Perspective ceramic composite materials based on aluminum-yttrium binder composition

M S Varfolomeev¹, V S Moiseev¹ and G I Shcherbakova²

¹ Moscow Aviation Institute (National Research University), 121552, Moscow, Russia
² SSC RF “State Research Institute for Chemistry and Technology of Organoelement Compounds”, 105118, Moscow, Russia

E-mail: varfolom2a@yandex.ru

Abstract. The paper presents the studies results of the aluminum-yttrium ceramics, e.g. melting crucible and casting mold, influence on the surface layer defects of cast products made from titanium alloys. As a result of the Ti–Al (4–6%) titanium melt high-temperature interaction with the ceramics material having an aluminum-yttrium composition, no defects were found on the surfaces of the cast products.

1. Introduction
Titanium alloys due to their unique properties, such as high corrosion resistance, low density, high specific strength, are widely used in various industries: aviation and aerospace engineering, shipbuilding and mechanical engineering, energy and chemical industry, in medicine [1-6].

A casting of titanium alloys in ceramic molds according to investment pattern is used for the complex thin-walled casts for important purposes. However, titanium alloys have a high melting point and high reactive capacity to the material of a ceramic mold and a melting crucible. In the process of pouring and cooling, the physicochemical interaction of the melt with gases released from ceramics takes place, as well as during direct contact with its material. As a result, in the cast, a contaminated surface alpha layer is formed, which significantly increases the surface hardness and leads to great difficulties in the machining of titanium casts. In addition, the gas-saturated layer can lead to the crack initiation and propagation, which significantly reduces its operational reliability [7-11].

The high melting point and reactive capacity of titanium alloys lead to their interaction with most refractory materials. This requires the development of fundamentally new ceramic materials that do not interact with the melt at elevated melting and pouring temperatures [12-25].

Recently, expensive refractory oxides of refractory metals (Y₂O₃, ZrO₂, CaZrO₃) and nitrides (AlN, BN) have been used for the manufacture of inert foundry ceramic molds and crucibles, and colloidal silica sols are used as a binder. As a result, having the thermodynamic effect on the metal being avoided, the chemical effect of the silica issued from the binder material remains. The alpha layer thickness on the surface of titanium cast products is 100-500 microns [26-34].

The purpose of this work is the complex designing of a highly heat-resistant ceramic casting mold and a melting crucible that can significantly reduce the alpha-layer on the surface of titanium products.

2. Experimental details
Granular corundum α-Al₂O₃ and an alumoxane binder modified with yttrium compounds [35] were
used as raw materials for the manufacture of ceramic melting crucibles and casting molds.

The melting crucibles were molded using the method of dry-pressing ceramic mass on a hydraulic press. The sintering of crucibles was carried out in a resistance box furnace at a temperature of 1500 °C.

Ceramic casting molds were made by layer-by-layer deposition on a ceramic suspension cluster consisting of an aluminium-binder and dust fused corundum α-Al₂O₃. The calcination of ceramic forms was carried out in an electric furnace at temperature of 1350 °C. The ceramic casting molds centrifuging was carried out using a Ti–Al titanium alloy (4–6%) in vacuum.

The microstructure of the ceramics was studied using an FEI Quanta 250 scanning electron microscope, the elemental composition was determined using Philips SEM505 X-ray elemental microanalysis.

A mapping according to elemental composition using overlapping of elements on a single map was performed on a Tescan Mira LMU scanning electron microscope equipped with an INCA X_MAX-50 Oxford Instruments X-ray energy-dispersive X-ray spectrometer.

The preparation of polished sections for metallographic analysis was carried out on a Tecmet 2000 grinding and polishing machine with an adaptor for automated operation using suspensions having different dispersions.

3. Results and discussion

Fused corundum (α-Al₂O₃) widely used in precision casting as a refractory material has a negative Gibbs free energy relative to titanium dioxide (TiO₂) and can be used to make heat-resistant casting ceramics. Therefore, instead of binder materials containing, after calcination, SiO₂, which are reactive with respect to titanium alloys, an aluminum-sodium binder was used in the work.

In the process of hard firing of ceramics, all organic components are removed, and the binder sinters densely the fused corundum grains, forming mixed oxides: Y₃Al₅O₁₂-α-Al₂O₃ (from the binder material), α-Al₂O₃ (main refractory material) [35]. The high stability of the oxides formed at the melting and pouring temperatures of the melt reduces the likelihood of transferring their oxygen to titanium, thereby improving the surface quality of molded products.

Melting crucibles were made by the method of dry-pressing of the ceramic mass on a hydraulic press. The element-oxane polymers solutions used as binding materials give the ceramic mass a certain plasticity and moldability properties in the process of crucible molding, and in the process of firing them alumina structures modified with refractory yttrium compounds are formed (figure 1).

A mapping according to elemental composition, with the imposition of elements on one map showed that yttrium aluminate, Y₃Al₅O₁₂ issued from the binder material, is evenly distributed along the grain boundaries of corundum, α-Al₂O₃.

The ceramic crucibles manufactured have a high heat resistance and a resistance to thermal cycling and can be used for chemically active titanium alloys melting and casting. Along with the developed technology of manufacturing high-heat-resistant melting crucibles, chemical-resistant ceramic molds were made by layer-by-layer deposition of an aluminum-yttrium slurry and granular fused corundum on a wax model.

Aluminum-yttrium forms were filled with a titanium Ti–Al alloy (4–6%) by a centrifugal method in a vacuum arc furnace (figure 2). The ceramics and cast products surface were examined for the presence of a reaction layer.

After casting and knocking out the titanium cast from ceramic molds using an electron microscope, the microstructure and chemical composition of the contact surface of ceramics (figure 3) were examined, and the cast products were examined for the presence of a reaction layer (figure 4).

The elemental microanalysis of an aluminum-yttrium casting mold shows that there are only chemical elements issued from ceramics: aluminum, yttrium and oxygen in the contact layer (Y₃Al₅O₁₂-α-Al₂O₃ – α-Al₂O₃). The content of the TiO₂ phase in the contact layer of ceramics was not found. This indicates the absence of thermochemical interaction of the metal with the casting mold.

A microanalysis of the contact layer of cast products obtained in an aluminum-yttrium casting mold shows that the surface of titanium cast has a defect-free structure. The sharpness of the border
indicates the high surface quality of the molded product.

**Figure 1.** Appearance, microstructure, elemental composition and mapping of the crucible surface according to elemental composition: red – Y, green – Al.

**Figure 2.** Casting mold, titanium cast and appearance of the contact surface of ceramics after casting.

**Figure 3.** Micrographs and elemental composition of the contact surface of ceramics.
The elemental microanalysis of an aluminum-yttrium casting mold shows that there are only chemical elements issued from ceramics: aluminum, yttrium and oxygen in the contact layer \(Y_3\text{Al}_5\text{O}_{12}\cdot\alpha\text{-Al}_2\text{O}_3\). The content of the TiO\(_2\) phase in the contact layer of ceramics was not found. This indicates the absence of thermochemical interaction of the metal with the casting mold.

![Micrographs of the titanium cast surface contact layer.](image)

**Figure 4.** Micrographs of the titanium cast surface contact layer.

A microanalysis of the contact layer of cast products obtained in an aluminum-yttrium casting mold shows that the surface of titanium cast has a defect-free structure. The sharpness of the border indicates the high surface quality of the molded product.

### 4. Conclusions

The study carried out for improvement of technology of making ceramic crucibles for melting and casting titanium alloys made it possible to obtain heat-resistant aluminum-yttrium crucibles with high performance properties.

The combined use of aluminum-yttrium molds and melting crucibles can significantly improve the surface quality of cast products made from titanium alloys.

### References

[1] Loria E A 2000 *Intermetallics* 8 1339–45
[2] Peters M, Kumpfert J, Ward C H and Leyens C 2003 *Adv. Eng. Mater.* 5(6) 419–27
[3] Hai N, Cheng-mu X and Jia-qi Z 2005 *China Foundry* 2(4) 239–45
[4] Froes F H, Gungor M N and Imam M A 2007 *J. of Metals*. 59(6) 28–31
[5] Clemens H and Mayer S *Adv. Eng. Mater.* 2013 15 191–215
[6] Khorasani A M, Goldberg M, Dooen E H and Littlefair G 2015 *J. of Biomaterials and Tissue Eng.* 5 593–619
[7] Kim M G and Kim Y J 2002 *Materials Transactions* 43(4) 745–50
[8] Sung S Y and Kim Sung Y J 2005 *Materials Science and Eng.* 405 173–7
[9] Barbosa J, Puga H, Ribeiro C S, Teodoro O and Monteiro A C 2006 *J. of Cast Met. Res.* 19(6) 331–8
[10] Ohkubo C, Hosoi T, Ford J P and Watanabe I 2006 *Dental Materials* 22 268–74
[11] Choi B-J, Lee S and Kim Y-J 2014 *J. of Mat. Eng. and Perf.* 23(4) 1415–23
[12] Frueh C, Poirier D R, Maguire M C and Harding R A 1996 *Int. J. Cast. Metal. Res.* 9 233–9
[13] Kuang J P, Harding R A and Campbell J 2000 *Mater. Sci. Tech.* 16 1007–16
[14] Lapin J, Ondruš L and Nazmy M 2002 *Intermetallics* 10 1019–31
[15] Duarte T P, Neto R J, Félix R and Lino F J 2008 *Materials Science Forum* 587–588 157–61
[16] Gomes F, Barbosa J and Ribeiro C S 2008 *Intermetallics* 16 1292–7
[17] Cheng X, Sun X D, Yuan C, Green N R and Withey P A 2012 *Intermetallics* 29 61–9
[18] Ertuan Z, Fantao K, Yanfei C, Ruirun C and Yuyong C 2012 *China Foundry* 9(2) 125–30
[19] Choi B-J, Lee S and Kim Y J 2013 Mat. sc. and Techn. 29(12) 1453–62
[20] Kulakov B A, Dubrovin V K, Karpinskiy A V and Chesnokov A A 2013 Bulletin of the South
Ural State University, Series “Metallurgy” 13(1) 51–5
[21] Gomes F, Barbosa J and Ribeiro C S 2013 Mat. Science Forum. 730–732 769–74
[22] Cheng X, Yuan C, Blackburn S and Withey P A 2015 Metall. Mater. Trans. A. 46 1328–36
[23] Yuan C, Cheng X and Withey P A 2015 Mater. Chem. Phys. 155 205–10
[24] Fan J, Guo J, Wang S, Tian S, Su Y, Liu J and Fu H 2015 Mater. Sci. Tech. 31 1727–34
[25] Chamorro X, Herrero-Dorca N, Rodríguez P P, Andrés U and Azpilgaina Z 2017 J. of Mater.
Proc. Techn. 243 75–81
[26] Kim M G and Kim Y J 2002 Metals and Materials International 8(3) 289–93
[27] Cui R-J, Zhang H-R, Tang X. X, Ma L-M, Zhang H and Gong S K 2011 Trans. Nonferrous
Met. Soc. China 21 2415–20
[28] Lapin J, Gabalcová Z and Pelachová T 2011 Intermetallics 19 396–403
[29] Tetsui T, Kobayashi T, Kishimoto A and Harada H 2012 Intermetallics 20 16–23
[30] Bauristhene A M, Mutombo K and Stumpf W E 2013 The J. of The Southern African Institute of
Mining and Metallurgy 113 357–61
[31] Zhanga H, Tanga X, Zhoua C, Zhanga H and Zhang S 2013 Journal of the European Ceramic
Society 33 925–34
[32] Cheng X, Yuan C, Blackburn S and Withey P A 2014 J. of the Eur. Cer. Soc. 34(12) 3061–8
[33] Wei Y-M, Lu Z-G, Wu G-P and Long X-Q 2016 Rare Met 35(12) 901–8
[34] Jianglei F, Jianxiu L, Shen W, Shuxia T, Hongxia G, Shengyong W, Jingjie G and Xiao W 2017
Sci. Rep. 7 45198
[35] Varfolomeev M S, Moiseev V S, Shcherbakova G I, Krivtsova N S and Yurkov G Yu 2015 Inorganic Materials 51(7) 722–7