Metal fuel for fast reactors, a new concept

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Choice of the fuel composition is important question to improve the competitiveness of fast reactors. It should have a high density and thermal conductivity, a high concentration of fissile nuclide, and high manufacturability. The best fuel composition of fast reactors remains a metallic nuclear fuel, based on uranium and plutonium alloys. The undeniable advantages of a metal fuel composition is high density of 15-18 g/cm3; high thermal conductivity $\lambda = 30\text{-}40$ W/m·K; the ability to achieve ultra-deep burnup; simplicity of recycling spent nuclear fuel, based on conventional metallurgical methods. Significant disadvantages of metallic fuels are the large gas swelling and the possibility of irradiation growth in the case of injection-molded parts with a pronounced texture, as well as the opportunity to interact with the fuel cladding above 700 C. As a solution to these problems is connected channel creation in the fuel core to output the gas fission products for the entire fuel campaign. It can be realized by creation of open porosity 15-25% of the entire volume of the fuel pellet by applying the methods of powder metallurgy. Due to the deformation of the porous structure of the fuel core reduces the risk of cladding damage, and close contact "fuel-clad" provides minimal thermal contact resistance. Usage of metallic fuel tablet or rods simplifies the fuel element technology and equipment, it makes possible to use fuel elements filled with He gas. The feature of uranium alloys is the difficulty of obtaining compacts by conventional pressing and sintering of powders. Mainly it is associated with high oxidative capacity of uranium powder. We use advance methods for compaction. High-voltage electro-discharge consolidation is based on passing an electric current through the powder compact, with the simultaneous application of pressure. The advantages of this method are the short time of compaction (milliseconds), products with controlled density. Due to the short sintering time consolidation comes with minimal changes in the microstructure (grain growth, recrystallization). Combining technological stages of sintering and pressing has a positive impact on performance. The final density of the product is achieved by selecting parameters such as pressure, voltage, current density.

Uranium alloy, metallic nuclear fuel, electro-discharge sintering.

1. Introduction

As a best candidate for fast reactors (BR) fuel remains metallic nuclear fuel based on uranium and plutonium alloy. The undeniable advantages of a metal fuel include: high density of 15-18 g / cm^3; high thermal conductivity of $\lambda = 30\text{-}40$ W/m·K; the ability to achieve ultra-deep burnup of 20%; ease of recycling of spent nuclear fuel [1,2,3]. At the same time, significant disadvantages of metallic fuels are a significant gas swelling and the possibility of irradiation growth (the so-called axial growth) in the case of injection-molded parts with a pronounced texture [4]. The possible solution of the problem is creation in the fuel open volume or porosity of 15 to 25% to release the gas fissile products (GFP) [4]. This may be realized by applying the methods of casting [4,5,6] or powder metallurgy [8]. The high deformation ability of the porous structure reduces risk of cladding damage, and close contact "fuel-cladding" provides minimal heat contact resistance. The main idea of this concept of a porous metal fuel is displayed in Figure 1, within the structure of the historical development of fuel rods from metal fuel for fast reactors.

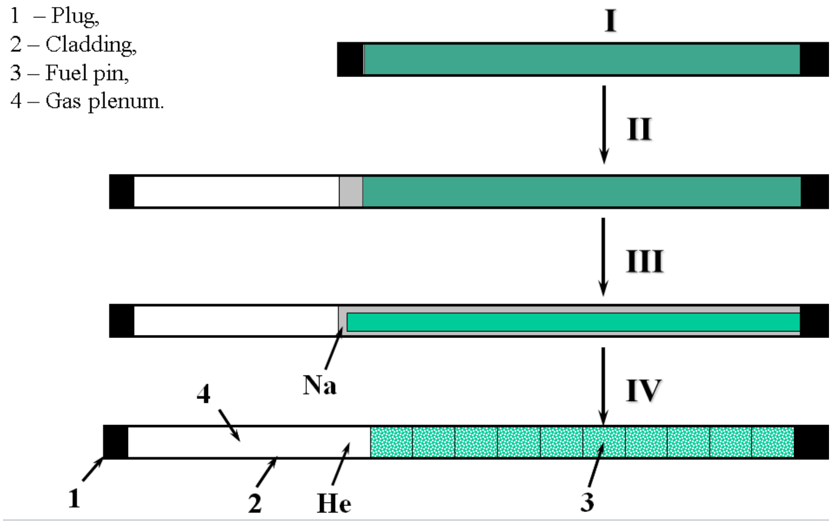

FIG.1. Historical development of fuel rods with metal fuel for fast reactors.

The use of porous metal fuel can improve the operational and technological parameters of the fuel.

Use of porous metallic fuel makes it possible to rejection from the sodium sublayer in fuel rods due to improved fuel pin thermal physics. Preliminary thermophysical calculations show that in the case of a fuel element design with a minimal technologically acceptable gap (taking into account the current level of technology) 0.1 mm, a helium sublayer is possible. It will ensure heat removal in the first weeks of fuel rod operation, after which the metal fuel will come into close contact with the cladding leading to temperature and swelling decrease.

Fuel pin with the porous fuel is, in fact, the object which equilibrium and is no fundamental change in the structure of the fuel, which is characteristic for the pins with cast fuel rods and low "smeared" density.

2. Features of fabrication of powders uranium alloys

The preliminary studies were carried out for producing fuel pellets from uranium alloys via powder metallurgy techniques. The peculiarity of uranium is the difficulty of producing compacts by traditional methods of powder metallurgy, which is associated with high oxidative capacity of the powder [7, 8]. So the advanced method of high-voltage electric pulse compaction (HVEPC) was considered. The method is based on passing an electric current through the powder compact, with the simultaneous application of pressure. The advantages of this method are the short time of compaction (milliseconds), ability to produce products with desired density. The short sintering time leads to minimal changes in the microstructure (grain growth, recrystallization). Combining technological stages of sintering and pressing in one has a expected positive impact on fuel performance. The final density of the product is achieved by selecting parameters such as pressure, voltage, current density.

In the first stage the alloys with Mo and Zr range from 6 to 12 wt.% prepared in an arc furnace. After melting the samples were obtained in the form of round bars. Uranium alloys are characterized by difficulties in the preparation of the powder, which is due to their high oxidative capacity. We propose two methods to obtain a powder of uranium alloys: hydrogenation-dehydrogenation and mechanical grinding. Uranium and uranium-zirconium alloys actively absorbs hydrogen and hydrogenation temperature characterized by the following: zirconium – (550-600) °C, uranium – (250) °C; uranium-zirconium alloys – (450-500) °C. The dehydrogenation temperature of zirconium is above 800 °C, uranium (350-400) °C, and for U-Zr alloys – (650-700) °C. A large number of cycles results in a strong powder milling and associated with great difficulties to work with them. The best is 1-2 cycles of hydrogenation-dehydrogenation. Alloys with Mo in γ - state very slowly hydrogenated, and the interaction with hydrogen is possible only if there is two-phase (eutectoid) structure obtained after prolonged annealing. The process of saturation with hydrogen is extremely durable, and the presence of a two-phase structure contradicts to the demand to fuel and is extremely undesirable. Therefore, in this study to obtain U-Mo alloy powder was performed by mechanical method.

Getting powder by mechanical method was carried out in two stages. In the first phase by milling zirconium ingots and uranium alloys produced chips of size 2-4 mm. The virtue of milling compared to the lathe cutting is that it is possible to obtain chips in the form of flakes rather than as a long, discharge of chips. As a consequence, there is significantly simplified handling of such chips, its grinding and cleaning. Milling cutter performed as the disk rotating at 280 rev/min and fed at a rate of 18 mm/min. In order to avoid ignition in chip cutting region the oil cooling was used. The chips after cleaning were dried and charged to a planetary mill "Pulverisette 5" and grinding was conducted during 3 cycles by 10 minutes each. As a result, powders were obtained with particle size from 15 µm to 3 mm.

3. Experimental results

The optimal compression modes are characterized by a low pressure of about 0.1 bars and a voltage not exceeding 2,5 kV. Analysis of compression modes showed the following features. On the final product density affects applied pressure, but the greatest influence has voltage (blue curve in Fig. 1). This is caused by local sintering of powder particles, which leads to greater compaction. The dependence of the density of tablets from the voltage is shown in Figure 2.

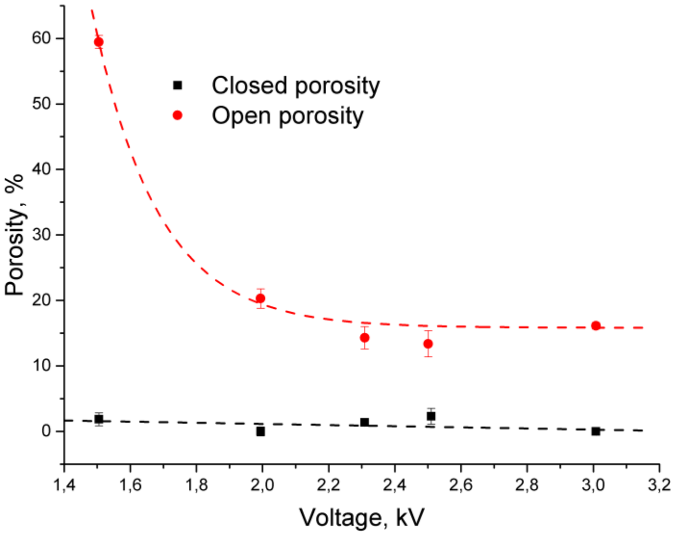

FIG.2. Relative density of zirconium and uranium samples from applied voltage

Pycnometric analysis of pellets showed the presence of open (connected) porosity and the weak dependence of pellets density from the pressing pressure and the size of powders, but strong influence of the applied voltage. Figure 3 shows the dependence of relative density of pressed compacts from voltage at different sizes of initial powders.

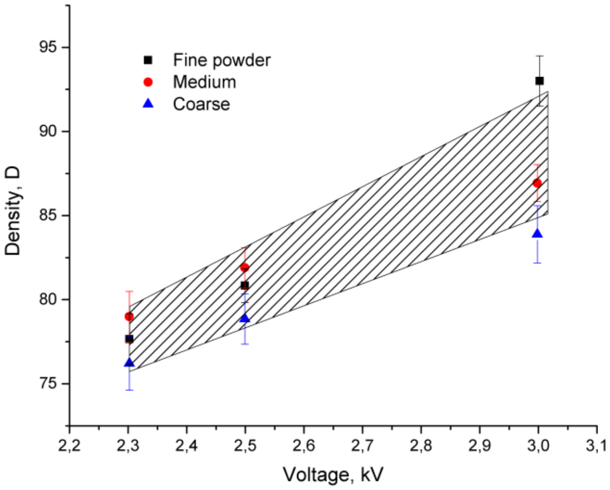

Figure 3 - Dependence of the relative density from the initial powder size

From Fig. 1 it can be seen that the powders of different particle size substantially equally pressed. Some difference observed for powder particles with a small size (40 microns) at a voltage of 2.3 kV. This is due to the high surface activity of the powder, which make sintering easier during the passage of electric discharge.

The pellets obtained by the HVEPC method have high strength. The shearability of the tablets was verified by dropping from a height of 2 meters onto a granite slab, no chips or cracking of the samples were observed.

Metallographic examination of the obtained images showed that the grain size in them is approximately equal to the grain size in the initial powders.

The possibility of compression demonstrates the high flexibility of the (HVEPC) method. HVEPC important feature is the possibility of obtaining high-quality outer surface, which mainly depends on the purity of the surface of the die and punches. General view and microstructure of sintered pellets U-10%Mo are shown in Fig. 4.

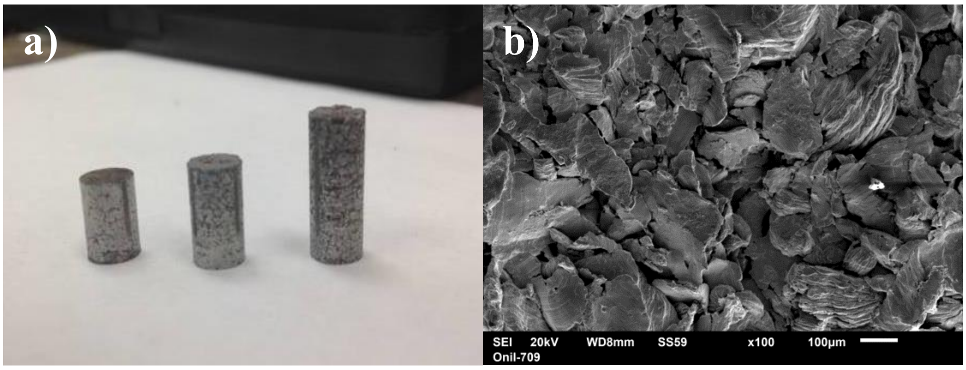

FIG.4. Structure of sintered U-10%Mo pellets - a) sintered pellets with different density; b)sample microstructure of sintered pellets

Evaluation of thermal conductivity of porous fuel pellets indicates a decrease in thermal conductivity with increasing porosity, so the thermal conductivity value of 25 W/m·K corresponds to a porosity of 13-17%.

Further studies were conducted by dilatometric analysis of porous pellet made from uranium alloys. Temperature program consisted of a heating rate of 10 K/min to 750º C, holding at this temperature for 4 hours and cooled. Analysis of dilatometric curve (porous alloy having a density of 87.6 % TD) showed that there is a slight shrinkage (about 0.09%), which is associated with sintering. Respectively pellet having a large porosity re-sintered stronger - in this case the shrinkage was 0.15 %. Also, we measured the coefficient of linear thermal expansion, which differs from $7.1\cdot10^{-6}$ 1/C (50-300 ºC) to $10.8\cdot10^{-6}$ 1/C (300-630 ºC), above 630 °C shrinkage of porous tablets starts.

With regard to the real conditions of operation in the reactor one can expect even greater magnitude of shrinkage due to radiation densification. This effect is negative in many ways, as it can result in an increase of the fuel-cladding gap. However, it should be noted that a swelling and the FGP accumulation can be a competitive process and interfere the densification process.

4. Conclusions

The metallic nuclear fuel based on gamma-alloys of uranium and plutonium is a special kind of fuel, due to its unique physical and chemical properties;

To lower swelling we propose to create an open porosity of 15 to 25% of the entire volume of the fuel pellet by applying the technique of powder metallurgy based on electromagnetic compaction methods.

The particle size from 15 µm to 3000 mm was made from alloys uranium with molybdenum and zirconium by mechanical means, and by means of a hydrogenation-dehydrogenation. It is shown that the optimum powder fabrication technology is the mechanical grinding followed by grinding in a ball mill.

Optimal consolidation modes are characterized by a low pressure of about 0.1 bars and a voltage not exceeding 2.5 kV. With increasing voltage and compaction pressure the deterioration of tablet occurs.

Pycnometric analysis of density showed the presence of open (connected) porosity with weak dependence of density on the pressing pressure, and the size of the starting powders. Mainly density depends on the applied voltage. The revealed possibility of compaction of very large powder (chips), larger than 3 mm, demonstrates the high flexibility of the high-voltage electric pulse compaction method.

Measurement of thermal conductivity of porous fuel pellets showed the thermal conductivity decreasing with increasing porosity, the thermal conductivity value of 25 W/m·K corresponds to a porosity of (13-17)%. Dilatometric study showed little shrinkage of porous tablets at a temperature of (600-750) °C, which is associated with the secondary sintering.

Thermophysical calculation of temperature fields in a fuel rod showed the possibility of using porous metal fuel in fast reactors.

5. Literature

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