Nanolattice is a new class of mechanical metamaterials with characteristic sizes on the order of hundreds of nanometers. Due to their extremely special size effects, structural characteristics and material selection, the mechanical properties of this type of porous materials are very different from those of bulk materials, and they can even have better mechanical properties at a lighter weight. They are expected to bring revolutionary applications in the field of high-performance functional materials in the future. Beam nanolattice is the main research object of nanolattice materials. However, to date, it is challenging to make breakthrough in the fabrication of metallic beam nanolattice with beam diameter of less than 100 nm, and thus their mechanical properties remain ambiguous.

In this work, a new type of quasi-body centered cubic (quasi-BCC) beam nanolattice mechanical metamaterial is proposed, which is experimentally implemented with ion track technology based on the Heavy Ion Research Facility in Lanzhou (HIRFL). The beam diameter of the quasi-BCC beam nanolattice can be as small as 34 nm, breaking through the size limit of the beam nanolattice mechanical metamaterials. The results of in situ compression experiments show that the energy absorption capacity of the copper quasi-BCC beam nanolattice exceeds that of the previously reported beam nanolattices (Fig. 1). In addition, the yield strength of the gold and copper quasi-BCC beam nanolattices exceeds that of the corresponding bulk materials at less than half the density. Furthermore, experiments and simulations reveal that the supernormal mechanical properties are mainly due to the synergistic effect of size effect, quasi-BCC geometry, and good ductility of metal.

This work proves that gold and copper quasi-BCC beam nanolattices have excellent energy absorption capacity and compressive strength, and deepens the understanding of the mechanical properties of beam nanolattices. At the same time, the application of ion track technology in the study of nanostructured materials has been realized, which provides a new idea for the exploration of beam nanolattice with ultra-high energy absorption capacity.

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5 - 30 Research Progress by Group of Energetic Materials in 2022

Zhang Chonghong

The evaluation and development of materials which can sustain high temperature and intensive neutron irradiation has always been the key issue for the service and safety of nuclear power plants. The in-pile intensive neutron irradiation can produce defects in materials, causing degradation of mechanical properties such as hardening and embrittlement, swelling and accelerated creep rupture. A full understanding of the basic mechanisms underlying the damage production and accumulation is fundamentally important for the optimalization of structure/properties of materials and the proper evaluation of the service lifetime of in-pile key components. For high-efficient assessment and screening purpose, the evaluation methodology of candidate materials based on ion accelerators is highly needed. Miniaturized specimen technology is given intensive consideration, because ions with several MeV/u energies (available by current large accelerators) have limited ranges (much less than 1 mm) in materials.

The Group of Energy Materials (GEM) in IMP has been engaged in the study of mechanisms underlying radiation damage of structural materials and the development of the evaluation method based on the irradiation conditions at HIRFL. In recent years, we have updated the experimental terminal SFC-T1 (facilitating homogeneous damage of specimens at a given temperature with a high precision) at HIRFL, and established corresponding miniature specimen test facilities for the post-irradiation examination.

In 2022, our progress is main in the following two aspects.

1. Research and development of structural materials for advanced nuclear reactors

The harsh in-pile conditions of the advanced nuclear reactors (fast reactors, fusion reactors) require materials sustaining higher temperature and more intensive neutron irradiation. After the Fukushima accident, materials for the accident tolerant fuel (ATF) technology have been getting much more attention. The Al-added oxide dispersion strengthened steels (ODS steels) possess high temperature strength and high resistance to oxidation in high-temperature vaper, and therefore are the prime candidates, whose irradiation tolerance is an important concern. The Zr or Hf addition was reported to enhance the stability of the oxide dispersoids. In 2021, we extended the study of the Zr added FeCrAl-base ODS alloys, and investigated the hardening mechanisms of the ODS alloys after irradiation to a high dose of 26 dpa by 9.45 MeV Bi ions at ambient temperature. Contribution of different pre-irradiation microstructures was investigated in terms of sink strength.

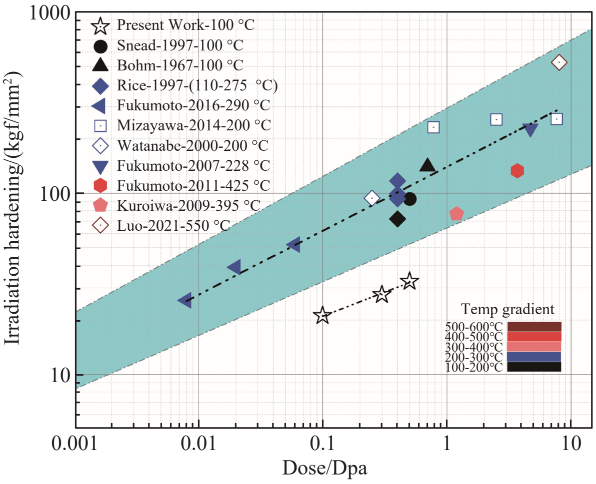

Fig. 1 (color online) Dose dependence of irradiation hardening of the vanadium alloy with 40% cold work followed by thermal annealing (present results represented with star symbols), in comparison with V–(4–5)Cr–(4–5)Ti specimens irradiated at varying temperatures with neutrons (represented with solid symbols) or ions (represented with open symbols). The dotted lines are the corresponding linear fitting results.

In addition, a novel collaborative research of on the irradiation resistance of vanadium alloys candidate to the advanced blankets of fusion reactors was carried out as a joint work with the Institute of Materials of GINFM. Beam of ^{56}Fe ions with 6.3 MeV/u was used to simulate the intensive irradiation of fusion neutrons. The results show that with increasing deformation amount by the pre-irradiation cold-work treatment, the degree of irradiation hardening decreased. The high-density of dislocations produced by the cold-work deformation is responsible for the improved hardening resistance, benefiting from the enhanced absorption ability of point defects. The sink strength was used to quantify the effects of dislocations. It is found that the irradiation hardening obviously decreased with increasing sink strength. Meanwhile, microcavities with a high number density were also observed in the irradiated alloy samples, and are proven to be efficient defects sinks. Compared with previous work, the present vanadium alloys with a heavy cold-deformation treatment exhibit a superior irradiation resistance (Fig. 1). The pre-irradiation modification of microstructures can effectively improve the radiation hardening resistance of the vanadium alloys, promoting their application in future fusion reactors as advanced blanket components.

Results of the study were published in top journals in the field of material science and nuclear energy (Material Science & Engineering A, Nuclear Fusion)[1,2], and are reported in a paper by Han Xuxiao in this proceeding.

2. New comprehensive experimental facility at SFC-T1

Besides the issues of irradiation embrittlement, the irradiation creep and the accelerated creep rupture are important factors limiting material service in especially advanced energy systems such as fast reactors or fusion reactors. In 2022, a new comprehensive experimental chamber was designed and built at the terminal of SFC-T1, includs a set of new two-wheel energy-degrader, three specimen holders with a capacity of multiple-specimen irradiation and wide range temperature control, and a cold trap facilitating better vacuum (Fig. 2). The new chamber combines with the in-beam creep facility which was built in 2021, supplying a comprehensive experimental platform for the investigation of irradiation hardening/embrittlement and irradiation creep of candidate materials for advanced nuclear energy.

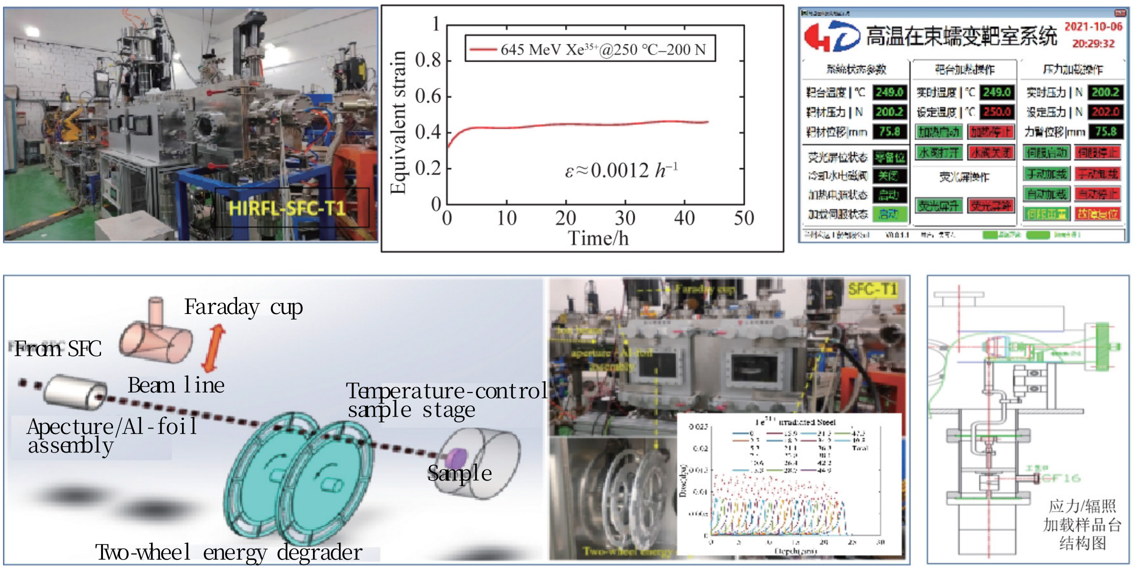

Fig. 2 (color online) New comprehensive experimental facility at SFC-T1 of HIRFL.

References

[1] X. HanM. NiuY. Yang, et al., Nucl. Fusion, 62(2022)126010.

[2] X. Han, C. Zhang, M. Niu, et al., Materials Science & Engineering A, 841(2022)143050.

5 - 31 The Thermal Stabilization Effect of Inert Gas Atoms on the Irradiation Hardening in V alloy

Yang Yitao

Vanadium (V) alloy is an attractive candidate materials for the tritium breeding modules (TBM) of blankets in fusion reactors. In this study, V-5Cr-5Ti alloy was irradiated by 122 MeV Ne ions (0.1 and 0.3 dpa) and 352 MeV Fe ions (0.06, 0.20 and 0.35 dpa), and subsequently was annealed in the temperature from 212 to 500 ℃. The hardening behavior and its thermal stability due to the existence of inert gas atoms were investigated. The Vickers hardness results (as shown in Fig. 1) indicate that more significant hardening was observed under Ne ion irradiation at damage levels higher than 0.05 dpa compared to Fe ion irradiation. During the annealing process, the hardening produced by Fe ion irradiation started to recover at a temperature higher than 212 ℃ and was eliminated at a temperature higher than 375 ℃. For the sample irradiated with Ne ions, the irradiation hardening of the sample with 0.3 dpa can sustain at a temperature up to 450 ℃, but an evident reduction of hardening in the sample with 0.1 dpa was observed after annealing at 212 ℃. This suggested that the existence of inert gas atoms had a thermal stabilization effect on radiation hardening, but it required a critical concentration of Ne atoms.

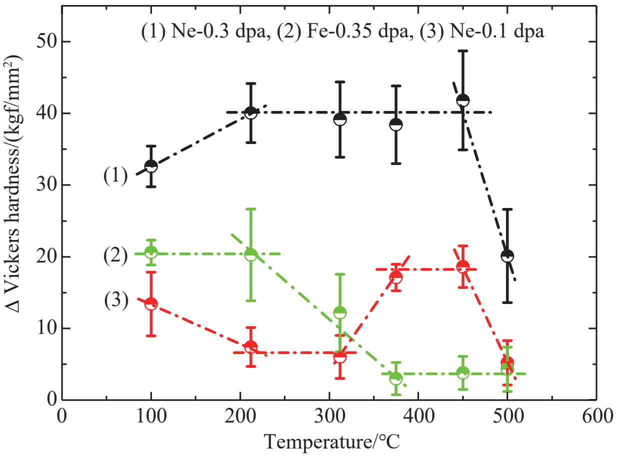

Fig. 1 (color online) The dependence of radiation hardening on annealing temperature for the samples irradiated with Ne and Fe ions.

After annealing at 500 ℃, TEM results showed that bubbles with a more homogenous distribution were observed in the sample with 0.1 dpa produced by Ne ion irradiation, but the corresponding hardness increment has been significantly reduced and is comparable to the hardness of the sample with 0.35 dpa produced by Fe ions followed by annealing at 500 ℃. This revealed that these small bubbles (~1.2 nm, as shown in Fig. 2) with high density have a weak contribution to the radiation hardening, and the major contribution to radiation hardening is still from dislocation loops.

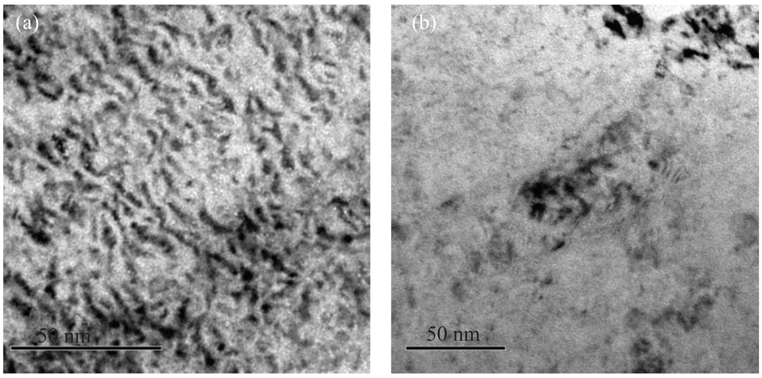

Fig. 2 (color online) TEM results of (a) the sample with 0.1 dpa produced by Ne ion irradiation and (b) sample annealed at 500 ℃ for 1 h under vacuum condition.

During the annealing process, an evident increase of hardness for the sample with 0.1 dpa was observed after annealing at 375 ℃, which can sustain at a temperature up to 450 ℃. However, the radiation hardening of the