New irradiation device at the Budapest Research Reactor

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Abstract. In close co-operation with the Paul Scherer Institute (Switzerland) two new rigs called BAGIRA (Budapest Advanced Gas-cooled Irradiation Rig with Aluminium structure) have been built [1–2]. The irradiation volume of the largest rig is 360 × 20 × 30 mm and it can operate in the temperature range of 150–650°C. The heating is combined gamma and electrical heating; the temperature measurement is performed by 6 thermocouples, and controlled by a helium-nitrogen gas mix flow. The neutron flux within the rig is about 2–6 × 10^{13} $n \cdot cm^{-2}s^{-1}$. Similar but smaller irradiation channel have been built for long term irradiations at lower temperature for testing the materials of the fusion reactor. Altogether 24 different irradiations have been performed until now studying the radiation resistance of RPV steels, model alloys, titanium and tungsten, aluminium alloys and ceramics. In 2010 the irradiation facilities of the BRR were under upgrade again. The purpose of the modernisation was to satisfy the requirements at the development and testing of materials for the third and fourth generation reactors, fusion devices and advanced testing of presently used materials. The new irradiation rig is: i) Shielded from the thermal neutrons by boron carbide shield (better fast/thermal neutron ratio, less gamma heat generation, less activation of the samples); ii) The temperature range of the operation is increased up to 600°C; iii) The minimum stable operation temperature is as low as 100°C; iv) The target can be rotated during irradiation to avoid self-shield; v) The temperature control became to electric resistance heating in 6 zones instead of the present 3 zones; vi) The sample removal after irradiation simplified and the personal dose during sample removal will be reduced; vii) The mass of the activated structure also reduced and also the preparation costs of a new irradiation reduced; viii) Further new feature of the design is the in-pile creep and low cycle fatigue test on small size specimens.

1. INTRODUCTION

Radiation embrittlement is one of the main ageing mechanisms of the materials of the fission and fusion reactors. In many cases it determines the lifetime of these devices.

The Budapest Research Reactor (VVR-SM type) built in 1957 and after full reconstruction and power upgrade to 20 MW was restarted in 1993. The reconstructed reactor passed successfully the 1 year test period, and since January 1994 it is on normal operation with 10 MW power. Radiation embrittlement research is available since then. The Budapest Research Reactor and the BAGIRA 1 and 2 irradiation rigs are widely used for studying the irradiation effects on the structural materials to evaluate the safety and lifetime of the presently operating and future nuclear energy sources.

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The institute participated in the IAEA co-ordinated research programs (CRP-3 to CRP-9) by performing irradiated material testing. Irradiations in the BAGIRA rigs have also been performed for many EU framework program (FRAME, GRETE, COBRA, ATHENE, PERFECT, COVERS, NULIFE) and for the European Fusion Program. National irradiation programs supported the lifetime extension of the Paks NPP. Nowadays further development of the irradiation facilities is going on to widen the irradiation temperature range, to produce harder spectra (better rate of fast/thermal neutrons), and to study the effect of combined mechanical load and irradiation.

2. THE BAGIRA 1 AND 2 IRRADIATION RIG SYSTEMS

In close co-operation with the Paul Scherer Institute (Switzerland) two new rigs called BAGIRA (*B*udapest *A*dvanced *G*as-cooled *I*rradiation *R*ig with *A*luminium structure) have been built during 1996–2003. [1–3]. The irradiation volume of the largest rig (BAGIRA 1) is 360 × 20 × 30 mm (see Fig. 2.1), and it can operate in the temperature range of 150–450°C. The heating is combined gamma and electrical heating; the temperature measurement is performed by 6 thermocouples, the temperature controlled by a helium-nitrogen gas mix flow. Foil dosimeter and fluence calculations are combined to support the evaluation of neutron flux, fluence and spectra. The fast fluence within the rig is about 2–6 × 10^{13} $n \cdot cm^{-2}s^{-1}$. Similar but smaller irradiation device (BAGIRA 2) has been built for low temperature long term irradiations for fusion materials testing.

2.1. Irradiations in the BAGIRA 1 and 2 rigs

2.1.1. RPV cladding tests

Most of the reactor pressure vessels (RPV) are clad inside with a stainless steel layer. It is generally made by welding, and 3–10 mm thick. Previously at Pressurized Thermal Shock (PTS) analysis the cladding was neglected, presently hypothetical cracks starting from the clad surface are considered. If the RPV cladding is ductile and free from defects, than the VERLIFE [4] and the IAEA PTS guide [5] doesn't requires the use hypothetical surface cracks during the PTS calculations. Without hypothetical surface cracks, the PTS calculations give 20–30% longer lifetime [6]. The irradiation damage of cladding is different from the ferritic and austenitic steels, interesting topic to study, and important for long operational life.

The results shows that the cladding ductility is the best around room temperature, and at 300°C the elongation of the unirradiated cladding is less, than the elongation of EOL irradiated cladding at room temperature. At 300°C testing the irradiation only slightly affects the elongation [7].

2.1.2. Application Cr-Mo-V steel on high temperature

The Cr-Mo and Cr-Mo-V steels are the vessel materials of the PWR's. The irradiation resistance of these materials are widely studied at the operating temperature range of the present PWR-s (250–320°C). To increase the efficiency of the future reactors higher operating temperature are required. First option is to increase the operating temperature into the 350–560°C range. The fossil plants are operating at this temperature and built from Cr-Mo and Cr-Mo-V steels. These materials are widely used by the industry; the nuclear application does not need too much technology development because the long term creep and thermal ageing properties of them are well known. They are candidate materials for the future fourth generation SCWR (supercritical water cooled) reactors. Irradiation of 15Ch2MFA steel performed in the BAGIRA-1 rig at 450°C and the results are promising [8].

2.1.3. Ti-alloys

Ti alloys has been irradiated and tested for ITER fusion device. In Tokamak type fusion devices the first wall and the vessel is connected with elastic elements. The high strengths and low Young modulus of Ti-alloys allow using them as spring elements. This part of the device suffers about 0.5 dpa irradiation. Ti-6l-4V alloy has been irradiated and the mechanical properties were tested.

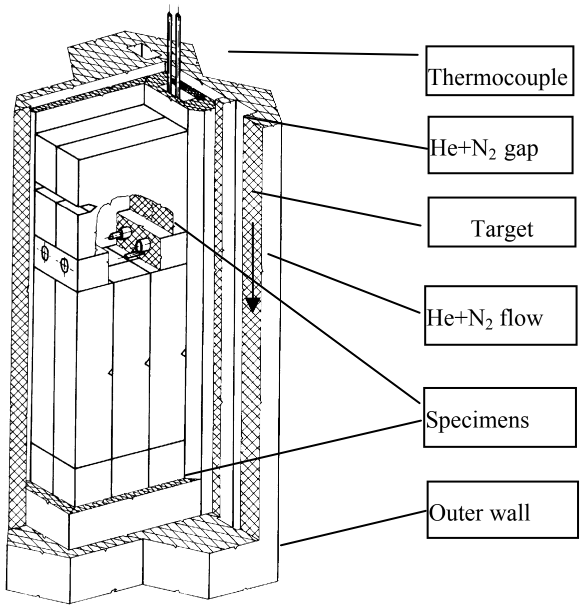

FIG. 2.1. Cross section of BAGIRA-1 irradiation rig.

2.1.4. Tungsten

Tungsten is resistant against high temperature. Divertors and other first wall elements of the fusion devices and some parts of the high temperature gas-cooled reactors are planned to be prepared from tungsten alloys. The radiation embrittlement of tungsten alloys were studied on samples irradiated in the BAGIRA rig. The irradiaton with 0.5 dpa reduced the conductivity, caused swelling and decreased the ductility of unalloyed tungsten rods.

2.1.5. 9% Cr steels

The 9% Cr containing ferritic-martensitic steels have high strengths at high temperature, resistant against creep and can be applied at the 650–900°C temperature range. It consist low half decay time elements, so after limited decay time it can be treated like low activity waste, and after 100 years decay it can be freely reused. In the power industry similar steels are regularly used and the production and machining technology is well-known. The purpose of the study was how much the fracture toughness can be measured on small size irradiated Euroferr specimens –which are the limitations of the use of reconstituted specimens and the so called Master Curve method [9].

3. FUTURE OF IRRADIATIONS IN VVR-SM REACTOR

The nuclear industry is facing the challenge of the development of fusion and Gen IV fission reactors. To increase the efficiency and decrease the impact on the environment high operation temperature will be used. Consequently high temperature irradiation combined with in pile creep and fatigue testing are the future tasks of the irradiation devices.

The future recators will suffer very high fluences (50–100 dpa) during their lifetime. Presently the medium research reactors (like the VVR-SM) can produce only ≈1 dpa/year. Although this fluence is not comparable to the expected target values, two facts support the future use of them:

- at very high fluxes the so called flux rate effect causes high bias in the material ageing results,
- considerable part of the ageing occurs at low fluence levels.

The radiation embrittlement is the sum of at least five different ageing mechanisms: precipitations, radiation induced segregations, increase of the dislocation density, thermal ageing and annelaing at irradiation temperature [10]. The first two ageing mechanism occur at low fluence (generally much less than 1 dpa) and quickly saturate. The time dependent annealing and thermal ageing also cannot be studied in high flux devices. Large size specimens cannot be used in high flux irradiation devices due to the high heat generation in the middle section of the specimens. These facts requires the combined use of the high flux devices (high flux reactors, spallation neutron sources, two and three beams accelerators) and the present research reactors.

3.1. Development of the BAGIRA3 rig for future irradiations

The future energetic reactors (fusion and fission) will be operated at higher temperature, and irradiation assisted fatigue and creep became releveant ageing mechanism. To study them the BAGIRA system is under upgrade development. The BAGIRA3 rig will be located in a fast neutron irradiation channel where the thermal neutrons will be filtered out by a boron carbid layer. The reduction of the thermal neutrons will decrease the nuclear heating and the activation of the specimens, consequently the temperature control will be more effective, and the decay time will be shorter after irradiation. A step motor will turn the target around to eliminate the self shielding effect of the specimens. Finally the irradiation spectrum will be harder, simulating better the future fission and fusion reactor spectra. The inside tructure (target holder) of the rig will be manufactured from titanium alloy to be able to operated up to 650°C. The cross section of the target holder will be 48 mm in diammeter (instead 20 × 30 mm in the BAGIRA 1) allowing to use bigger specimens if it is required .All of this development increases the operation window of the irradiation device.

3.2. Development compressed ring shape speciemens

For in situ loading few irradiation devices have been built. Traditionally tensile specimens are used for creep and fatigue study. Within the irradiation rigs at high temperature and radiation the precize measurement of elongation in the function of time is very difficult. Due to this a different type of specimens is considered: small size compressed rings. 10–20 rings with a diameter of 10 mm designed in the loading grip (see Figure 3.1).

The ring shape is selected because it is easy to produce, with the change of the lenghts or wall thickness of it the stresses in the loaded ring can be increased or decreased when applying the same load. The deformation of the rings are relatively large even at small creep, and easy to measure.

The geometry of the irradiation channel permits us to place specimens on each other, therefore several rings can be tested simultaneously. The mechanical stability of the vertically pile up ring-system is essential. Consequently mechanical stabilizer elements (beds) are installed between the rings to ensure that the rings will hold their position during the experiment. The geometry of the beds determines the results. Horizontal plane sheets (Fig. 3.2/a) would not be a good choice, because during the cycling loading the rings could move away in the horizontal direction. A bed with a cylindrical (Fig. 3.2/b) or a V-shape (Fig. 3.2/c) groove prohibits the horizontal displacement of the rings.

The most important parameters that describe the beds are Rb (Fig. 3.3/a) and α (Fig. 3.3/b).

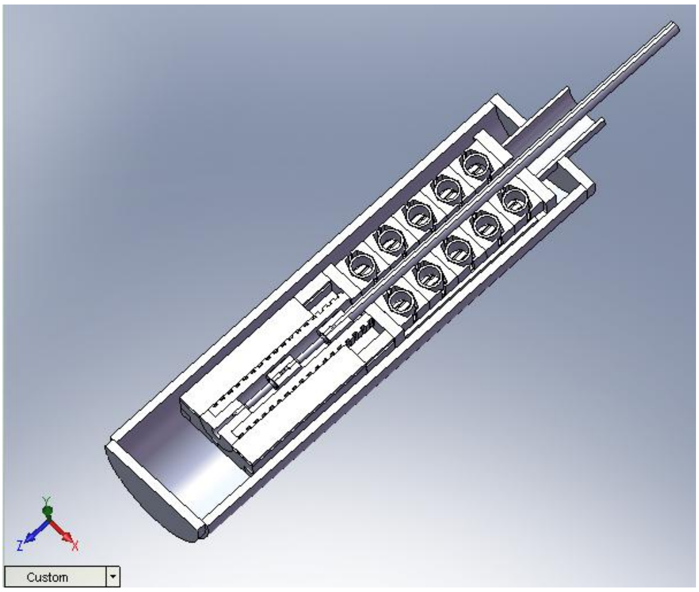

FIG. 3.1. Tensile specimens and compressed rings in the loading grip.

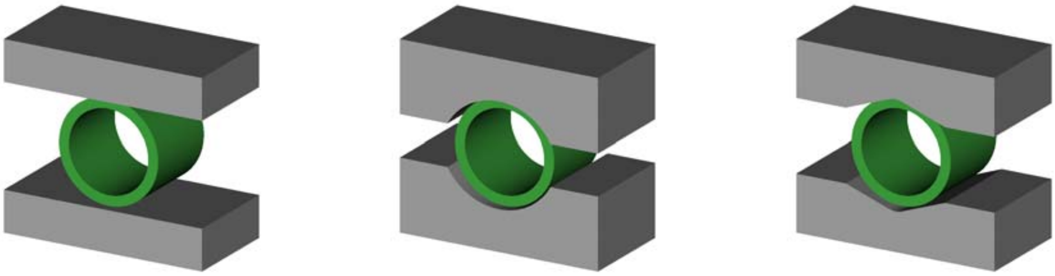

Fig. 3/a. *Fig. 3/b.*
Fig. 3/c.

FIG. 3.2. Different plane sheets of the tool. 3/a shows a horizontal shape, 3/b shows a cylindrical shape and the 3/c shows a V-shape .

FIG. 3.3. a) V-shape.

FIG. 3.3.b) Cylindirical shape.

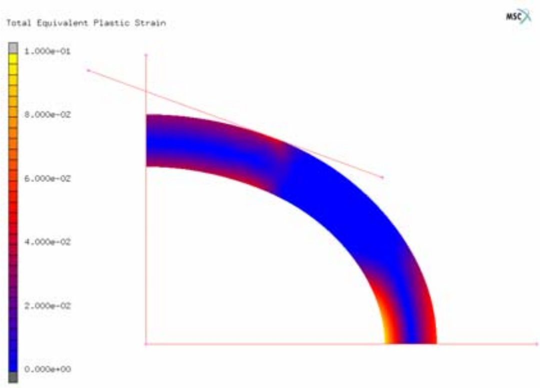

Fig. 5. Total equivalent plastic strain in ring.

Finite element model of the ring has been developed and the beds to design the details of the rig and to be able to simulate the future experiments. For this purpose we used the MSC.Marc 2005r3 general-purpose nonlinear finite element software has been used. The models are 2D, assuming plane strain deformation. The software applies the theory of large strain. A typical distribution of the total equivalent plastic strain in the ring is depicted in Figure 5.

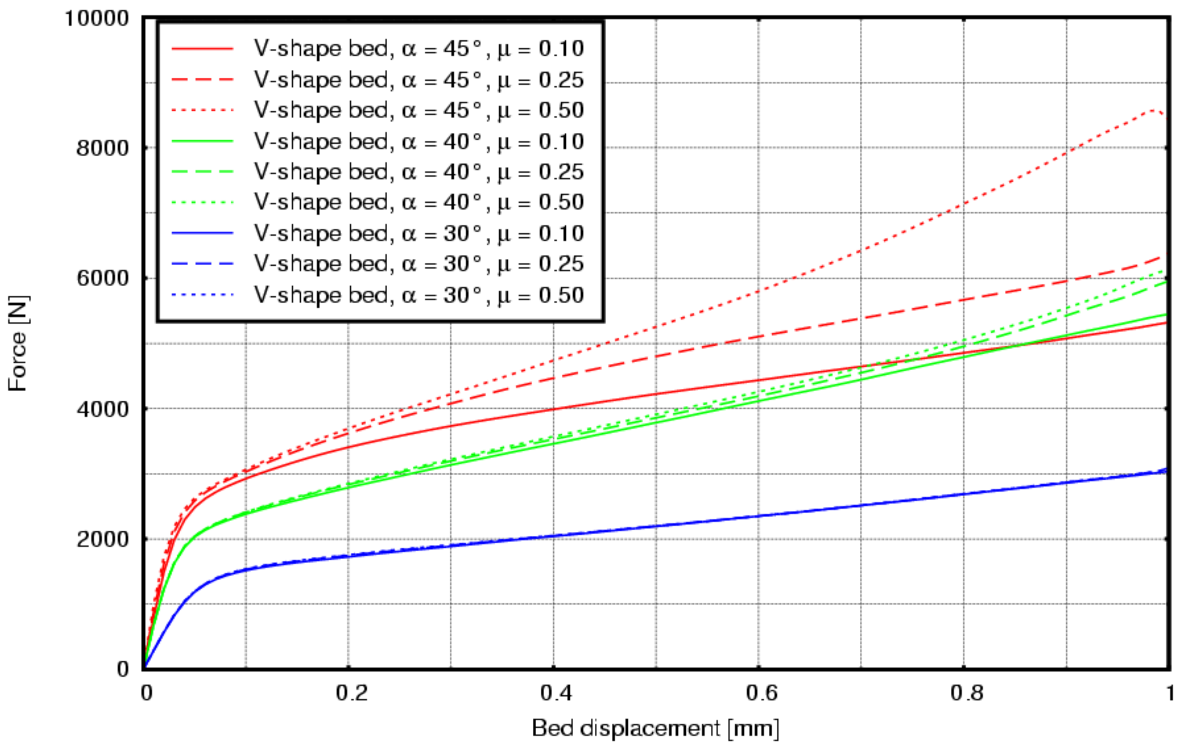

Fig. 6. Calculated results of the effect of different parameters.

In the simulations we calculated the role of the friction coefficient between the specimen and the bed. Coulomb friction model was applied with friction coefficients: μ = 0.10, 0.25 and 0.50. In Figures 6 and 7 the force–displacement results of the simulations are shown, where continuous lines represent μ = 0.10, the dashed lines μ = 0.25 and the dotted lines μ = 0.50. The force–displacement results are sensitive to the variation of μ if the bed is V-shaped and α is more then 30°. However with the decreasing α the required compression force is also getting smaller. At small displacements ($\delta \leq 0.2$ mm) the cylindrical bed acts like a horizontal plane sheet bed. At higher values of the displacement the ring gets jammed in the bed, a progressive geometrical hardening can be observed. The increase of Rb would delay the appearance of the jam, but it would also destabilize ring-system.

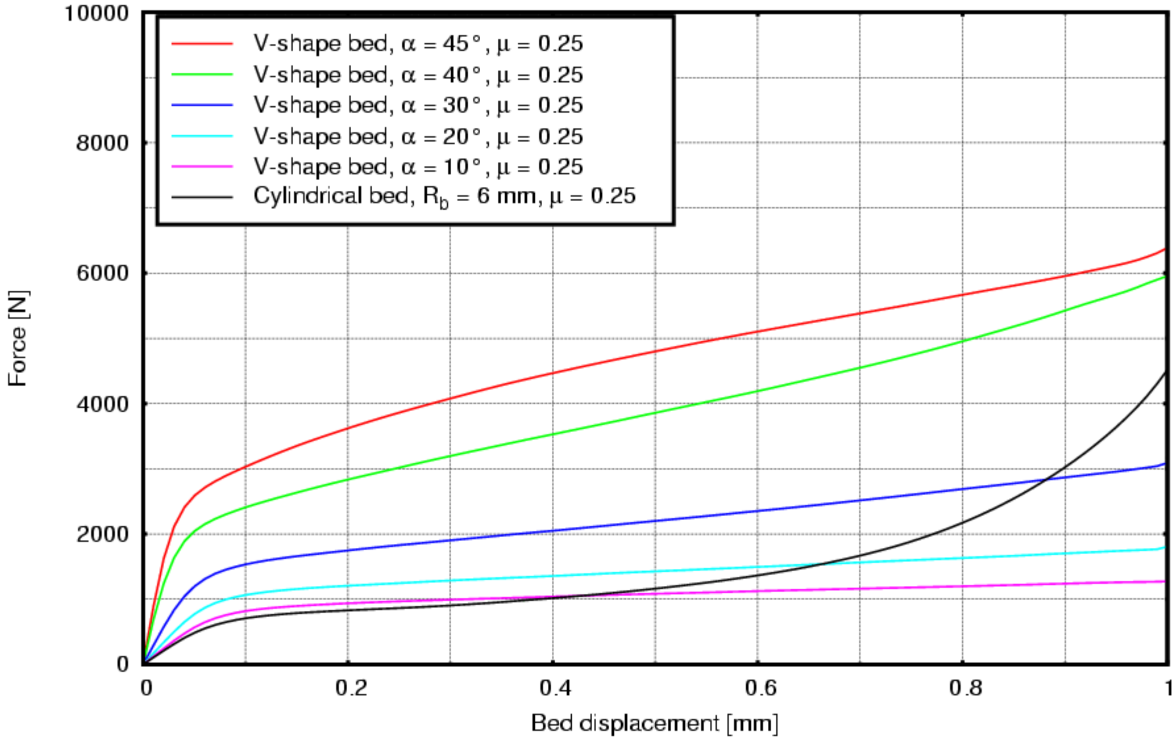

Fig. 7. Calculated results of the effect of different parameters

Since it is expedient to avoid the geometrical hardening and the sensitivity to the friction coefficient, the V-shaped bed with a low value of α (e.g. 20°) would be an optimal choice.
A furnace has been manufactured with electric heating, and a set of ring have been tested at 550°C. The recently performed tests verified the calculations.

4. Summary

The new BAGIRA3 rig is designed either for conventional irradiations in wide temperature range on tensile, impact and fracture toughness specimens, either it will be prepared to be able to perform irradiation creep and irradiation low/cycle fatigue tests on compressed rings or tensile bars.

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