italic font

nitrogen-containing alloying compositions in the conditions of filtration combustion. It allows to synthesize compositions with various level of nitrogen concentration and with possibility to vary within the wide range content of other components.

Gasless synthesis. The new method of internal chemical oven was successfully applied also during realization of the gasless variant of the metallurgical SHS process for fabrication of composite boron-containing alloying compositions [38]. In this case it allowed to implement combustion synthesis in the mixtures with alloys having low boron concentration. Calcium hydride titanium powder of PTM-1 grade in accordance with TU 14-22-57-92, ferroboron powder obtained from FB20 alloy in accordance with GOST 14848-69 and containing 21.4 % of boron with dispersity less than 0.05 mm, as well as aluminium powder of ASD-1 grade in accordance with TU 1791-99-019-98 were used. Introduction of 5–15 % Al in charge leads to increase of combustion rate. Such growth is eventually caused by additional heat release during forming of Fe and Ti aluminides. In this case, such reactions play the role of termite additives.

4. Chemical oven

Filtration synthesis. The scheme of nitriding of low carbon ferrochromium in a chemical oven is the same as presented in the **Fig. 8**. Powder of low carbon ferrochromium (powder No. 1) is placed inside a powder on the base of ferrosilicon of FS75 grade with 76.5 % Si (powder No. 1). Nitriding of such complex material was carried out in the pilot-industrial SHS reactor with useful volume 0.15 m^3. Powder of low carbon ferrochromium, which was nitrided in such chemical oven, contained 8.5 % of nitrogen. Nitrided ferrosilicon was synthesized in parallel way with nitrided low carbon ferrochromium. Both alloys can be sources of nitrogen during melting of various steel grades. The first alloy is recommended for melting of mainly nitrogen-containing stainless steels, while the second alloy – for transformer and other silicon-containing steels. In order to obtain an alloying composition with high nitrogen content, influence of additive of nitrided ferrochromium powder in the initial low carbon ferrochromium powder was examined. Relationship between nitriding degree of low carbon ferrochromium powder and amount of diluting nitrided low carbon ferrochromium powder, containing 8.5 % of nitrogen, in the initial mixture is displayed in the **Fig. 9**. It can be seen that higher content of nitrided ferrochromium powder in the initial charge leads to rise of nitrogen amount in combustion products. However, similar to other variants of nitriding process activation for low carbon ferrochromium in the conditions of filtration combustion, nitrogen concentration in finished materials is rather smaller than its maximal possible content (~16.8 % N).

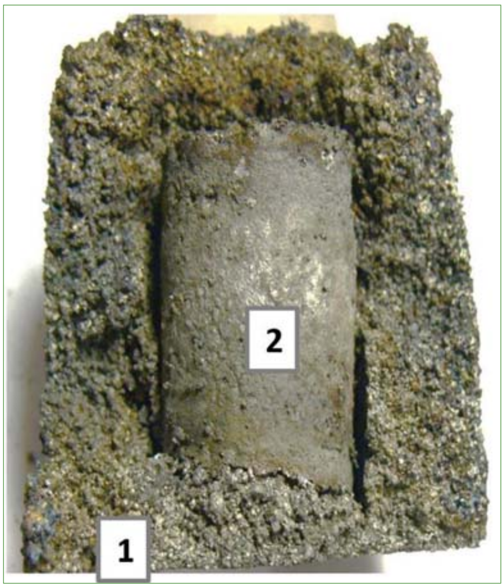

Fig. 8. Synthesis in the chemical oven: 1 – combustion products of the donor charge; 2 – combustion products of the acceptor charge

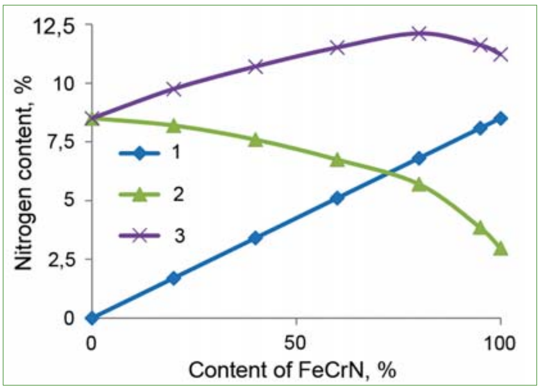

Fig. 9. Influence of diluting degree of low carbon ferrochromium by nitrided ferrochromium on nitrogen content in combustion products: 1 – nitrogen content in the initial mixture; 2 – nitrogen amount, absorbed during combustion; 3 – total nitrogen amount in the samples after combustion

Gasless synthesis. External chemical oven is used during metallurgical SHS synthesis in the case of incompatibility of combustion products of a donor mixture with synthesized metallic acceptors. The chemical oven was used for obtaining boride-based compositions during combustion synthesis with use of ferroalloys. Commercial ferroboron grades contain 15–20 % of boron. Thereby thermal effect in the mixtures with ferroboron is low and it is difficult to realize the process in self-sustaining mode. Synthesis of (TiB_2 + Fe) composition was successfully implemented using ferroboron (21.4 % B) and ferrotitanium (70.6 % Ti) powders. These powders had equal dispersity (– 0.05 mm), while atomic relationship Ti/B in an exothermic mixture was equal to 0.5. The mixture of titanium and silicon powders was used as an exothermic mixture in chemical oven.

Conclusion

Thus, low exothermicity of synthesis reactions for composite ferroalloys is not an obstacle for conduction of these reactions in combustion mode. Well-known and new stimulating methods for combustion synthesis allow to expand essentially the range of synthesized materials. Such technological methods as recovery oh thermal energy, mechanical activation of exothermic charge in an electric furnace, chemical heating of SHS charge by termite additives and use of chemical oven provide involvement of new raw materials with lower exothermicity in the SHS process and allow to carry out the process in more soft conditions.

This study was supported by the Tomsk State University Development Program (Priority-2030)

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