

T91 钢辐照损伤与动态铅铋腐蚀耦合行为研究

摘要

T91 铁素体/马氏体钢因其良好的高温强度、导热性能和抗辐照肿胀能力，被认为是铅冷快堆包壳及堆内结构件的重要候选材料之一。然而，在实际服役环境下，T91 不仅要承受高温流动铅铋共晶（LBE）引起的持续腐蚀，还将同步积累辐照诱导位移损伤及气体相关缺陷，因此其服役行为本质上受“辐照损伤—保护层形成—动态腐蚀失稳”共同控制。围绕这一问题，本工作结合 T91 在动态高氧 LBE 中的腐蚀行为与 He 预注入后 Fe 自离子辐照的损伤演化结果，构建其在铅冷快堆相关条件下的结构演化与性能退化认识。

在动态腐蚀方面，T91 在 500 °C、饱和氧浓度和 3 m/s 动态 LBE 条件下表现出典型的分层氧化特征。1000 h 时表面形成粗糙且不均匀的颗粒状腐蚀产物层，截面总厚度约为 14–19 μm；到 2000 h，腐蚀层增厚至约 21–30 μm，表面背景趋于细化和均匀；至 3000 h，总厚度约为 24–30 μm，净增厚速率明显放缓，但表面三维起伏和方向性失稳显著增强。结合截面 EDS 与 XRD 可知，腐蚀层由外层富铁氧化物和内层富铬氧化层共同构成，表面主导相属于磁铁矿/尖晶石。这说明 T91 在动态高氧 LBE 中并非简单经历氧化层持续增厚，而是在后期进入了外层氧化物生长、剥落与再生并存的竞争阶段。

在辐照损伤方面，T91 在 450 °C 下经 2000 或 6000 appm He 预注入后，再接受 3.25 MeV Fe 自离子辐照。结果表明，He 预注入显著改变了后续缺陷演化行为：随着预注入 He 浓度由 2000 appm 提高至 6000 appm，He 泡平均尺寸由约 3.42 nm 降至约 2.91 nm，而数密度由约 $0.71 \times 10^{23} \text{m}^{-3}$ 增加至 $2.42 \times 10^{23} \text{m}^{-3}$ ，提升约 3.4 倍；同时，位错环密度相较 Fe-only 条件提高近一个数量级，且高 He 条件下大量形成环泡复合体。纳米压痕结果显示硬化行为具有明显非单调性：在 100–200 nm 深度范围内，Fe-only、Fe+2000 appm He 和 Fe+6000 appm He 条件下的相对硬化增量分别约为 207.2%、187.9% 和 263.8%，即中等 He 水平下硬化略低于 Fe-only，而高 He 水平下硬化最强。该结果说明，中等 He 含量下 He-V 团簇和稀疏气泡主要作为空位陷阱，削弱了位错环主导的硬化；而高 He 条件下，致密纳米气泡与环泡复合体共同构成更强障碍场，从而显著增强辐照硬化。

综合来看，动态高氧 LBE 决定了 T91 表层保护层的形成、分层与后期失稳方式，而 He 泡、位错环及其复合缺陷则改变了近表层扩散条件、缺陷俘获能力和局部力学响应，进而可能影响氧化膜的早期建立与后期稳定性。尽管当前辐照实验采用的是 He 预注入—Fe 自离子辐照路径，但其揭示的“缺陷结构转变—障碍场重构—力学响应变化”规律，对于理解铅冷快堆条件下 T91 的辐照-腐蚀耦合行为具有重要启发意义，也为后续开展“预辐照后短时动态腐蚀”研究提供了基础。

关键词

T91 钢；铅冷快堆；动态腐蚀；辐照硬化

Abstract

T91 ferritic/martensitic steel is regarded as one of the most important candidate structural materials for lead-cooled fast reactors because of its good high-temperature strength, thermal conductivity, and resistance to irradiation swelling. Under actual service conditions, however, T91 is subjected not only to continuous corrosion in flowing lead-bismuth eutectic (LBE), but also to irradiation-induced displacement damage and gas-related defects. Therefore, its long-term performance should be understood from the combined effects of irradiation damage, oxide-scale evolution, and dynamic corrosion instability rather than from corrosion or irradiation alone.

In this work, the dynamic corrosion behavior of T91 in oxygen-saturated flowing LBE and the microstructural evolution induced by sequential helium implantation and Fe self-ion irradiation were jointly considered in order to establish an integrated understanding of T91 degradation under lead-cooled fast reactor-relevant conditions. Under dynamic LBE corrosion at 500 °C, saturated oxygen concentration, and 3 m/s, T91 exhibited a typical layered oxidation structure. After 1000 h, a rough and non-uniform corrosion layer had already formed on the surface, with a total thickness of about 14–19 μm. After 2000 h, the corrosion layer thickened to about 21–30 μm, while the surface background became relatively finer and more uniform. At 3000

h, the total thickness remained in the range of about 24-30 μm , indicating that the net thickening rate had markedly decreased. Nevertheless, three-dimensional surface topography revealed a pronounced increase in height fluctuation and directional instability at the late stage. Combined cross-sectional EDS and XRD analyses showed that the corrosion scale consisted of an Fe-rich outer oxide and a Cr-enriched inner oxide, and that the dominant surface phases belonged to the magnetite/spinel family. These results indicate that the late-stage corrosion behavior of T91 in flowing oxygen-saturated LBE is no longer governed by simple oxide thickening, but rather by a competition between oxide growth and outer-layer degradation, exfoliation, and regeneration.

To characterize the irradiation-induced near-surface defect state, T91 was pre-implanted with 2000 or 6000 appm He at 450 $^{\circ}\text{C}$, followed by 3.25 MeV Fe self-ion irradiation. The results showed that helium pre-implantation significantly altered the subsequent defect evolution. When the He content increased from 2000 to 6000 appm, the average bubble diameter decreased from about 3.42 nm to about 2.91 nm, whereas the bubble number density increased from about $0.71 \times 10^{23} \text{ m}^{-3}$ to about $2.42 \times 10^{23} \text{ m}^{-3}$, i.e., by a factor of about 3.4. Meanwhile, the dislocation-loop density increased by nearly one order of magnitude compared with the Fe-only condition, and abundant bubble-loop complexes were formed in the high-He sample. Nanoindentation measurements further revealed a non-monotonic hardening response. In the 100-200 nm depth range, the normalized hardness increments for the Fe-only, Fe + 2000 appm He, and Fe + 6000 appm He conditions were about 207.2%, 187.9%, and 263.8%, respectively, meaning that the 2000 appm He sample was slightly softer than the Fe-only sample, whereas the 6000 appm He sample exhibited the strongest hardening. This behavior suggests that, at a moderate helium level, He-V clusters and sparse bubbles mainly act as vacancy traps and mitigate loop-controlled hardening, whereas at a high helium level, dense nanoscale bubbles and bubble-loop complexes become the dominant obstacle field and significantly enhance irradiation hardening.

Taken together, the present results suggest that the service degradation of T91 under lead-cooled fast reactor-relevant conditions should be interpreted through the coupling of two interconnected processes. Dynamic high-oxygen LBE determines the formation, stratification, and late-stage instability of the protective oxide scale, while irradiation-induced bubbles, dislocation loops, and their coupled complexes modify the near-surface defect structure, diffusion pathways, and local mechanical response, thereby potentially affecting oxide nucleation, growth, and scale stability. Although the current irradiation experiments follow a helium pre-implantation plus Fe self-ion irradiation route, the observed defect evolution and hardening behavior provide important implications for understanding the irradiation-corrosion coupling of T91 in lead-cooled fast reactor systems and provide a basis for future work on pre-irradiation-assisted short-term dynamic corrosion experiments.

Keywords

T91 steel; lead-cooled fast reactor; dynamic corrosion; irradiation hardening

Author: 凌峰, 杨 (华北电力大学)

Co-authors: Mr 琦, 管 (华北电力大学); Ms 卉平, 朱 (华北电力大学); Mr 风雷, 牛 (华北电力大学)

Presenter: 凌峰, 杨 (华北电力大学)

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