Design and Fabrication of a Dead Weight Equipment to Perform Creep Measurements on Highly Irradiated Beryllium Specimens

M. SCIBETTA[1], A. PELLETTIERI, P. WOUTERS, A. LEENAERTS, G. VERPOUCKE
SCK•CEN, Boeretang 200, B-2400 Mol (Belgium)

Abstract

Beryllium is an important material to be used in the blanket of fusion reactors. It acts as a neutron multiplier that allows tritium production. In order to use this material effectively, some data on creep and swelling behaviour are needed. This paper describes preliminary microstructural investigations and the qualification of a creep set-up that will be used to measure creep of highly irradiated beryllium from the BR2 research reactor matrix.

Keywords: *Fusion reactor, blanket, tritium breeding, beryllium, creep, irradiation*

Introduction

Beryllium is an important material to be used in the blanket of fusion reactors. It acts as a neutron multiplier that allows tritium production. Taking into account the availability of highly irradiated beryllium from the BR2 research reactor matrix, the objective of this task is to complement missing data on swelling, helium release and creep of beryllium in conditions relevant to the end of life of a fusion power reactor: helium concentrations up to 30,000 appm and temperature peak values up to 800 °C.

The ultimate goal is to extend the validity of the Analysis of Fusion Irradiated Beryllium (ANFIBE) code, developed at ForschungsZentrum Karlsruhe (FZK) in the context of the Helium Cooled Pebble Bed blanket design. This code describes the beryllium pebble bed behaviour, up to the anticipated high helium concentrations and temperatures.

Creep and swelling measurement on highly irradiated beryllium at high temperature is not straightforward. It requires dedicated instrumentation that should be operated remotely. The preliminary results related to swelling are first given in this paper. The requirements of the creep measurements are then reviewed. Next, different creep set-up options are investigated to select the most appropriate one. Finally the selected creep set-up is designed and fabricated. It should also be demonstrated that the fabricated dead weight machine is adequate before using it on irradiated material.

Material and specimen procurement

Large amount of highly irradiated beryllium from the BR2 material testing reactor is available, since the beryllium matrix has been replaced in 1997 due to helium poisoning. The irradiation temperature is 50°C, and the neutron fluence is about 1 10^{23}n/cm² (E>1MeV). The expected Helium build-up due to the nuclear reactions is about 20 000 ppm.

Specimens for creep and microstructural investigations are extracted from broken pieces of hexagonal channel from the BR2 matrix as illustrated in Fig. 1.

From the beryllium material, several specimens are extracted:

- Samples of 3 mm³ are used for Helium measurement using Hot Vacuum Extraction instrument. These measurements allow to assessing the irradiation damage expressed in term of Helium build-up.

[1] Tel. (+32-14) 333043, Fax. (+32-14) 333043, mscibett@sckcen.be

- Samples of 5 mm³ are used for high-resolution optical microscopy. Size and density of Helium bubbles that are produced do to thermal annealing will be quantified. These measurements are very important, as they will allow the understanding of swelling resulting from bubble formation.
- Samples of 9 mm³ are used for density measurements using a Picnometer. These measurements will assess the swelling directly by evaluating the change in density.
- Parallelepiped al samples 4x4x20 mm are used for creep measurements. These samples are difficult to produce as they require high fabrication accuracy. In particular parallelism of face on which the load will be applied should be guaranteed. Moreover, Beryllium is very brittle, neutron activated and toxic.

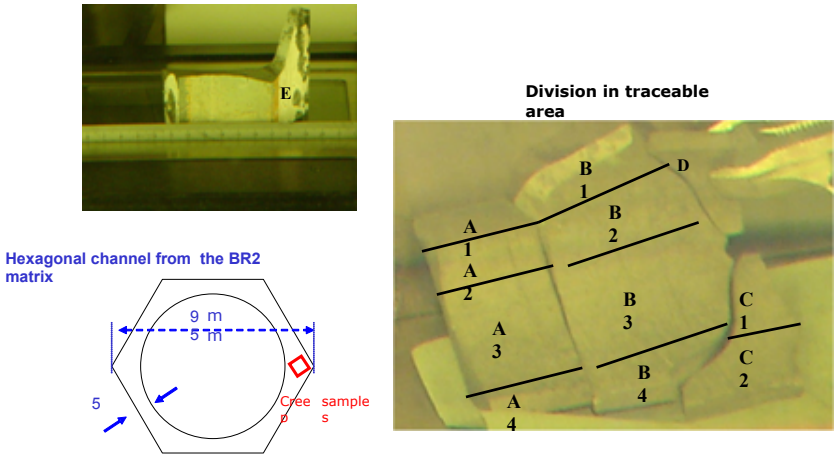

Fig. 1 BR2 beryllium matrix used for this research

Preliminary microstructural results

Irradiated samples were heat treated at 500, 750 and 900 °C for 50, 200 and 720 hours. These heat treatments simulate fusion irradiation conditions. High temperature should increase the mobility of Helium resulting in Helium bubble formation and swelling due to the internal pressure inside the bubble.

After irradiation some samples were embedded and polished to be examined using a high resolution optical microscope. Fig. 2 shows samples heat treated at different temperatures during 50 hours. Pictures given in Fig. 3 shows the microstructure of heat treated samples at 900°C. It is observed that for the same heat treatment duration, the size of the bubble increases with temperature.

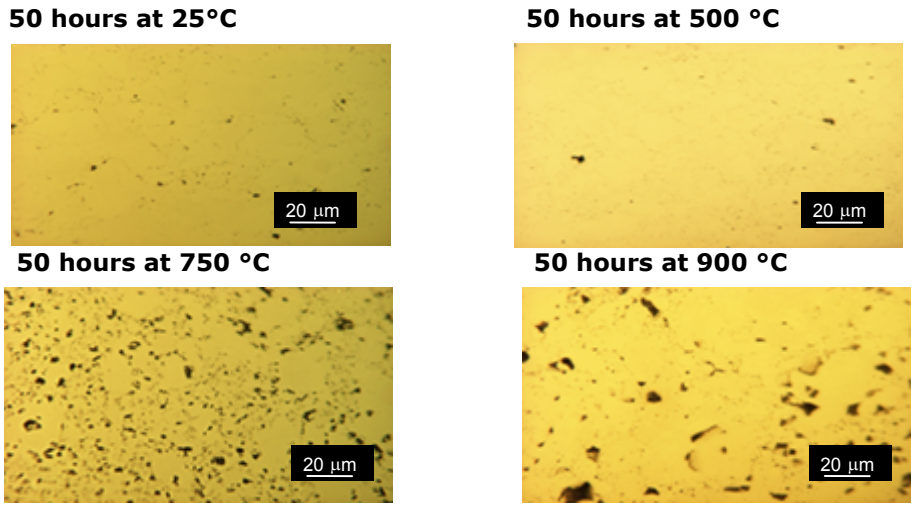

Fig. 2 Optical microscopy after 50 hours heat treatment

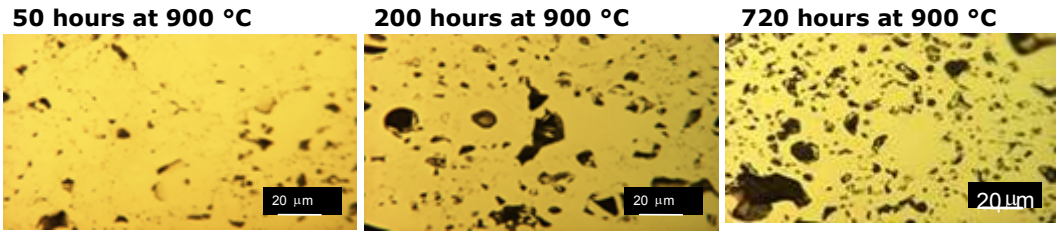

Fig. 3 Optical microscopy after heat treatment at 900°C

After heat treatment the Helium concentration was measured using the Hot Vacuum Extraction instrument. Results are presented in Fig. 4. After irradiation the Helium content is about 10000 ppm which confirms the high irradiation doses received by the samples. After thermal heat treatment at high temperature the Helium concentration decreases. It can be explained by the fact that Helium mobility has increased and therefore escaped from the material. It is then expected that then swelling should saturate after such heat treatment. It also explains that the microstructure at 900°C does not evolve after 200 hours treatment. Density measurements still need to be performed to confirm this hypothesis.

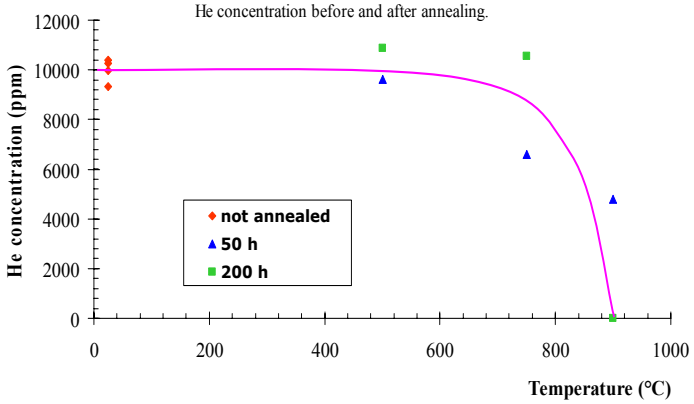

Fig. 4 Helium measurement

Creep testing requirements

The equipment should be designed for remote handling in a hot cell in order to accommodate the highly radioactive beryllium samples. Furthermore, creep test conditions have to be as representative as possible of the working conditions in a future fusion device. The target is to perform the tests in an inert environment (e.g. vacuum or argon), at very high temperature (i.e. 500 °C, 750 °C and 900 °C) and during long periods of time (i.e. 9, 6 and 3 months respectively). The rising temperature rate should be lower than 10 °C/min to avoid Helium burst release. The loading should be between 6 and 10 MPa.

Creep tests are performed either at constant load or at constant displacement. In the first case the strain is monitored as a function of time, in the second case the stress is monitored. It has been demonstrated that both test methodologies can provide the same inherent material property [1]. However, in this project a constant load is requested.

Due to the brittleness of the material, it is recommended to design the set-up in order to apply load in compression. The deformation due to creep should be measured as a function of time or at defined intervals. The magnitude of the displacement to be measured is unknown, therefore a transducer with accuracy equal or better than one micrometer should be used.

Creep testing set-up

Several options were investigated – i.e.: creep on an actual universal tensile machine, creep using a spring loading system and a dead weight machine.

The universal tensile machine has the advantage to be a very versatile system allowing constant load or constant displacement creep technique. However, the magnitude of the load to be applied and monitored is particularly low and the equipment is immobilized for a long period.

The spring loading creep set-up was initially selected as it has the advantage to use a standard vacuum furnace. The specimen is preloaded using a spring and is loaded in the furnace. After a given amount of time the specimen is retrieved to measure its deformation. However, this option was finally not selected, as it turned out to be extremely difficult to design an adequate spring that would provide a well defined and constant rigidity in the required very high temperature range.

The finally selected technique is the dead weight machine that has the advantage of not immobilizing other hot cell equipment. It has the capability of continuous creep monitoring trough adequate LVDT measurement. It is rather simple to operate in hot cell and has a guarantee of accurate constant loading during a long period of time.

Creep testing design

As no commercial instruments are available on the market that can perform creep measurements in the specified condition, a dedicated set-up is designed and fabricated.

The dead weight machine is designed as schematically presented in Fig. 5 and shown in Fig. 6. The system accommodates for specimens with nominal size 4 × 4 × 20 mm. In order to measure the creep of the material investigated and not the creep of the whole system one did pay particular attention to the material selected for the design. A Nickel super-alloy NIMONIC 90 (PER2U) has been selected due to its very good resistance to high temperature and good creep properties. By adding weight, the system allows to load a cross section of 16 mm² from 2 MPa to 10 MPa.

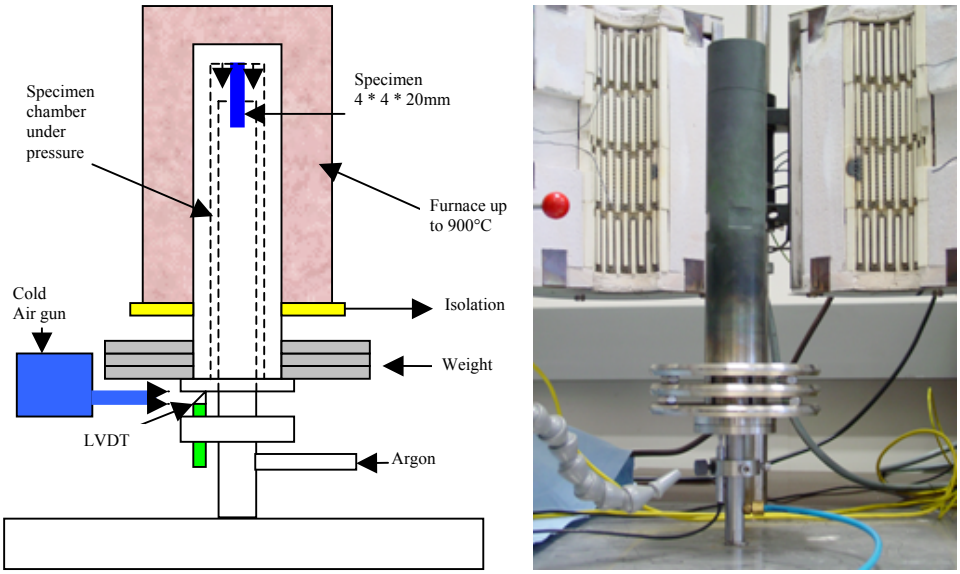

Fig. 5 Schematic and picture of the creep dead weight system

A calibrated Linear Variable Differential Transformer, LVDT, is used to monitor creep displacement. This LVDT is placed outside the furnace. It has been found that due to temperature conduction and convection, the temperature of the LVDT increased up to 75 °C, which is close to the maximum operating temperature of the selected LVDT. Therefore, an external cooling system is used. The first attempt was done using the patented Vortec cooling gun [2]. This is a high-performance system allowing reaching sub

zero temperatures. It has no moving part and just needs compressed air. However, the compressed air circuit of the hot laboratory contains too much humidity resulting in obstructing the outlet with ice. Consequently, another system was used that blows compressed air all around the LVDT. The SATEC split furnace uses radiant elements that can operate up to 1000 °C. A Eurotherm controller is used to control the three zones of the furnace. The upper opening is closed with isolating material. The lower opening allows the creep system to pass through.

In order to perform the creep test within an inert atmosphere, argon is blown inside the specimen support. In order to minimize the amount of argon to be used, the whole system should be tight. A teflon rope allows the weight to slide on the specimen support and prevents argon to escape. The low friction coefficient of the teflon ensures that the correct load is applied on the system.

Fig. 6 Picture of the creep test system inside a glove box

Creep set-up qualification

Three experiments were performed to qualify the equipment according to Table 1. The selected geometry is 4 × 4 × 20 mm. All specimens are machined from Nimonic 90 material.

Run number	Temperature (°C)	Duration (days)	Stress (MPa)	Specimen ID
1	500	7.8	7.8	dummy 1
2	500	7.1	7.8	dummy 1
3	900	2.0	7.8	dummy 2

Table 1 Test matrix for the qualification work

A creep test has been performed on a 4 × 4 × 20 mm Nimonic 90 specimen at 500 °C under a stress of 7.84 MPa. The specimen was carefully measured before and after the test using a profile projector and a micrometer. The specimen length measures 20.002 mm before and 20.054 mm after the test. Hence a -52 µm or -0.26% creep is obtained. This negative creep is probably due to the fact that the construction material needs to stabilize.

The LVDT based on-line creep measurements are as follows. Before switching the furnace on, the LVDT reading is zeroed. After temperature stabilization at 500 °C, the LVDT indicates an initial displacement of -0.28 mm and a final displacement of -0.286 mm after 8 days that results in a -6 µm creep (Fig. 7). Once the temperature is brought back to room temperature after the test, the LVDT indicates -12 µm.

All foregoing measurements demonstrate a negative creep of the specimen. The expected accuracy of the whole system is in the order of 10 µm and will probably be improved as the system and the material has been stabilized. Fig. 7 also gives the ambient temperature. It shows that ambient temperature should be kept constant in order to ensure accurate measurements.

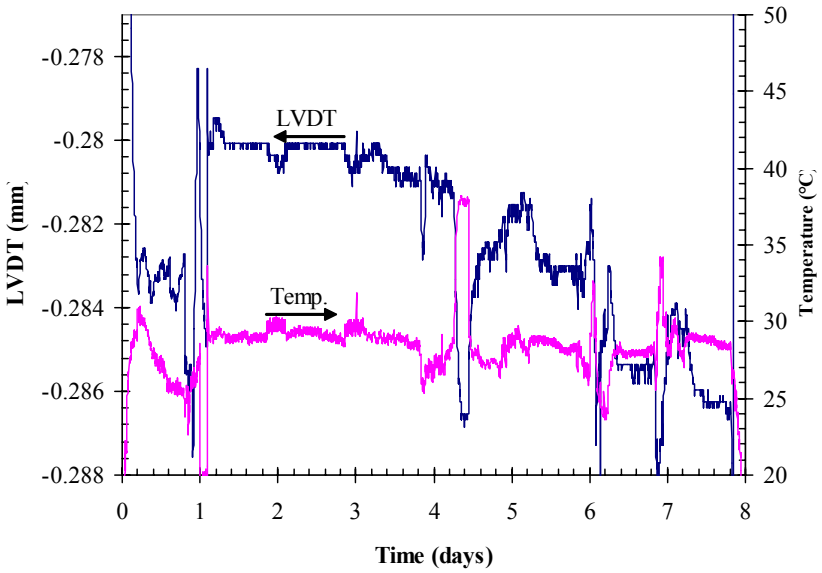

Fig. 7 Displacement and temperature at the LVDT position during a 500°C creep test performed on Nimonic 90 under a constant load of 12.8 kgf that corresponds to a stress of 7.84 MPa

Discussion

The developed creep set-up is designed to measure creep, i.e., specimen dimension reduction due to applied compressive loading. In the studied example, Nimonic material has a good resistance to creep and was therefore selected as structural material for the creep set-up. Only limited creep is observed when used at 900 °C under 8 MPa. In the actual set-up the stress will be even lower than 8 MPa. It is also observed that swelling due to annealing can occur concurrently with creep. Swelling induces specimen elongation due small micro-structural changes. In the case of irradiated beryllium, swelling will occur due to helium bubble formation. In order to distinguish the two phenomena, two options remain open:

- Perform a pre-annealing to produce swelling up until saturation is reached. In a second step measure creep on the same sample.
- Perform a creep experiment concurrently with swelling. Volumetric changes due to swelling will be inferred from other measurements and subtracted in order to determine actual creep.

For the final set-up to be installed in hot cell, the produced heat should be evacuated properly trough ventilation and additional cooling system.

Conclusions

Performing creep measurements on highly irradiated beryllium at high temperature is not straightforward. It is found that the developed dead weight machine is adequate to perform such measurements. The accuracy should be in the order of 10 µm and can be monitored on line. It should also be emphasied that swelling could occur concurrently with creep. An adequate strategy should be selected in order to unmask swelling and to reveal only the creep properties on actual irradiated beryllium samples.

References

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[2] http://www.vortec.com/cold_air_guns.php