New method of obtaining heat-resistant biomorphic composites with carbide reinforcement

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Abstract
In this work, an original method of obtaining biomorphic composites of the Me — MeCx type, consisting of several stages, has been proposed. One of the steps is the Infiltration through Nonreactive Solvent (INS) method, which consists in converting biomorphic carbon preforms into porous microchannel MeCx ceramics by transferring a carbide-forming element to carbon through a solvent that does not react with carbon. The interaction of biomorphic alder-based carbon templates with melts of Cu — Ti and Sn — Ti systems has been investigated. It has been shown that as a result of the interaction of biocarbon templates with Cu-10Ti and Cu-20Ti alloys, carbon walls turn into TiC grains of micron and nanometer sizes, which partially repeat the template microstructure. The mechanism of formation of such a structure has been proposed. It has been demonstrated that, upon the interaction with Sn — Ti system, TiC and Ti2SnC layers are formed on the surface of the microchannels with good preservation of the initial template structure.

1. Introduction
The development of new heat-resistant materials is one of the main directions of modern materials science. Such materials are in demand in many industries. However, the most difficult problem is to increase the working temperatures and improve the efficiency of gas turbine engines, in particular by increasing the working temperatures of turbine blades. The main requirements for the materials used in their manufacture are high strength, creep resistance, and phase stability at temperatures above 1300 — 1400 °C, combined with good crack resistance at room temperature and low material density [1, 2].

There are three main types of heat-resistant materials, which are considered promising: composites with a metal matrix (MMCs), composites with a ceramic matrix (CMCs), and high-entropy alloys (HEAs). At the same time, blades made of MMCs are used in almost all existing engines. High characteristics of heat-resistant materials of this type are provided by their complex composite structure consisting of a viscous matrix based on a solid metal solution and a hardening phase, which is the elongated grains of intermetallic compounds, carbides, silicides, and other high-strength refractory compounds. At present, nickel alloys continue to be the most widespread material for the manufacture of blades. However, their operating temperatures are close to the theoretical limit, and their further increase is impossible [2]. Materials based on Nb — Si, Nb — Al, Mo — Si — B, and many other systems are being actively investigated [1 — 8].

There are many types of metal-matrix composites obtained by various methods. However, the method of directed crystallization by the lost-wax model is mainly used today for the manufacture of real products. This method allows manufacturing blades of a given shape, practically requiring no
finishing. In this case, due to directed crystallization, the material structure contains uniformly distributed elongated inclusions of the strengthening phase in the metal matrix (eutectic structure), which ensure high operational characteristics of the blades [1, 2, 8]. With all the advantages of this technology, when changing the composition of melted alloys, additional work on determination of the optimal crystallization rates is required. The transition to other systems of elements causes search for new materials for the manufacture of crucibles that are resistant to melt effect, and due to high melting points and duration of the crystallization process, this is a separate difficult task. The lack of suitable crucibles is one of the main reasons limiting the preparation of promising heat-resistant composites of the Me – MeCₙ type, where Me is a refractory metal (Nb, Hf, Ta, W, Ti, Zr, V, Cr), and MeCₙ is its carbides. Hence, researchers are trying to use other methods of manufacturing such composites, in particular, layered composites obtained by diffusion welding, fiber-reinforced composites obtained by powder metallurgy, SHS, additive technologies, and others. Each of them, however, has its drawbacks, in particular, the presence of pores, non-uniform distribution of the hardening phase, low phase stability at high temperatures, high manufacturing costs, and many other factors that impede the widespread use of the materials obtained. In this regard, the search for new approaches to obtaining heat-resistant materials of this type is an urgent task.

2. Biomorphic Me – MeCₙ composites. Method of obtaining.

This article proposes a new method of obtaining Me – MeCₙ composites, consisting of several stages:

Stage 1 – obtaining a microchannel biomorphic carbon template.

Biomorphic carbon templates are obtained by pyrolysis of wood in an oxygen-free atmosphere to high temperatures [9, 10]. As a result, a porous carbon material is obtained that preserves the microchannel structure of wood. The specific parameters of this material (diameter and length of channels, total density, etc.) are determined by the choice of an initial species (figure 1). In addition to choosing a species, the structure of biomorphic materials can also be affected by prepressing of wood [11], which allows varying the characteristics of the materials obtained in an even wider range. An important feature of biomorphic materials is the ability to shape the final product at the stage of soft carbon preform, which enables minimizing the cost of subsequent processing.

![Figure 1. Microstructure of carbon template: a) birch; b) pine.](image)

Stage 2 – obtaining a microchannel biomorphic MeCₙ template.

The next task is to convert a biocarbon template into a microchannel template made of refractory metal carbide, and the treatment should not significantly disrupt the initial structure of the material. This problem can be solved by several methods, for example, CVD, PVD, sol-gel techniques [12, 13]. Such methods, however, have a number of disadvantages, in particular, low productivity, high requirements for equipment and reagents, and the difficulty of obtaining large-size samples.

As a result, in this paper, it is proposed to use the Infiltration through Nonreactive Solvent (INS) method, which needs to be described in more detail.

The main idea of this method coincides with the idea of the LMTA (liquid metal transfer agent) method and consists in using a melt that does not react with carbon as an agent for transporting a carbide-forming element to carbon [14]. The LMTA method is commonly used for coating carbon
fibers that are placed in a bath with a melt, i.e., the process of carbide formation occurs along the entire surface of the fiber at a constant concentration of the carbide forming element.

Infiltration into a microchannel preform is noticeably different, which can be shown by the example of the interaction of a biocarbon preform with S+Me melt, where S is an inert to carbon solvent, Me is a carbide forming element. Upon contact of the preform with the melt, it will begin to penetrate into the microchannels, but Me will be spent on the formation of MeCx compound. Since the solvent does not form compounds with carbon and does not wet it, the infiltration process will slow down and will be determined by the rate of Me diffusion from the melt to the infiltration front. Due to this, Me carbide will gradually grow on the carbon surface, which will accurately preserve the wood structure (figure 2).

![Figure 2. Diagram of biomorphic carbon template infiltration.](image)

The main advantage of the method is that the process can be carried out at sufficiently low temperatures (800 – 1200 C). This greatly simplifies the selection of crucible materials, allows using long curing time and carrying out the process in inexpensive furnaces with metal or ceramic heaters, which removes restrictions on the size and shape of the resulting samples or details.

The second most important advantage is that the proposed scheme is universal, and in this way it is possible to obtain carbides of various (including refractory) elements for which suitable solvents exist.

The solvent must satisfy several requirements:
1. The solubility of carbon in the solvent melt should be small so that the microchannel structure of the biocarbon template is not destroyed.
2. The solvent cannot form stable carbides.
3. The solubility of the carbide-forming element in the melt should be sufficiently large at temperatures up to ~ 1100 – 1200 °C. This requirement is not critical. However, the higher the concentration of a carbide-forming element in the melt, the faster it will diffuse through the melt into the template. The solubility of refractory elements can be increased by increasing the melt temperature; however, the solubility of carbon also increases. In addition, with increasing temperature, the requirements for equipment increase.

When the melt interacts with carbon, the system becomes at least three-component; therefore, additional requirements arise.
4. The addition of a carbide-forming element to the solvent should not lead to a significant increase in the solubility of carbon in the melt.

5. The alloy of a solvent with a refractory element must not react with the carbide of this element

Based on paragraphs 1 – 2, one can propose several possible types of solvents:

Firstly, these are melts of some elements with a low melting point, such as Ag, Au, Bi, Cu, Ga, Ge, In, Pb, Sb, Sn, Zn. Taking into account paragraph 3, for almost all refractory metals, several possible solvents can be selected, which are presented in table 1, although there are difficulties with molybdenum and tantalum.

Secondly, these are melts of salts, in particular fluorides and chlorides, which weakly react with carbon. This method is a modification of the MSS (molten salt synthesis) process, where molten salts are usually used as a medium for the obtainment of complex oxides. It has already been used in a number of works, and biomorphic SiC and ZrC ceramics were obtained in this way [15, 16]. An
additional advantage of using salts is that they dissolve in water, which simplifies the extraction of the melt from the microchannels after the process is carried out.

Table 1. Refractory metals solvents.

| Metal | Solvent                  |
|-------|--------------------------|
| Ti    | Cu (70 % at 1100 °C), Sb, Sn |
| V     | Ga (35 % at 1100 °C), Ge  |
| Cr    | Sb (45 % at 1100 °C), Ge, Ga |
| Zr    | Cu (75 % at 1100 °C), Ag  |
| Nb    | In (40 % at 1100 °C), Sb  |
| Mo    | Ga, Ge (~5 % at 1100 °C) |
| Hf    | Cu (45 % at 1100 °C)     |
| Ta    | Au (15 % at 1100 °C)     |

Probably, some multicomponent solvents can also be considered, for example, Ni – Pd, Cu – Sn, and other alloys. However, an increase in the number of components significantly complicates the process and analysis of the results obtained.

The proposed solvents satisfy paragraphs 1 – 3. The fulfillment of requirements 4 and 5 is much more difficult to predict in advance since an analysis of phase diagrams with three or more components that are often not built yet is required. Moreover, the situation is complicated by the fact that, firstly, the alloy changes its composition depending on the depth of penetration into the sample along the channel axis due to depletion of the refractory element on carbide formation. Secondly, carbides of refractory elements have a rather large region of homogeneity, and the ratio of an element to carbon can vary widely. All this can affect the processes of chemical interaction of carbide and a melt. As an example, we can cite the data from [17], where it was shown that the stability of TiC_x (where x vary from 0.5 to 1) in (Cu, Sn, Ag, Au) – Ti melts depends not only on titanium content in the melt, but also on the value of x.

Stage 3 – filling microchannels with metal and obtaining Me – MeC_x composites.

The main advantage of biomorphic carbide template is their microchannel structure. Provided that the carbide is wetted, the melt will quickly fill the preform under the action of capillary forces. This significantly reduces the duration of the process, lowers the requirements for crucible materials and equipment, and also allows using crucible-free methods.

As a result of the infiltration, a biomorphic composite will be obtained, where the hardening phase is a continuous carbide skeleton. In the view of mechanical characteristics, such a structure is not optimal, since cracks can propagate through the entire bulk of the sample. In this regard, it is necessary to divide the skeleton into separate fibers to obtain a classic fiber-reinforced MMC. To achieve this, deformation and/or heat treatment, electron-beam floating zone melting, or combinations of these methods can be used.

This concept is at an early stage of development, and many possible problems may arise during its implementation. However, there are several main advantages that make this method promising.

Advantages of the method of obtaining composites.
1. A wide range of possible Me – MeC_x systems.
2. The possibility of controlling the size and volume fraction of the hardening phase by selecting the source species.
3. Low requirements for crucible materials. The possibility of using crucible-free methods.
4. The possibility of manufacturing large-size products of a complex shape.
5. Minimum porosity of the material

3. Experimental.

To create composites according to the scheme above, it is necessary to obtain biomorphic carbide templates, for which purpose the interaction of biocarbon templates with Cu – Ti and Sn – Ti melts
was studied in this work. The phase diagrams of these systems are shown in figure 3. Alder wood (Alnus incana) was used as an initial material. Large wood samples were pyrolyzed in the self-generated atmosphere of wood decomposition products in a semihermetic reactor, separated from the exterior atmosphere by a water seal (temperature of 900 °C, heating rate of 5 °C/h to 500 °C and 100 °C/h to 900 °C). The obtained samples were additionally annealed in vacuum at 1450 °C for 30 minutes to completely decompose the organic components. The density of the obtained preforms was measured. Then, samples for microscopic investigations (cleavages along the characteristic wood planes), as well as samples with sizes of ~ 6×6×23 mm, elongated in the direction of wood growth, were made from the preforms for the further examination.

**Figure 3.** Phase diagrams: a) Sn – Ti; b) Cu – Ti. [18, 19]

Cu – Ti and Sn – Ti alloys were prepared by alloying from pure components (Ti – 99.9, Sn – 99.9, Cu – 99.8) in vacuum in a graphite crucible at 1300 and 1200 °C, respectively. The content of the elements varied from 10 to 70 at. % for Cu – Ti system and was 30 at. % for Sn – Ti system.

An alloy sample was placed on the bottom of a graphite crucible with an inner diameter of 10 mm to carry out the INS process. A biocarbon perform additionally loaded with a graphite weight with a mass of ~ 5 g was placed onto the sample. For short exposures (several hours), the process was carried out in a vacuum induction furnace, for long processes (several days) the process was carried out in evacuated and sealed quartz ampoules in a resistive furnace with a metal heater. The process parameters are described in more detail in Table 2. After the process was carried out, the samples were cut along the long side, polished, and examined using scanning electron microscopy (Tescan Vega II XMU, Carl Zeiss SUPRA 50 VP) and X-ray diffraction (Siemens D500, Cu Kα).

**Table 2.** Samples and experiments description.

| Alloy   | Titanium concentration (at. %) | Temperature (°C) | Duration of the INS process (h) |
|---------|--------------------------------|------------------|---------------------------------|
| Cu-70Ti | 70                             | 1150             | 17                              |
| Cu-10Ti | 10                             | 1150             | 108                             |
| Cu-20Ti | 20                             | 1150             | 108                             |
| Cu-30Ti | 30                             | 1150             | 108                             |
| Sn-1150 | 30                             | 1150             | 4                               |
| Sn-1000 | 30                             | 1000             | 72                              |
| Sn-900  | 30                             | 900              | 72                              |
| Sn-800  | 30                             | 800              | 72                              |
It should be noted that in a number of experiments, gas emission was observed during the interaction of biocarbon templates with alloys. This was particularly true for Cu – Ti system, which is probably related to the reduction of Cu₂O present in the melt by the carbon of the preform and crucible. Due to the fact that the crucible had an inner diameter of 10 mm, the resulting bubbles could not always leave the melt, and in some cases they combined into a large bubble, which separated the infiltrated sample from the main alloy bulk. This impeded the uniformity of infiltration, and made it difficult to determine the kinetics of the process. The characteristic infiltration rates for alloys with titanium content of 30 at. % or less were ~ 5 – 10 mm/day. However, in view of the above, the infiltration kinetics will not be considered in this paper in detail.

4. Results and discussion.

4.1 The structure of biocarbon template.

As a result of pyrolysis, alder samples lost ~ 73 % of the mass and decreased in size. Shrinkages in the axial, tangential and radial directions were 20, 35 and 27 %, respectively. The resulting density was 0.36 g/cm³. Simple calculation can show that upon the complete conversion of carbon into TiC of stoichiometric composition, the resulting volume fraction of the material will be 36 %, which is close to the optimal content of the hardening phase.

The microstructure of bioC is demonstrated in figure 4. In the microstructure, vessels with a large (~ 50 µm) diameter, libriforms with a small (~ 10 µm) diameter, elongated along the growth axis, and rays directed in the radial direction can be distinguished. The characteristic thickness of the cell walls is 3 – 5 µm. A large number of pores are also present in the cell walls. Pores bind all the microchannels to each other, which should ensure an effective infiltration of the melt into the entire bulk of the sample during the INS process.

Figure 4. Microstructure of alder-based carbon template: a) axial; b) tangential; c) radial.

4.2 Cu – Ti system

The microstructure of the samples after the interaction with Cu – Ti alloys, shown in figure 5, depended significantly on titanium content. At a concentration of 70 at. %, an active reaction of the sample with the melt occurred, its shape was not preserved, and large pores with sizes up to several millimeters were present in the structure. An initial microchannel structure was preserved neither, and after cooling, the sample consisted of large grains of titanium carbide with sizes of ~ 10⁰ – 10¹ µm in a copper alloy matrix.

With a decrease in the titanium concentration to 20 at. % or lower, the samples retained a macroscopic directional structure close to the microchannel structure of wood. However, the solid walls were divided into separate well-faceted grains with sizes from hundreds of nanometers to several microns. The presence of grains of a submicron size with a high total surface energy is a rather unexpected fact, since holding times were several days at 1150 °C, i.e., the conditions for recrystallization processes seem to be suitable, especially taking into account the presence of a contact between the grains and the liquid phase. A similar structure was observed in the central part of the
samples after the interaction with Cu-30Ti alloys; however, grains with sizes of ~$10^0$ – $10^1$ µm were mainly present in the outer layer bordering the melt.

![Figure 5](image)

**Figure 5.** Microstructure of samples after reaction with Cu-Ti alloys: a) Cu-70Ti; b, c) Cu-10Ti; d) Cu-20Ti.

Probable explanation of the formation of such structures in this system is the features of thermodynamic equilibrium in Cu – Ti – C system.

The authors were unable to find a triple diagram of Cu – Ti – C system. However, it can be assumed that the solubility of carbon in Cu-70Ti melt is high, and the melt wets carbon well. Upon the contact of the melt with the biocarbon template, under the action of capillary forces, the microchannels are rapidly filled up, which is accompanied by dissolution of the cell walls. Due to high solubility of carbon in the melt, dissolution-crystallization of titanium carbide grains is actively taking place, which leads to an increase in their size.

The following model can be proposed to explain the formation of submicron TiC particles and maintain the texture. At low Ti concentrations in Cu, biocarbon does not dissolve in the melt, but turns into TiC, while the melt is depleted in titanium, and the infiltration front is shifted deeper into the sample. As the infiltration front moves forward, the regions being closer to the melt are enriched with titanium due to diffusion and, according to [17], TiC – Cu-Ti system is out of the local thermodynamic equilibrium. Stoichiometric titanium carbide begins to be depleted in carbon, and this process occurs by dissolving TiC in the melt, followed by precipitation of TiC$_x$, where $x < 1$. As a result, fragmentation of the walls occurs, and due to the fact that their initial thickness is small, the sizes of the formed grains have micron and submicron sizes. Considering that it is energetically more profitable for TiC$_x$ grains to crystallize on a substrate, the fragmented walls remain connected for some time. Preservation of submicron grains during long exposures is probably related to the fact that after the formation of TiC$_x$ with the minimum carbon content and as titanium content in the melt being
In contact with it increases, the system again becomes thermodynamically stable, and the dissolution-crystallization processes significantly slow down. Nevertheless, this issue requires further study.

In the case of the interaction of biocarbon template with Cu-30Ti alloy, at an initial moment of time, the sample carbon actively dissolves in the melt. However, at a certain moment, the melt is saturated with carbon, and the process begins to occur similarly to alloys with low titanium content.

Thus, upon the interaction of bioC with melts of Cu – Ti system with titanium content of 10 to 70 at. % at 1150 °C, microchannel TiC template cannot be obtained. Nevertheless, the results obtained are quite promising from a practical viewpoint as a simple method of obtaining porous ceramics with nanoscopic grain size, as well as submicron-size TiC powders, which does not require complex equipment. Low rates of recrystallization of submicron TiC grains in this system are also of interest.

Figure 6. Microstructure of samples after reaction with Sn-Ti alloys: a) Sn-1150; b) Sn-1150, area near the melt/sample border; c) Sn-1150 front of infiltration area; d) Sn-1000 area near the melt/sample border; e, f) Sn-900.
4.3 Sn – Ti system
In Sn – Ti system, experiments were carried out at different temperatures (800 – 1150 °C) and at the same titanium concentration of 30 at. %. Due to the fact that the solubility limit of titanium at temperatures below ~980 °C is less than 30 at. %, in the experiments performed below this temperature, a part of titanium in the melt remained in the form of Ti₅Sn₅ compound.

At figure 6 it is seen that an initial structure of the wood was preserved much better than that in Cu – Ti system. At 1150 °C the cell walls are clearly visible in the region of the infiltration front, although their structure is rather incoherent, and in the channels there are also individual grains, which, according to the X-ray diffraction and EMPA analyzes, are Ti₂SnC compound. In addition, in the region directly bordering the melt, the cell walls were destroyed. Reducing the temperature to 1000 °C prevented the destruction of the cell walls in the region of a contact with the melt; however, the walls are also quite incoherent, and separate grains are present in the channels. At 800 °C, there are no individual grains in the microchannels; however, the carbon walls practically did not react with the melt.

The most interesting is the structure of materials obtained at 900 °C. It is clearly seen that carbon reacted quite actively with the melt, and the walls are a layered structure consisting of a central carbon part coated with a layer of titanium carbide and a dense Ti₂SnC layer at the boundary with the melt in the microchannels.

To explain the mechanisms of formation of such layers, one can use the data of [14], where TiC coatings on carbon fibers were obtained by the LMTA method at 1200 °C using Sn-Ti melt. It was shown that a TiC layer is formed directly on carbon: however, if Ti content in the melt exceeds 2.6 at. %, the Ti₂SnC phase is additionally formed at the boundary with the melt. The mechanism of formation of this phase consists in the diffusion of carbon through a layer of titanium carbide, its dissolution in the melt, followed by precipitation of grains and formation of a Ti₂SnC layer on the TiC surface.

This mechanism allows explaining the structure of the samples obtained at 1000 and 1150 °C, in particular, the presence of Ti₂SnC grains in the microchannels. The porosity of the Ti₂SnC layer can be related to the exposure time and the development of dissolution and recrystallization processes. A decrease in the temperature to 900 °C reduces the solubility of carbon in the melt, as evidenced by the absence of individual grains in the microchannels. In this regard, the mechanism of formation of the Ti₂SnC layer changes and occurs not due to the crystallization from the melt, but due to the interaction of diffusing carbon with tin at the boundary of TiC and later Ti₂SnC.

Thus, carrying out infiltration processes at 900 °C is the most promising, since it allows obtaining melt-resistant microchannel Ti₂SnC materials, which enables for long exposures and, as a result, removes restrictions on the volume of the parts obtained.

5. Conclusion.
In this work, an original method of obtaining biomorphic composites of the Me – Me₅C₅ type, consisting of several stages, has been proposed. One of the steps is the INS method, which consists in converting biomorphic carbon preforms into porous microchannel Me₅C₅ ceramics by transferring a carbide-forming element to carbon through a solvent that does not react with carbon. The interaction of alder-based biomorphic carbon templates with Cu-Ti and Sn-Ti systems, has been investigated. According to the research results, one can conclude that the proposed method of obtaining carbide templates can be used. However, the processes are quite complicated. This is due to a change in the chemical compositions of the alloy and carbide during the process, as well as the possibility of the formation of ternary compounds. These processes, in particular, have led to the formation of micron and nanometer TiC grains as a result of the interaction of biocarbon preforms with Cu-Ti alloys, as well as the formation of TiC and Ti₂SnC layers on the surface of microchannels while interacting with the Sn-Ti system.
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References.
[1] Zhao J C and Westbrook J H 2003 Ultrahigh-temperature materials for jet engines. MRS bulletin 28, 622-630.
[2] Soboyejo W O and Srivatsan T S 2006 Advanced structural materials: properties, design optimization, and applications. CRC press.
[3] Svetlov I L, Karpov M I, Neuman A V and Stroganova T S 2018 Temperature Dependence of the Ultimate Strength of in situ Multicomponent Nb–Si–X (X= Ti, Hf, W, Cr, Al, Mo) Composites. Russian Metallurgy (Metally) 4 348-353.
[4] Bewlay B P, Jackson M R, Subramanian P R and Zhao J C 2003 A review of very-high-temperature Nb-silicide-based composites. Metallurgical and Materials Transactions A 34 2043-2052.
[5] Guan D L, Brooks C R and Liaw P K 2002 Microstructure and mechanical properties of as-cast and aged Nb–15 at.% Al–10 at.% Ti,–25 at.% Ti and–40 at.% Ti alloys. Intermetallics 10 441-458.
[6] Jéhanno P, Heilmaier M, Saage H, Heyse H, Böning M, Kestler H and Schneibel J H 2006 Superplasticity of a multiphase refractory Mo–Si–B alloy. Scripta Materialia 55 525-528.
[7] Korzhov V P, Ershov A E, Stroganova T S and Prokhorov D V 2016 Structure and mechanical properties of a multilayer carbide-hardened niobium composite material fabricated by diffusion welding. Russian Metallurgy (Metally) 4 313-320.
[8] Svetlov I L, Kuzmina N A, Neiman A V, Ishadzhanova I V, Karpov M I, Stroganova T S, Korzhov V P and Vnukov V I 2015 Effect of the rate of solidification on the microstructure, phase composition, and strength of Nb/Nb₄Si₃ in-situ composites. Bulletin of the Russian Academy of Sciences: Physics 79 1146-1150.
[9] Greil P, Lifka T and Kaindl A 1998 Biomorphic cellular silicon carbide ceramics from wood: I. Processing and microstructure. Journal of the European Ceramic Society 18 1961-1973.
[10] Byrne C E and Nagle D C 1991 Carbonization of wood for advanced materials applications Carbon 35 259–266.
[11] Ershov A E and Klassen N V 2015 Control of functional characteristics of biomorphous carbon matrices, SiC-Si-C composites, and SiC-C ceramics by prepressing wood Inorganic Materials: Applied Research 6 79-90.
[12] Vogli E, Sieber H and Greil P 2002 Biomorphic SiC-ceramic prepared by Si-vapor phaseinfiltration of wood Journal of the European Ceramic Society 22 2663-2668.
[13] Sun B, Fan T and Zhang D 2002 Porous TiC ceramics derived from wood template Journal of Porous Materials 9 275-277.
[14] Vincent H, Vincent C, Mentzen B F, Pastor S and Bouix J 1998 Chemical interaction between carbon and titanium dissolved in liquid tin: crystal structure and reactivity of Ti₂SnC with Al. Materials Science and Engineering: A 256 83-91.
[15] Kan X, Ding J, Yu C, Zhu H, Deng C and Li G 2017 Low-temperature fabrication of porous ZrC/C composite material from molten salts. Ceramics International 43 6377-6384.
[16] Ding J, Deng C J, Yuan W J, Zhu H X and Li J 2013 Preparation of porous TiC/C ceramics using wooden template in molten salt media. Advances in applied ceramics 112 131-135.
[17] Fragé N, Froumin N and Dariel M P 2002 Wetting of TiC by non-reactive liquid metals. Acta Materialia 50 237-245.
[18] Phase diagrams of binary metallic systems Vol. 2 Ed. Lyakishev N P 1997 Moscow: Mashinostroenie 337
[19] Phase diagrams of binary metallic systems Vol. 3 Book 2 Ed. Lyakishev N P 2000 Moscow: Mashinostroenie 330