PAPER • **OPEN ACCESS**

Titanium beryllide as an alternative to beryllium in nuclear and thermonuclear engineering, capabilities of UMP JSC in the technology development and beryllides products manufacture

To cite this article: Ye Frants *et al* 2022 *J. Phys.: Conf. Ser.* **2155** 012015

Titanium beryllide as an alternative to beryllium in nuclear and thermonuclear engineering, capabilities of UMP JSC in the technology development and beryllides products manufacture

Ye Frants[1], A Borsuk[1], A Vechkutov[1], K Zenkov[1], B Zorin[1], M Kylyshkanov[1], M Podoinikov[1], S Udartsev[1*], P Vladimirov[2], R Gaisin[2]

[1]Ulba Metallurgical Plant JSC, Ust-Kamenogorsk, Republic of Kazakhstan.
[2]Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1 76344 Eggenstein-Leopoldshafen, Germany

[*]E-mail: UdartsevSV@ulba.kz

Abstracts. For many decades, beryllium has been used as a structural element in nuclear installations as a moderator / breeder of fast neutrons. The consequence of neutron irradiation is a significant production of gas products in the form of helium and tritium, which leads to swelling and loss of strength properties of beryllium reflectors. The relatively low melting point of beryllium also imposes restrictions on the high-limit temperature regimes of the reactor core.As an alternative to pure beryllium, it is necessary to consider intermetallic compounds based on it, in particular titanium beryllide. Preliminary studies on the thermal desorption of helium and tritium from titanium beryllide have shown that this material has a much lower retention tendency and a lower release temperature. The higher melting point of titanium beryllide compared to pure beryllium is also an advantageous characteristic.Over the past years, UMP JSC, thanks to its research in this area, has achieved significant success in the development of technology for obtaining intermetallic billets and articles based on titanium and chromium beryllides. As a technology demonstrator, prototypes of structural elements of a helium-cooled blanket breeder module of the projected DEMO reactor were made by order of the Karlsruhe Institute of Technology, Germany.The advantages of titanium beryllide, as well as the success achieved in the production of billets and products from it, open up opportunities for a more extensive study of the nuclear, physical and mechanical properties of this material with the possibility of further use in nuclear technology, including thermonuclear reactors, and in high-temperature instrumentation.

1.Introduction

For many decades beryllium has been used as a structural element in nuclear research reactors as reflector, moderator or neutron multiplier depending on the energy.

During operation gas products as helium and tritium are produced in beryllium according to the known threshold reactions together with the neutron multiplication reaction due to nuclear transformations caused by neutron irradiation:

$^{9}Be + n \rightarrow {}^{8}Be + 2n$ $(E_n > 2.7\ MeV)$

$^{8}Be \rightarrow 2\,{}^{4}He$ $T_{1/2} = 0.067 sec.$

$^{9}Be + n \rightarrow {}^{7}Li + {}^{3}H$ $(E_n > 10.5 MeV)$

$^{7}Li + n \rightarrow {}^{4}He + {}^{3}H + n$

$^{3}H \rightarrow {}^{3}He + \beta^{-}$ $T_{1/2} = 12.5\ years$

$^{9}Be + n \rightarrow {}^{6}He + {}^{3}H$ $(E_n > 0.6\ MeV)$

$^{6}He \rightarrow {}^{6}Li + \beta^{-} + \nu$ $T_{1/2} = 0.808 sec.$

$^{6}Li + n \rightarrow {}^{4}He + {}^{3}H$

The reactions demonstrate that the disappearance of one beryllium atom leads to the appearance of two or three gas atoms.

Depending on the operating conditions (temperature, neutron flux, irradiation time, and reflector freedom degree in the structure) this causes embrittlement, cracking, shape deformation or beryllium reflectorsswelling in nuclear reactors.

As a result, the service life of reflectors turns out to be significantly shorter than the service life of the reactor itself which causes a need to periodically replace reflectors with new ones and dispose of the decommissioned radioactive waste in storage facilities. As a rule the service life of reflectors in reactors is limited by maximum fast neutron fluence of$(1 \div 6)\cdot 10^{22}$n/cm^2.

2. Aadvantages of titanium beryllide over beryllium

Thermal desorption studies carried out earlier established temperature of tritium and helium releasefrom beryllium of various grades. Example, [1]describes studies of tritium releasefrom beryllium of S-65C, S-200F, I-220H grades produced by Materion, USA, as irradiated at 40°C until fast neutron fluence of the order of $1.5\cdot 10^{20}$ n/cm^{2}has beenreached. Fig. 1 showsthat tritiumreleasefrom I-220H grade occurs in the temperature range of 900 to 1200°C (release rate peak value), and from beryllium of S-65C and S-200F grades – in the range of 700-800°C to 1100°C (release rate peak value). It was also determined that in beryllium of S-65C and S-200F grades a significantportion of tritium and helium is releasedonly during melting. Similar results were obtained in [5].

In [2] it was found that in JMTR reactor swelling was about 60% at neutron irradiation of beryllium samples at a temperature of 500°C to reach fast neutron fluence of (E_n> 1 MeV) $4\cdot 10^{20}$ n/cm^2.

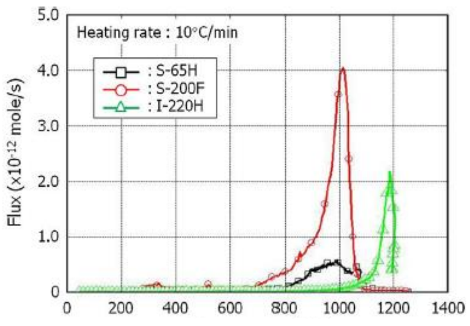

Figure 1. Temperature dependence of tritium releasefrom irradiated beryllium of S-65C, S-200F and I-220H grades [1]

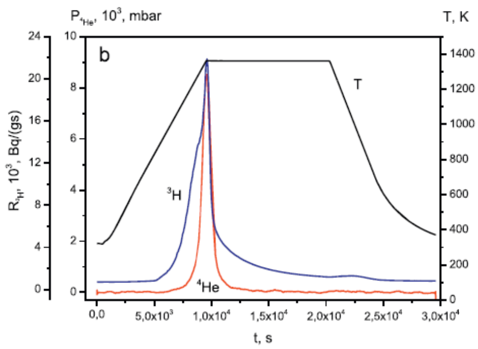

Figure 2. Release of tritium and helium from beryllium after irradiation at 370°C (743K) when heated at a rate of 7K/min.[5]

Journal of Physics: Conference Series **2155** (2022) 012015 doi:10.1088/1742-6596/2155/1/012015

It follows that temperature of release of tritium and helium produced in the process of neutron irradiation from beryllium is much higher than the temperature limit of its operation.

This excludes the possibility of timely removal of tritium and helium from beryllium reflectors during operation and also during hypothetical regeneration of reflectors outside the reactor due to the complete loss of shape and operational properties of blocks during degassing at temperatures which are high for beryllium.

The service life of beryllium reflectors can be increased by the improvement of the stability of their properties at high temperatures, reduction of the release temperature of helium and tritium generated during operation below maximum operating temperature as well as by increasing this limit itself.

All this becomes possible provided that reflectors are manufacturedfrom binary intermetallic compounds - beryllides - rather than from pure beryllium metal.

In recent decades the attention of researchers has mostly been directed to $Be_{12}Ti$ intermetallic compound which has a number of advantages as compared topure beryllium.

In [2, 4] it is demonstrated that titanium beryllide ($Be_{12}Ti$)is characterized by a high melting point (1593°C), lower activability and increased corrosion resistance as compared to pure beryllium. At the same time titanium beryllide has sufficiently higher beryllium content (69.3 wt. %) for effective neutron multiplication/moderation.

Swelling of titanium beryllide ($Be_{12}Ti$) as a result of exposure to neutron irradiation occurs to much less extent than swelling of pure beryllium. Thus, in[3]it was demonstrated that swelling value of titanium beryllide ($Be_{12}Ti$)disks after neutron irradiation at 330, 400 and 500°C to reachneutron fluence of $4{\cdot}10^{20}$ n/cm^2 (E_n> 1 MeV) was 0.8, 1.0 and 0.5%, respectively.

In [6] it was shown that tritium release from titanium beryllide samples irradiated at different temperatures was observed mostly in the temperature range of 600-700°C.

Thermal conductivity of titanium beryllide ($Be_{12}Ti$) was determined on samples as disks (in the direction of their symmetry axis) irradiated in JMTR reactor at a temperature of 330, 400 and 500°C until neutron fluence of $4{\cdot}10^{20}$ n/cm^2 (E_n> 1 MeV) was reached [7]. It was shown that thermal conductivity of nonirradiated titanium beryllide ($Be_{12}Ti$)was 40-48W/m·K up to a temperature of 1000°C. Thermal conductivity of irradiated titanium beryllide ($Be_{12}Ti$)was in the range 28-32W/m·K up to a temperature of 800°C. Thermal conductivity value almost completely recovered to its initial value when heated to 1000°C (Fig. 3).

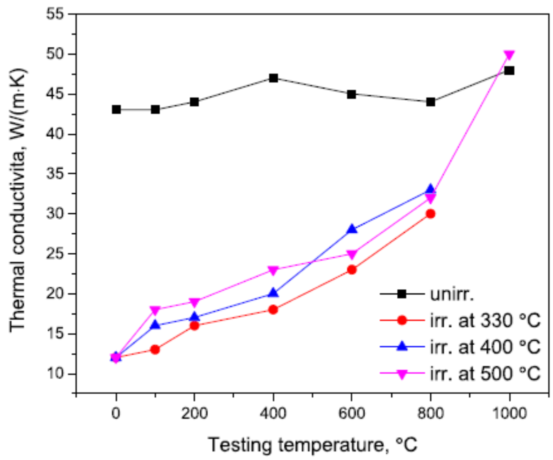

Figure 3. Thermal conductivity of $Be_{12}Ti$ after irradiation at 330, 400 and 500°C to reach neutron fluence of $4{\cdot}10^{20}$ n/cm^2 (E_n> 1MeV) [7]

Studies of thermal desorption from titanium beryllide irradiated by fast neutrons demonstrate that this material has much lower tendency to confinement and lower temperature of gas release. Much lower tendency to the material swelling and the ability to keep thermal conductivity at high operating temperatures are also observed. Higher melting point of titanium beryllide as compared to pure beryllium is also an advantageous characteristic both for high-temperature applications and for annealing outside the reactor in order to restore properties.

The revealed advantages of titanium beryllide ($Be_{12}Ti$)as compared to pure beryllium make it possible to consider it as the material for neutron reflectors/multipliers in nuclear reactors. In this case it is possible not only to increase their long-term resistance under existing conditions but also to use it under conditions of a higher temperature limit of operation as well as more severe neutron fluxes and maximum fast neutrons fluences.

3. UMP JSC capabilities in manufacturing $Be_{12}Ti$ products

UMP JSC has significant experience in the manufacture of beryllium reflectors for various research nuclear reactors. Fig. 4 shows some of the manufactured reflectors.

Figure 4. Beryllium reflectors manufactured at UMP JSC

During the last few years, thanks to its researches on the development of manufacturing process of beryllium based intermetallic compounds UMP JSC achieved significant success in the manufacture of titanium beryllide ($Be_{12}Ti$)structural products [8, 9]. In particular, prototypes of structural elements of heliumcooled blanket module of the projected DEMO reactor were manufactured on request of the Karlsruhe Institute of Technology, Germany, to demonstrate the developed technology. Fig. 5 shows a diagram of a prototype block. Three identical products were manufactured in 2019 and 2020.

Each product represented a regular hexagonal prism of 150mm height with a distance between the planes of 125mm. A through hole of ∅80mm diameter was made in the prism center.

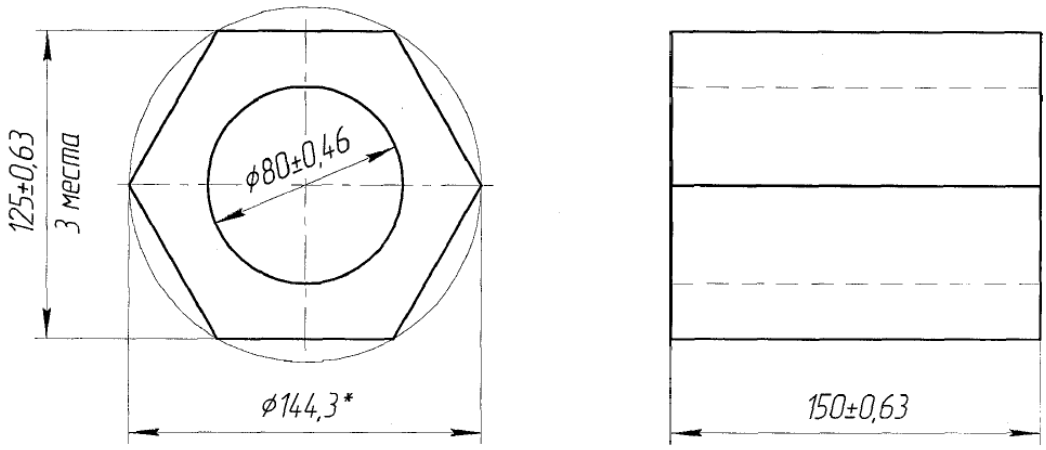

Figure 5. Diagram of the structural element prototype of the blanket module of the projected EU-DEMO fusion reactor

$Be_{12}Ti$ billets of ∅150×170mm size were manufactured according to the technology developed at UMP JSC. Moreover, their density measured by the hydrostatic method was about 2.25g/cm^3 (or 98.7% of theoretical density). Structural defects as cracks and pores were not found.

Billets were machined at the electric-spark machine. At the same time,both a complete product was manufactured to demonstratea block for DEMO fusion reactor and its fragmented copy for thermal cycling testing.

Appearance of billets as manufactured and also at the stage of treatment to the final product is shown in Fig. 6-8.

Figure 6. Appearance of hot-pressed $Be_{12}Ti$ billets

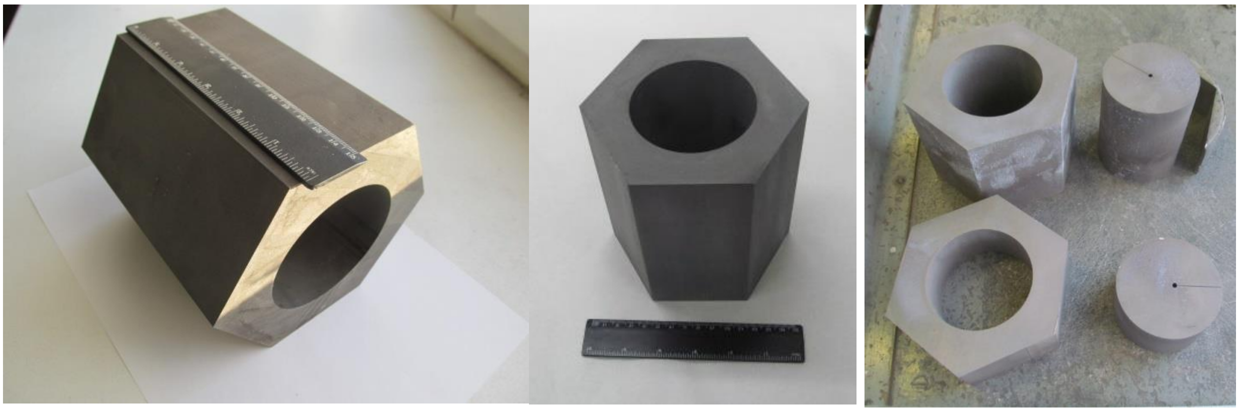

Figure 7. Appearance of $Be_{12}Ti$ products

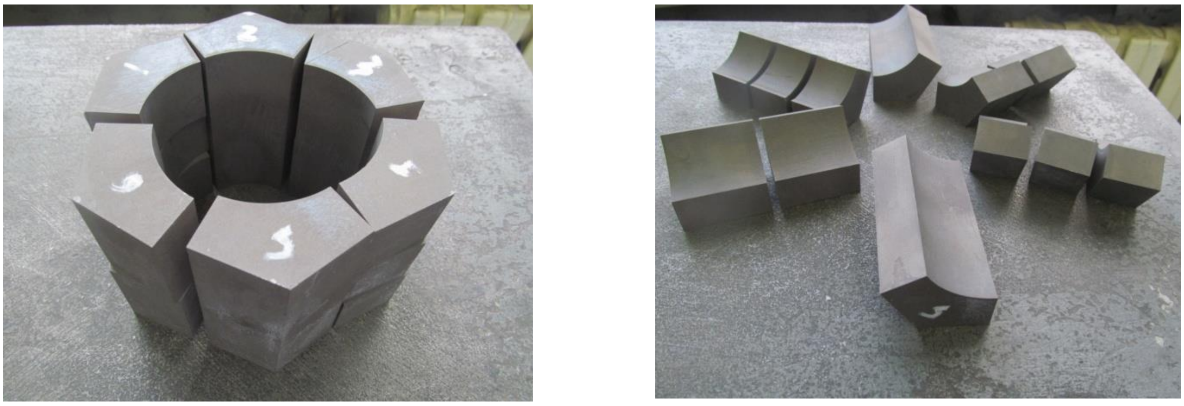

Figure 8. $Be_{12}Ti$ block fragments for thermal cycling testing

X-ray diffraction analysis of titanium beryllide product sample proved a single-phase structure with Be12Ti phase only. Diffractogram is given in Fig. 9.

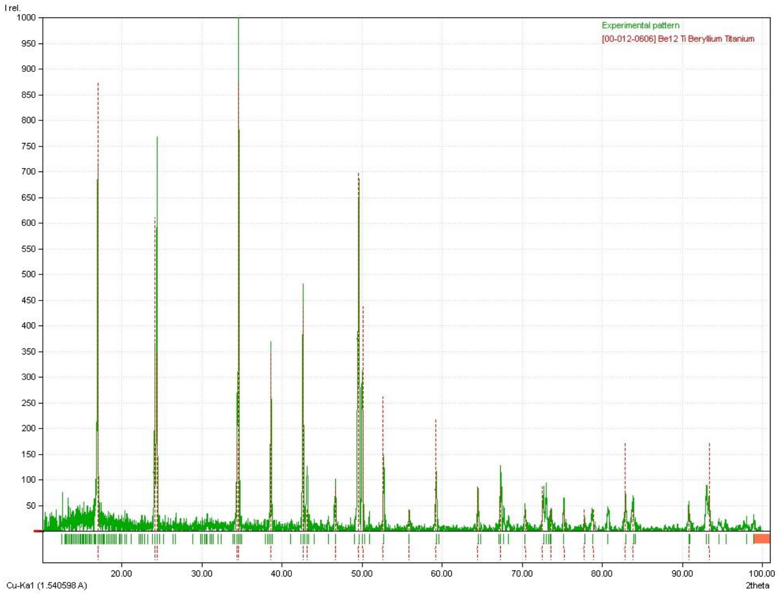

Figure 9. Results of X-ray diffraction analysis of a sample cut from titanium beryllide ($Be_{12}Ti$) billet

Conclusion

The advantages of titanium beryllide as well as successes achieved in the manufacture of titanium beryllide billets and products open up opportunities for a more extensive study of nuclear, physical and mechanical properties of this material with the possibility of further application in nuclear technology including fusion reactors as well as in high-temperature instrumentation.

According to the authors promising researches are those in which reflector elements made of titanium beryllide will be tested in the operating research reactors.

References:

[1] Chekushina L, Dyussambaev D et al 2014 *J. Nucl. Mater.* **452** 41 – 45.
[2] Kawamura H, Takahashi H, Shestakov V et al 2002 *Fus. Eng and Des* **61** 391-397
[3] Uchida M, Ishitsuka E, Kawamura H 2002 *J. Nucl. Mater.* **307-311** 653 – 656.
[4] Nakamichi M et al 2018 *Nucl. Mater. and Ener.* **15** 71-75
[5] Chakin V et al 2015 *Fus. Eng. and Des.* **98-99** 1728-1732
[6] Fedorova A V et al 2016 *Fus. Eng and Des* **102** 74-80
[7] Uchida M, Ishitsuka E, Kawamura H 2003Fus. Eng. Des. **69** 499 – 503.
[8] Gaisin R et al 2020 *Fus. Eng and Des* **161** 111862
[9] Vladimirov P et al 2021 *J. Nucl. Mater.* **543** 152593.