phase induced by specific Ti addition achieve the synergy of optimized corrosion resistance and improved mechanical properties. This work provides an idea for searching reliable structure materials in advanced nuclear systems under the extreme environment of strong radiation and water corrosion.

# 5 - 3 Structure and Fracture Behavior of Ion-beam-modified SiC-$Al_2O_3$-$ZrO_2$ Ceramic Composites

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The dense $Al_2O_3$-$ZrO_2$-SiC ceramic was prepared and irradiated with Si ions to different damage levels at room temperature. The irradiation induced microstructural evolution and mechanical properties were investigated. The mechanism of the transformation and amorphization induced by ion irradiation were discussed.

According to GIXRD patterns, the phase structures of α-$Al_2O_3$ and β-SiC remained unchanged after the ion irradiation, while the peak broadening for β-SiC indicated the degradation of the crystallinity (Fig. 1). In contrast, $ZrO_2$ particles undergo a phase transition from m→t due to the accumulation of oxygen vacancies[1,2]. Once oxygen vacancy concentration reached a threshold value, the strain fields around m-$ZrO_2$ generated by the presence of oxygen vacancies were enough to lower the transition temperature. Moreover, the point defects, defect complexes, and lattice strain accumulated with irradiation, which increased the free energy of the initial compound to form a high-energy metastable phase[3,4]. Furthermore, nuclear energy loss could also induce the phase transition[5,6]. At 5.5 dpa, it was found that SiC particles were completely amorphous, which attributed to the ion bombardment induced interstitials form point defect clusters. The result was the destruction of ordered structures and formation of amorphization regions. Also, the amorphous regions were connected with each other in banded distribution at 55 dpa, and caused the softening of materials. As shown in Fig. 2, due to the consumption of fracture energy, the toughness was improved remarkably with the increase of damage levels.

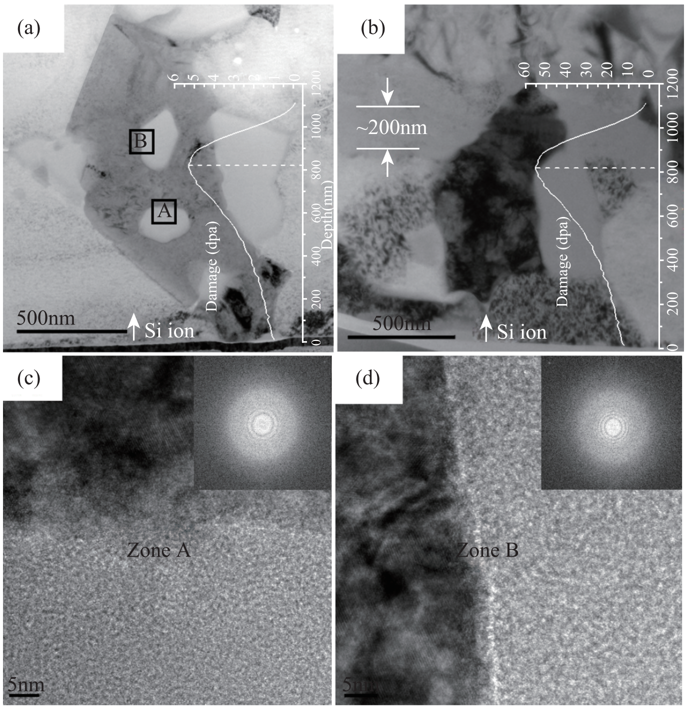


Fig. 1 (color online) TEM images of samples irradiated by Si ions: (a) 5.5 dpa, (b) 55 dpa, (c) and (d) are HRTEM and FFT of Zone A and Zone B.

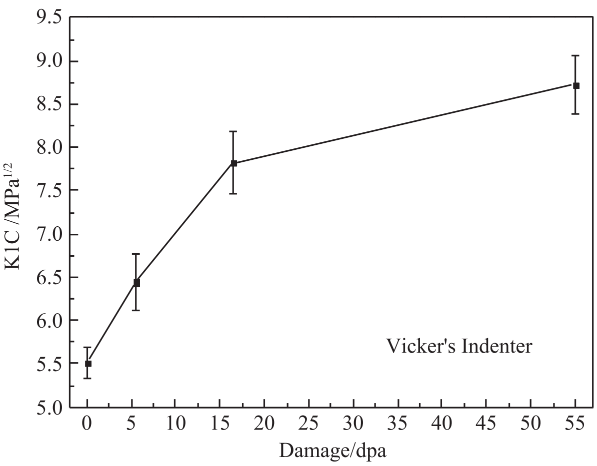


Fig. 2 (color online) Indentation toughness of ceramic composites with Si-ion bombardmentas as a function of damage level.

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## 5 - 4 Phase Transitions and He Bubble Evolution in $Ti_3AlC_2$ under Sequential He Ion Implantation and Fe Ion Irradiation

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Ternary $M_{n+1}AX_n$ phase, where M stands for an early transition metal, A is an A-group element, and X is either C or N, has exhibited the combination properties of ceramics and metals. Their excellent performance leads them to be a very promising candidate for applications involving extremely harsh nuclear environments, acting as a candidate pump impeller and bearing materials for lead cooled fast reactor, and fuel pellet coatings and accident tolerant fuel coatings (ATFCs). However, radiation damage in structural materials and accumulation of He introduced either by radiation or by transmutation through the (n, α) nuclear reaction, are known to cause the degradation of the mechanical properties of materials, thereby threatening the safe operation of reactor. $Ti_3AlC_2$, as typical materials of the MAX phase family, has received a great deal of research interest, because it has excellent resistance to irradiation and high tolerance for He.

Ion implantation or irradiation experiments were carried out on the material terminal of 320 kV multi-discipline research platform for highly charged ions in IMP, CAS, and Heavy Ion Research Facility in Lanzhou (HIRFL). $Ti_3AlC_2$ samples were irradiated by energetic Fe ions and He ions in the sequence and reverse order.

The obtained results show there are some large differences between the two irradiation sequences. In the sequential (Fe+He) irradiation, it is found that two types of ions created their own relatively independent irradiation effects in the material, with a weak interaction between them. In sequential (He+Fe) irradiation, however, the observation is quite opposite. Compared with the single Fe ion irradiation or sequential (Fe+He) irradiation, the (He+Fe) irradiation maintains the higher content of original α phase, as shown in Fig. 1. It indicates that the pre-implanted He significantly suppresses the phase transitions caused by the following Fe ion irradiation. The following Fe ion irradiation was also found to promote the evolution of the pre-formed He bubbles. It can cause not only the growth of He bubbles, but the re-solution of He bubbles, as shown in Fig. 2. This will improve the resistance to He bubbles induced damage for $Ti_3AlC_2$.

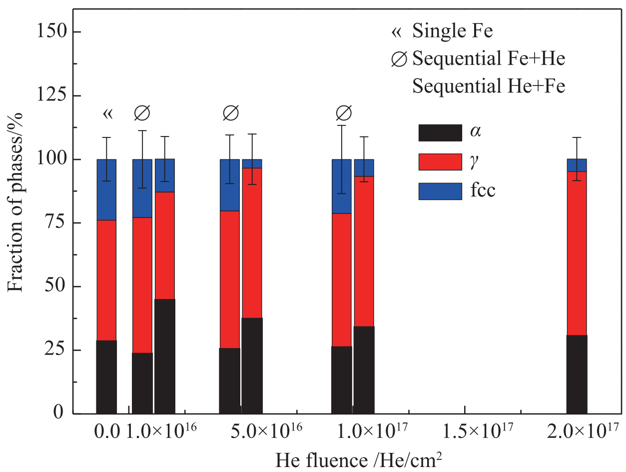


Fig. 1 (color online) The fraction of phases α, γ and fcc of the $Ti_3AlC_2$ samples with various irradiation conditions.

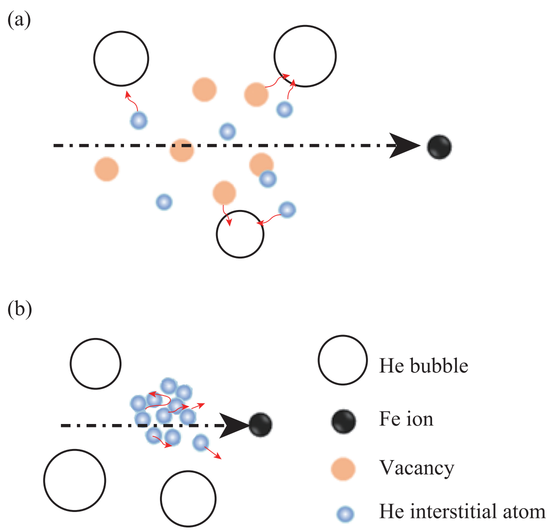


Fig. 2 (color online) Schematic illustration of the evolution mechanism of He bubbles driven by the following Fe ion irradiation. (a) The growth process of He bubbles, (b) The re-solution process of He bubbles.