

SELF-PROPAGATING HIGH-TEMPERATURE SYNTHESIS

The Synthesis of Cast Materials Based on the MAX Phases in a Cr–Ti–Al–C System

V. A. Gorshkov^{a, *}, N. Yu. Khomenko^{a, **}, and D. Yu. Kovalev^{a, ***}

^a Merzhanov Institute of Structural Macrokinetics and Materials Science, Russian Academy of Sciences,
Chernogolovka, Moscow oblast, 142432 Russia

*e-mail: gorsh@ism.ac.ru

**e-mail: natashayrievna@gmail.com

***e-mail: kovalev@ism.ac.ru

Received May 22, 2020; revised December 18, 2020; accepted December 23, 2020

Abstract—Two variants of the self-propagating high-temperature synthesis (SHS) process, namely, SHS from elements and SHS metallurgy, are combined to obtain cast materials based on the Cr₂AlC and (Cr_{0.7}Ti_{0.3})₂AlC MAX phases. The experiments involve mixtures with the compositions calculated according to the chemical scheme 70% (Cr₂O₃ + 3Al + C)/(2Ti + Al + C) + 30% (3CaO₂ + 2Al). The synthesis is carried out in a 3-L reactor at a pressure of argon of 5 MPa. The structure and phase composition of the reaction product are studied by X-ray diffraction and scanning electron microscopy. It is found during the research that the ratio of the initial reagents has a substantial effect on the synthesis parameters and phase composition of the desired products. The possibility of obtaining a cast material based on the titanium-doped Cr₂AlC phase is shown. It is found that the product is a composite material based on the (Cr_{1-x}Ti_x)₂AlC ($x = 0.18–0.28$) phase, the concentration of which is 43–62 wt % depending on the initial ratio of the reagents. The microstructure of the material is characterized by the presence of laminate layers with the inclusions of carbide grains. The end product contains carbide (Ti_{0.9}Cr_{0.1}C, Cr₇C₃, Cr₃C₂) and intermetallic (Al₈Cr₅, AlTi₃) impurities, which is determined by the insufficient lifetime of the melt formed in the combustion wave.

Keywords: SHS metallurgy, MAX phase, Cr–Ti–Al–C system, microstructure, composite material

DOI: 10.3103/S1067821221060092

INTRODUCTION

Ternary carbides Cr₂AlC and Ti₂AlC are the representatives of the family of MAX phases with the formula M_{n+1}AX_n, where M is a transition *d* metal, A is an element from Groups IIIA–VIA (Al, Si, Ge, etc.), and X is carbon or nitrogen ($n = 1–5$). MAX phases are characterized by hexagonal close packing *P6/mmc* and have a layered crystal structure, in which the [M_{n+1}X_n] carbide or nitride blocks are spaced by the monolayers of elements from Groups IIIA–VIA. The interest in such compounds is determined by a special combination of physicochemical properties associated with the layering at the level of the crystal structure. The materials based on MAX phases possess a high potential for use in industrial sectors because they have a unique combination of the characteristic features of both metals and ceramics [1, 2] and are promising for application under the conditions of high temperatures and oxidizing environments. Similar to metals, they are characterized by high electrical and thermal conductivity, are readily processed, and are not sensitive to thermal shocks, while as ceramics they have a low density and a high Young modulus, heat

resistance, and high-temperature strength [3–6]. Currently, over 70 compounds have been obtained which belong to the family of MAX phases, among which Cr₂AlC is the most widely studied after Ti₂AlC, Ti₃AlC₂, and Ti₃SiC₂ [7–9].

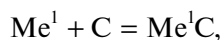
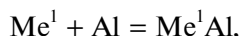
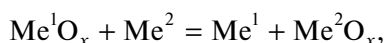
The main preparation methods of Cr₂AlC are the synthesis from elements by hot isostatic pressing (HIP), spark plasma sintering (SPS), and vacuum pulse discharge sintering; here, Cr₅Al₈, Cr₂Al, and Cr₇C₃, as well as unreacted Cr and C, are present in the composition of the material in addition to the main phase [10–12]. A series of solid solutions of MAX phases with the 211 composition—(Cr_{1-x}Ti_x)₂AlC with $x = 0.05–0.2$ —was obtained from a mixture of the powders of CrC_x, TiC_x, and Al by hot isostatic pressing [13]. It turned out to be impossible to synthesize (Cr_{1-x}Ti_x)₂AlC at $x > 0.2$; secondary carbide phases (Cr₇C₃, Cr₃C₂, TiC) appeared in the composition of the material when increasing the concentration of CrC_x in the initial mixture. MAX phases with the 312 and 413 compositions—(Cr_{2/3}Ti_{1/3})₃AlC₂ and

$(\text{Cr}_{5/8}\text{Ti}_{3/8})_4\text{AlC}_3$ —were obtained by hot isostatic pressing of the powders of the elements at $t = 1500^\circ\text{C}$ for 1 h under a pressure of 30 MPa in an argon flow [14]. The $(\text{Cr}_{2/3}\text{Ti}_{1/3})_3\text{AlC}_2$ formulation showed a high stability. At the same time, it is challenging to synthesize a material that contains the $(\text{Cr}_{1-x}\text{Ti}_x)_{n+1}\text{AlC}_n$ phase only, and the product contains the impurities of carbide (TiC_x , $(\text{TiCr})\text{C}_x$, CrC_x) and intermetallic phases of the Ti–Al–Cr system.

According to the thermodynamic calculations [15], the regions of existence of the solid solutions Ti_2AlC – Cr_2AlC are extremely limited. In [16], attempts were undertaken to synthesize MAX phases with the 211 and 312 compositions using reactive sintering of the powders of Cr, TiH_2 , Al, and graphite. It was noted that both the replacement of titanium by chromium in Ti_3AlC_2 and mutual solubility of Ti_2AlC and Cr_2AlC are limited by several atomic percents. The materials contained a significant amount of the TiC and Al–Cr secondary phases.

Therefore, upon obtaining MAX phases in a Cr–Ti–Al–C system by HIP, SPS, and reactive sintering, the end products always contain the impurities of carbide and intermetallic phases.

A promising preparation method of MAX phases is self-propagating high-temperature synthesis (SHS). This technology requires almost no energy expenditures and possesses high productivity and environmental friendliness [17–19]. Ti_2AlC , Ti_3AlC_2 , and Ti_3SiC_2 MAX phases were obtained by SHS from the elements [20–22]. In these works, the authors used the initial mixtures consisting of the powders of titanium, aluminum, carbon, and silicon. One of the technological trends of SHS is SHS metallurgy, which makes it possible to obtain cast materials due to the full melting of the components in the combustion wave. Its characteristic feature consists in the use of the mixtures consisting of metal oxides, a reducing metal (Al or Mg), and carbon, as well as high-energy additives, e.g., $\text{CaO}_2 + \text{Al}$. The process is based on the occurrence of the following exothermic reactions:



where Me^1 is an early transition metal and Me^2 is Al or Mg.

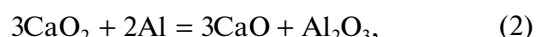
SHS metallurgy was applied for the first time for the synthesis of the Cr_2AlC MAX phase in [23]. At a certain ratio of the reagents, the combustion temperature exceeds the melting point of the initial reagents and end products. As a result, the product is formed in the liquid state in the combustion wave. The separa-

tion of the heavy metal-like and light oxide phases of the formed products occurs under the action of gravity due to the different specific gravities [23–25]. Initial mixtures consisting of chromium(VI) and chromium(III) oxides with aluminum and carbon were used in these works. It was shown that the key synthesis parameter determining the composition of the end products is the lifetime of the melt, which depends on the combustion temperature of the initial mixture. In [26], mixtures based on chemically coupled chemical reactions were used for the synthesis of the Cr_2AlC cast phase: weakly exothermic $\text{Cr}_2\text{O}_3 + 3\text{Al} + \text{C}$ (a heat acceptor) and strongly exothermic $3\text{CaO}_2 + 2\text{Al}$ (a heat donor). It was found that the maximum concentration of the Cr_2AlC phase of 66% is achieved at the concentration of the $3\text{CaO}_2 + 2\text{Al}$ additive in the initial charge of 30%.

The aim of this study was to determine the possibility of obtaining a titanium-doped Cr_2AlC phase upon combining two processes, namely, SHS from elements and SHS metallurgy.

MATERIALS AND EXPERIMENTAL PROCEDURE

Powders of analytical grade chromium oxide Cr_2O_3 (Pervoural'skoe PO Khrompik) and chemically pure grade calcium oxide CaO_2 (NPK Reaktiv, Novosibirsk), as well as aluminum of the ASD-1 brand (Vologradskaya aluminievaya kompaniya), PTM titanium (AO POLEMA, Tula), and MPG graphite (OOO Grafit-resurs, Chelyabinsk oblast) with a particle size smaller than 100 μm , were used as the initial components. The ratios of the components of the initial mixtures were calculated using the following chemical reactions:



A charge corresponding to schemes (1) and (2) was used as the base charge, the composition of which 70% ($\text{Cr}_2\text{O}_3 + 3\text{Al} + \text{C}$) + 30% ($3\text{CaO}_2 + 2\text{Al}$) was tested in [26]. This mixture is combustible in the steady-state mode. After the passage of the combustion wave, the material is in the liquid-phase state, which leads to the separation of the product to two layers, namely, a lower metal-like layer and an upper oxide layer, due to the different specific gravities.

To obtain a titanium-doped Cr_2AlC phase, a mixture composed by Eq. (3) was added to the base composition. The weight ratios between mixtures ($\text{Cr}_2\text{O}_3 + 3\text{Al} + \text{C}$) (1) and ($2\text{Ti} + \text{Al} + \text{C}$) (3) were varied, while the concentration of high-energy component ($3\text{CaO}_2 + 2\text{Al}$) (2) was constant of 30% of the weight of the charge (Table 1). The charge was prepared in a plane-

Table 1. Composition of the initial mixtures and synthesis parameters

No. of the composition	Fractions of the mixtures according to Eqs. (1), (2), and (3)	Calculated composition of the ingot	U_c , cm/s	η^1 , %	η^2 , %
1	0.7(1) + 0.3(2)	Cr_2AlC	0.60	34	8
2	0.7[0.85(1) + 0.15(3)] + 0.3(2)	$(\text{Cr}_{0.85}\text{Ti}_{0.15})_2\text{AlC}$	0.76	49	9
3	0.7[0.7(1) + 0.30(3)] + 0.3(2)	$(\text{Cr}_{0.7}\text{Ti}_{0.3})_2\text{AlC}$	0.65	46	7

tary mixer. The ready-to-use mixture with a weight of 20 g was placed into a quartz container with a diameter of 20 mm and a height of 50 mm. The synthesis processes were performed in a 3-L SHS reactor (Fig. 1) at an initial pressure of argon of 5 MPa.

The reaction was initiated using a tungsten spiral. The combustion rate was determined by the formula

$$U_c = h/\tau,$$

where h is the height of the powder filling; τ is the burn-up time of the sample, which was determined using a stopwatch and a video camera by the average value from three experiments.

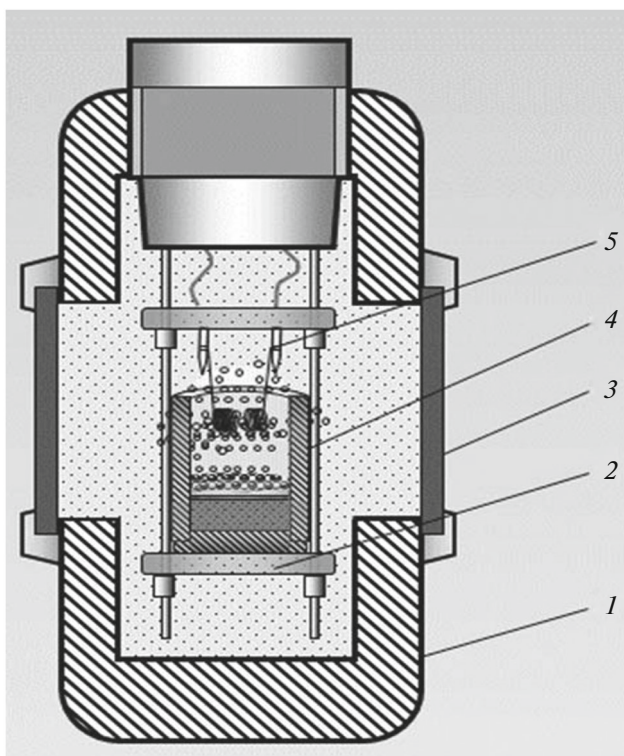


Fig. 1. SHS reactor diagram: (1) a body, (2) a base, (3) inspection windows, (4) a quartz mold with the mixture, and (5) an initiating spiral.

The following quantities were used to evaluate the synthesis parameters:

(i) the ingot yield of the product

$$\eta^1 = M_{\text{ing}}/M_{\text{mix}} \times 100\%,$$

(ii) the weight loss due to the dispersion of the components upon combustion

$$\eta^2 = (M_{\text{mix}} - M_{\text{end}})/M_{\text{mix}} \times 100\%,$$

where M_{ing} is the weight of the ingot, M_{mix} is the weight of the initial mixture, and M_{end} is the total weight of the product after combustion.

The X-ray diffraction analysis (XRD) was performed on a DRON-3 diffractometer with a graphite monochromator on a secondary beam (a CuK_α radiation). The X-ray diffraction patterns were recorded in the mode of step-by-step scanning in a range of angles $2\theta = 12^\circ - 100^\circ$ in increments of 0.02° and with the exposure of 4 s in a point. The quantitative analysis was performed by the Rietveld method in the PDWin software package (NPP Burevestnik, Russia). The structural data of the identified phases presented in the Crystallography Open Database [27] were used as the initial model for the refinement. The profile parameters of the reflections, background, unit cell parameters, and percentage of the phases were refined.

The weighted divergence factor calculated during the refinement, which takes into account the background, was within a range of $R_{\text{wp}} = 8 - 12\%$ for all the samples. A method of internal standard, in the capacity of which silicon (NIST SRM 640b) was used, was utilized for the precision determination of the unit cell parameters. The study of the microstructure and elemental analysis of the samples were performed on an Ultra plus ultra-high-resolution field-emission scanning electron microscope based on Ultra 55 (Carl Zeiss, Germany).

RESULTS AND DISCUSSION

The XRD data for the ingot (Fig. 2) formed upon the combustion of the base charge showed that the product included the Cr_2AlC , Cr_7C_3 , and Cr_5Al_8

phases (Table 2). Upon adding mixture 3 to the charge, synthesis parameters such as combustion rate U_c and weight loss η^2 insignificantly change (Table 1). However, the ingot yield of the desired product η^1 increases by 30% for the formulations with compositions 2 and 3 in comparison with the base mixture.

The phase composition of the ingots formed after the combustion of mixtures 2 and 3 is characterized by the presence of more than five compounds (Fig. 3, Table 2). A comparison with the ICDD PDF2 powder diffraction database showed that the angular position of the reflections of one of the phases corresponded to Ti_2AlC . The positions of the diffraction lines of the second MAX phase are close to Cr_2AlC ; however, they are displaced towards smaller angles; i.e., its unit cell parameters are greater when compared to Cr_2AlC .

The fragment of the X-ray diffraction patterns in a region of angles $2\theta = 52.5^\circ - 58.0^\circ$, which shows the angular displacement of the 106 reflection of the MAX phases, is presented in Fig. 4. It can be assumed that this displacement is induced by the isomorphous replacement of some Cr atoms by Ti atoms in the cell. It is known that doping of the Cr_2AlC phase with titanium leads to an increase in its unit cell parameters [13] as a result of the difference in the atomic radii of titanium (2.0 Å) and chromium (1.85 Å).

The fraction of titanium in the $(Cr_{1-x}Ti_x)_2AlC$ phase obtained upon the combustion of compositions 2 and 3 was evaluated based on the linear approximation of the dependence of the unit cell volume of Cr_2AlC [28], Ti_2AlC [29], and $(Cr_{1-x}Ti_x)_2AlC$ [13] on the composition (Fig. 5) and data of this work (Table 3). It turned out that the replacement of 18–28 at % Cr by titanium occurs depending on the initial composition of the mixture.

The microstructure of the ingot fracture (composition 3) and elemental analysis of the structural components confirm the presence of an MAX phase (Fig. 6). A layered structure characteristic for the

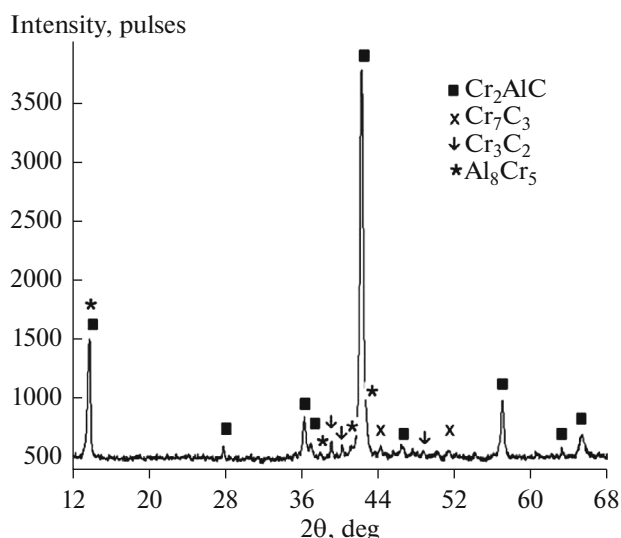


Fig. 2. X-ray diffraction pattern of the material obtained upon the combustion of the base mixture with composition 1.

MAX phases is observed on the fracture, in the bulk of which roundish carbide and intermetallic grains are located. The composition of the layered phase calculated by points 4–7 determines $x = 0.29$ and formula $(Cr_{0.71}Ti_{0.29})_2AlC_{0.97}$, which is similar to the value of $x = 0.28$ obtained based on the data on the unit cell metric (see Table 3).

The results of these studies show that, upon adding mixture 3 to the base charge, the combustion rate and weight loss insignificantly change; however, an increase in the ingot yield of the desired product is observed. This is associated with the fact that mixture 3 does not contain an oxide phase and consists of the elements (Ti, Al, and C) that migrate into the ingot in the composition of the compounds. Apparently, the presented scheme of reactions (1)–(3), based on which the equi-

Table 2. Phase composition of the synthesis products

Phase	Syngony, space group	ICDD PDF2 card	Composition of the mixture, wt %		
			1	2	3
Cr_2AlC	$P6_3/mmc$	29-0017	66.0	–	–
$(Cr_{1-x}Ti_x)_2AlC$	$P6_3/mmc$	–	–	62.1	42.9
Ti_2AlC	$P6_3/mmc$	29-0095	–	5.6	12.2
$Ti_yCr_{1-y}C$	$Fm3m$	70-2903	–	5.6	10.0
Cr_7C_3	$Pmcm$	36-1482	8.1	0.2	6.0
Cr_3C_2	$Pnam$	35-0804	8.2	–	–
Al_8Cr_5	$R3m$	71-0140	17.7	26.5	8.4
AlTi	$P4/mmm$	65-5414	–	–	3.9
C	$P6_3/mmc$	41-1487	–	–	16.6

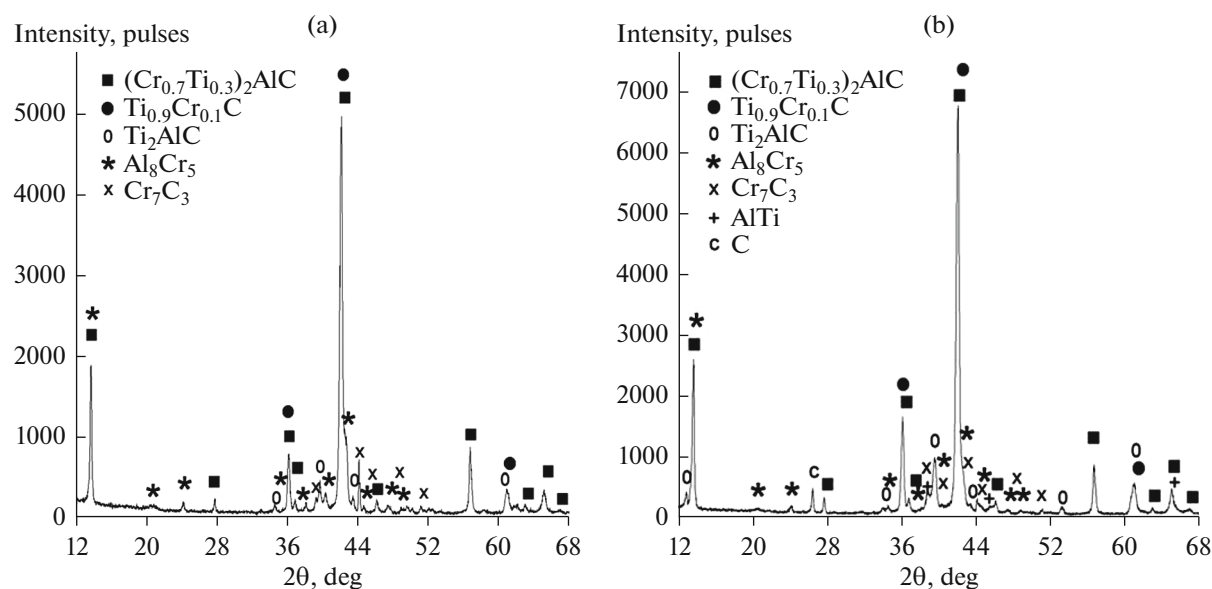


Fig. 3. X-ray diffraction patterns of the materials obtained upon the combustion of the mixtures with compositions (a) 2 and (b) 3.

librium composition of the desired MAX phase was calculated, will not reflect all the interactions that actually occur in the multiphase system during SHS. Indeed, XRD of the synthesized material showed that

its phase composition substantially differed from the calculated composition. This gives the evidence of the fact that the processes occurring in the liquid phase being formed in the combustion wave and upon its fast crystallization lead to the formation of a nonequilibrium composition of the product.

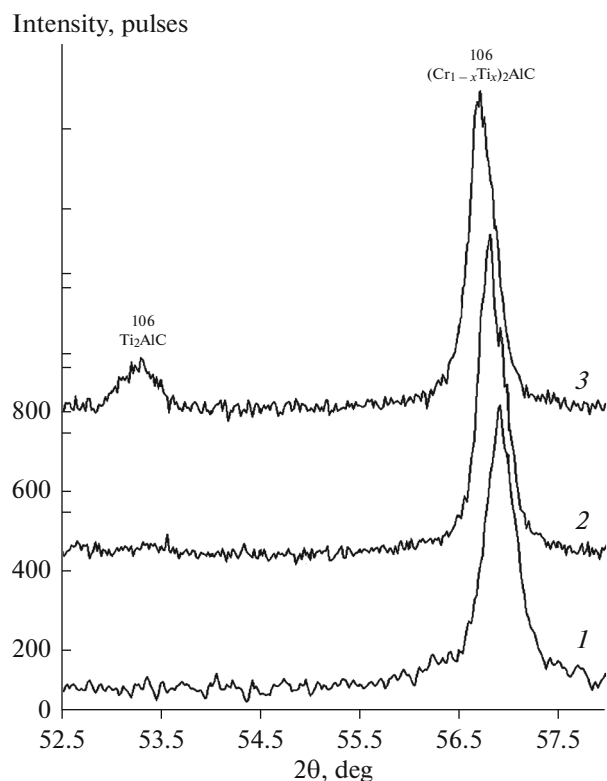


Fig. 4. Fragments of the X-ray diffraction patterns with the 106 reflection of the $(\text{Cr}_{1-x}\text{Ti}_x)_2\text{AlC}$ MAX phases with compositions 1–3.

Let us consider the characteristic features of the synthesis of solid solutions Cr_2AlC – Ti_2AlC upon combining the technologies of SHS from elements and SHS metallurgy. In the first case, the process is based on the metal (Ti, Mo, Ta, etc.) + nonmetal (C, B, N) reactions when the adiabatic combustion tem-

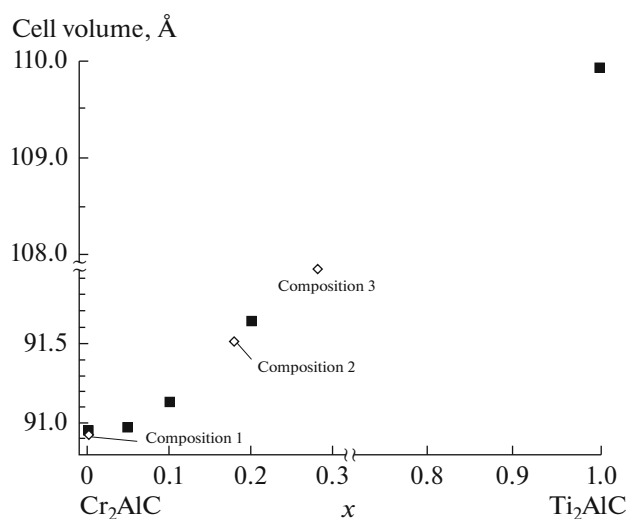


Fig. 5. Unit cell volume of Cr_2AlC , Ti_2AlC , and $(\text{Cr}_{1-x}\text{Ti}_x)_2\text{AlC}$ depending on the atomic fraction of Ti based on the data of [13, 28, 29] and results of this work.

Table 3. Unit cell parameters of the MAX phases in a Cr₂AlC–Ti₂AlC system

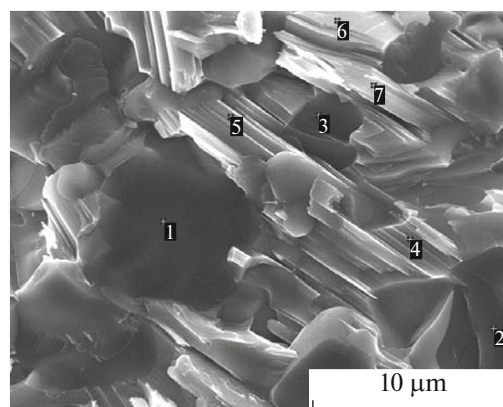
Atomic fraction of Ti <i>x</i>	Phase	Cell parameters			Ref.
		<i>a</i> , Å	<i>c</i> , Å	<i>V</i> , Å ³	
0	Ti ₂ AlC	3.051	13.637	109.93	[29]
0	Cr ₂ AlC	2.863	12.814	90.96	[28]
0.05	(Cr _{0.95} Ti _{0.05}) ₂ AlC	2.862	12.825	90.98	[13]
0.1	(Cr _{0.9} Ti _{0.1}) ₂ AlC	2.864	12.829	91.13	
0.2	(Cr _{0.8} Ti _{0.2}) ₂ AlC	2.869	12.855	91.64	
0	Cr ₂ AlC (Composition 1)	2.8606(8)	12.8314(9)	90.9(4)	This work
0.18	(Cr _{1-x} Ti _x) ₂ AlC (Composition 2)	2.8685(4)	12.8421(6)	91.5(1)	This work
0.28	(Cr _{1-x} Ti _x) ₂ AlC (Composition 3)	2.8705(8)	12.886(8)	91.9(5)	This work

perature does not exceed the melting point of the interaction products, i.e., the products are in the condensed state in the combustion wave. In the second case, the SHS metallurgy process is based on the oxidation–reduction reactions of the thermite type ($\text{Me}_1\text{O}_x + \text{Me}_2$). The main chemical transformations occur in the liquid phase, being formed upon the passage of the combustion wave. The key parameter affecting the formation of the MAX phases in SHS metallurgy is the lifetime of the melt, which depends on the heat release of the thermite reaction and synthesis parameters such as the weight of the mixture and heat removal [23–25].

Introducing a 2Ti + Al + C elemental mixture with $T_{\text{ad}} = 2468$ K [30] into a 70% (Cr₂O₃ + 3Al + C) + 30% (3CaO₂ + 2Al) base mixture with $T_{\text{ad}} = 2820$ K [26] leads to a decrease in the combustion temperature of the mixtures with compositions 2 and 3. As a result, the lifetime and time of homogenization of the melt decrease.

One common mechanism of formation of the MAX phases during SHS is when the highest temperature carbide phases are formed at the first stage of the process and then dissolve in the surrounding intermetallic melt, followed by the crystallization of the ternary compounds $\text{M}_{n+1}\text{AX}_n$ [20–22]. As a result of the decrease in the combustion temperature, carbides (TiCr)C, Cr₇C₃, and Cr₃C₂ do not fully dissolve in the surrounding melt Al–Cr–Ti, and a certain amount of Al₈Cr₅ and AlTi₃ intermetallic phases is present in the composition of the synthesized material (see Table 2). For composition 3 with the largest amount of the 2Ti + Al + C mixture, the decrease in the adiabatic combustion temperature is maximum and, as a result, seven phases including unreacted graphite have been found in the product.

The analysis of the results of works [13, 14] on the synthesis of MAX phases in a Cr–Ti–Al–C system showed that the end products obtained by powder metallurgy also contained the impurities of carbide (TiC_x, TiCrC_x, and CrC_x) and intermetallic (Al₈Cr₅ and AlTi) phases.



Spectrum	Concentration, wt %				Total
	C	Al	Ti	Cr	
1	18.2	0.4	63.9	17.5	100
2	0.3	45.7	0.3	53.7	100
3	18.7	0.2	63.7	17.4	100
4	8.5	19.3	20.5	51.7	100
5	8.6	19.9	20.1	51.4	100
6	7.9	18.7	19.6	53.8	100
7	8.1	18.9	20.6	52.4	100

Fig. 6. Microstructure of the ingot fracture and composition of the structural components of the material obtained upon the combustion of mixture 3.

The authors of [15] showed, based on thermodynamic calculations, that the regions of existence of solid solutions in a $Ti_2AlC-Cr_2AlC$ system are extremely limited. Close to the side of Ti_2AlC , the maximum concentration of Cr in the phase of the solid solution $(Ti_{1-x}Cr_x)_2AlC$ is $x = 0.07$ at $t = 1600^\circ C$, and it drops with decreasing temperature almost down to zero at $450^\circ C$. Close to the Cr_2AlC phase, the maximum concentration of Ti in the solid solution $(Cr_{1-x}Ti_x)_2AlC$ at $t = 1600^\circ C$ is $x = 0.055$. As a result, according to [15], the existence of the $(Cr_{1-x}Ti_x)_2AlC$ equilibrium phase is impossible throughout the entire range of compositions x .

A two-phase region including individual Ti_2AlC and Cr_2AlC ternary phases is more thermodynamically favorable. At the same time, the experimental results of [13, 31] and data obtained by us evidence the possibility of formation of a titanium-doped Cr_2AlC phase containing up to 30 at % Ti.

CONCLUSIONS

A study of the phase composition of the combustion products of 70% $(Cr_2O_3 + 3Al + C)/(2Ti + Al + C) + 30\%$ $(3CaO_2 + 2Al)$ mixtures upon combining the processes of SHS from elements and SHS metallurgy has shown the possibility of obtaining a cast material based on a titanium-doped Cr_2AlC phase. The concentration of $(Cr_{1-x}Ti_x)_2AlC$ in the product is 43–62%, and the fraction of doping Ti that replaces Cr is 0.18–0.28%.

The microstructure of the material is characterized by the presence of laminate layers with the inclusions of carbide grains. The maximum concentration of the titanium-doped MAX phase (62%) has been obtained upon using 15% $(2Ti + Al + C)$ in the base mixture, which corresponds to composition 2 (see Table 1).

Upon increasing the fraction of the elemental mixture in the charge, twofold the adiabatic combustion temperature decreases, which leads to a decrease in the lifetime of the melt. As a result, for composition 3, which contains 30% $(2Ti + Al + C)$, the combustion product includes a significant amount of undesired phases—intermetallics, carbides, and graphite.

REFERENCES

- Barsoum, M.W., *MAX Phases. Properties of Machinable Ternary Carbides and Nitrides*, Weinheim: Wiley VCH, 2013.
- Hettinger, J.D., Lofland, S.E., Finkel, P., Meehan, T., Palma, J., Harrell, K., Gupta, S., Ganguly, A., El-Raghy, T., and Barsoum, M.W., Electrical transport, thermal transport, and elastic properties of M_2AlC ($M = Ti, Cr, Nb$, and V), *Phys. Rev. B*, 2005, vol. 72, pp. 115–120.
- Barsoum, M.W. and Radovic, M., Elastic and mechanical properties of the MAX phases, *Annu. Rev. Mater. Res.*, 2011, vol. 41, pp. 195–227.
- Radovic, M. and Barsoum, M.W., MAX phases: Bridging the gap between metals and ceramics, *Am. Ceram. Soc. Bull.*, 2013, vol. 92, no. 3, pp. 20–27.
- Poon, B., Ponson, L., Zhao, J., and Ravichandran, G., Damage accumulation and hysteretic behavior of MAX phase materials, *J. Mech. Phys. Solids*, 2011, vol. 59, pp. 2238–2257.
- Md. Atikur Rahman and Md. Zahidur Rahaman, Study on structural, electronic, optical and mechanical properties of MAX phase compounds and applications review article, *Am. J. Mod. Phys.*, 2015, vol. 4, no. 2, pp. 75–91.
- Tian, W.B., Wang, P.L., Zhang, G., Kan, Y., Li, Y., and Yan, D., Synthesis and thermal and electrical properties of bulk Cr_2AlC , *Scr. Mater.*, 2006, vol. 54, pp. 841–846.
- Lin, Z., Zhou, Y., and Li, M., Synthesis, microstructure, and property of Cr_2AlC , *J. Mater. Sci. Technol.*, 2007, vol. 23, no. 6, pp. 721–746.
- Schneider, J.M., Sun, Z., Mertens, R., Uestel, F., and Ahuja, R., Ab-Initio calculations and experimental determination of the structure of Cr_2AlC , *Solid State Commun.*, 2004, vol. 130, pp. 445–449.
- Tian, W., Vanmeensel, K., Wang, P., Zhang, G., Li, Y., Vleugels, J., and Biest, O., Synthesis and characterization of Cr_2AlC ceramics prepared by spark plasma sintering, *Mater. Lett.*, 2007, vol. 61, pp. 4442–4445.
- Tian, W., Sun, Z., Du, Y., and Hashimoto, H., Synthesis reactions of Cr_2AlC from $Cr-Al_4C_3-C$ by pulse discharge sintering, *Mater. Lett.*, 2008, vol. 62, pp. 3852–3855.
<https://doi.org/10.1016/j.matlet.2008.05.001>
- Tian, W., Wang, P., Kana, Y., Zhang, G., Li, Y., and Yan, D., Phase formation sequence of Cr_2AlC ceramics starting from Cr-Al-C powders, *Mater. Sci. Eng., A*, 2007, vol. 443, pp. 229–234.
<https://doi.org/10.1016/j.msea.2006.08.064>
- Kim, C., Hwang, S., Ha, J., Kang, S., and Cheong, D., Synthesis of a $Cr_2AlC-Ti_2AlC$ ternary carbide, *J. Ceram. Process. Res.*, 2010, vol. 11, no. 1, pp. 82–85.
- Zhimou Liu, Liya Zheng, Luchao Sun, Yuhai Qian, Jingyang Wang, and Meishuan Li, $(Cr_{2/3}Ti_{1/3})_3AlC_2$ and $(Cr_{5/8}Ti_{3/8})_4AlC_3$: New MAX-phase compounds in Ti–Cr–Al–C system, *J. Am. Ceram. Soc.*, 2013, vol. 97, no. 1, pp. 1–3.
<https://doi.org/10.1111/jace.12731>
- Duong, T.C., Talapatra, A., Son, W., Radovic, M., and Arróyave, R., On the stochastic phase stability of $Ti_2AlC-Cr_2AlC$, *Sci. Rep.*, 2017, vol. 7, p. 5138.
<https://doi.org/10.1038/s41598-017-05463-1>
- Horlait, D., Grasso, S., Al Nasiri, N., Burr, P.A., and Lee, W.E., Synthesis and oxidation testing of MAX phase composites in the Cr–Ti–Al–C quaternary system, *J. Am. Ceram. Soc.*, 2016, vol. 99, no. 2, pp. 682–690.
<https://doi.org/10.1111/jace.13962>
- Merzhanov, A.G., SHS on the pathway to industrialization, *Int. J. Self-Propag. High-Temp. Synth.*, 2001, vol. 10, no. 2, p. 237.

18. Merzhanov, A.G., The chemistry of self-propagating high-temperature synthesis, *J. Mater. Chem.*, 2004, vol. 12, pp. 1779–1786.
19. Levashov, E.A., Mukasyan, A.S., Rogachev, A.S., and Shtansky, D.V., Self-propagating high-temperature synthesis of advanced materials and coatings, *Int. Mater. Rev.*, 2017, vol. 62, no. 4, pp. 203–239.
<https://doi.org/10.1080/09506608.2016.1243291>
20. Łopacinski, M., Puszynski, J., and Lis, J., Synthesis of ternary titanium aluminum carbides using self-propagating high-temperature synthesis technique, *J. Am. Ceram. Soc.*, 2001, vol. 84, no. 12, pp. 3051–3053.
<https://doi.org/10.1111/j.1151-2916.2001.tb01138.x>
21. Chun-Cheng Zhu, Jia Zhu, Hua Wu, and Hong Lin, Synthesis of Ti_3AlC_2 by SHS and thermodynamic calculation based on first principles, *Rare Met.*, 2015, vol. 34, no. 2, pp. 107–110.
<https://doi.org/10.1007/s12598-013-0174-2>
22. Konovalikhin, S.V., Kovalev, D.Yu., Sytschev, A.E., Vadchenko, S.G., and Shchukin, A.S., Formation of nanolaminate structures in the Ti-Si-C system: A crystallochemical study, *Int. J. Self-Propag. High-Temp. Synth.*, 2014, vol. 23, no. 4, pp. 217–221.
<https://doi.org/10.3103/S1061386214040049>
23. Gorshkov, V.A., Miloserdov, P.A., Luginina, M.A., Sachkova, N.V., and Belikova, A.F., High-temperature synthesis of a cast material with a maximum content of the MAX phase Cr_2AlC , *Inorg. Mater.*, 2017, vol. 53, no. 3, pp. 271–277.
<https://doi.org/10.1134/S0020168517030062>
24. Gorshkov, V.A., Miloserdov, P.A., Sachkova, N.V., Luginina, M.A., and Yuhvid, V.I., SHS Metallurgy of Cr_2AlC MAX phase-based cast materials, *Russ. J. Non-Ferrous Met.*, 2018, vol. 59, no. 5, pp. 570–575.
25. Gorshkov, V.A., Miloserdov, P.A., Karpov, A.V., Shchukin, A.S., and Sytschev, A.E., Investigation of the composition and properties of a Cr_2AlC MAX phase-based material prepared by metallothermic SHS, *Phys. Met. Metallogr.*, 2019, vol. 120, no. 5, pp. 471–475.
<https://doi.org/10.1134/S0031918X19050041>
26. Gorshkov, V.A., Miloserdov, P.A., Khomenko, N.Yu., and Sachkova, N.V., Production of cast materials based on Cr_2AlC MAX phase by SHS metallurgy using coupled chemical reaction, *Russ. J. Non-Ferrous Met.*, 2020, vol. 61, no. 3, pp. 362–367.
<https://doi.org/10.3103/S1067821220030086>
27. Crystallography Open Database. <http://www.crystallography.net/cod>.
28. Barsoum, M.W. and El-Raghy, T., Synthesis and characterization of a remarkable ceramic: Ti_3SiC_2 , *J. Am. Ceram. Soc.*, 1996, vol. 79, pp. 1953–1956.
<https://doi.org/10.1111/j.1151-2916.1996.tb08018.x>
29. Lee, D.B. and Nguyen, T.D., Cyclic oxidation of Cr_2AlC between 1000 and 1300°C in air, *J. Alloys Compd.*, 2008, vol. 464, pp. 434–439.
<https://doi.org/10.1016/j.jallcom.2007.10.018>
30. Ying, G.B., He, X., Du, S., Zheng, Y., Zhu, C., Wu, Y., and Wang, C., Kinetics and numerical simulation of self-propagating high-temperature synthesis in Ti–Cr–Al–C systems, *Rare Met.*, 2014, vol. 33, no. 5, pp. 527–533.
31. Schuster, J.C., Nowotny, H., and Vaccaro, C., The ternary systems: $CrAlC$, $VAlC$, and $TiAlC$ and the behavior of H-phases (M_2AlC), *J. Solid State Chem.*, 1980, vol. 32, no. 2, pp. 213–219.
[https://doi.org/10.1016/0022-4596\(80\)90569-1](https://doi.org/10.1016/0022-4596(80)90569-1)

Translated by E. Boltukhina