

A statistical analysis of early-stage Ni-Si clusters in irradiated 316L stainless steel

摘要

辐射诱发的溶质团簇化在核反应堆用不锈钢的性能退化过程中起着关键作用。然而，Ni-Si 团簇的早期形核机制仍未完全明确。本研究利用原子探针断层扫描技术，对离子辐照的 316L 不锈钢中 Ni 和 Si 的初始团簇化行为进行了研究。将无硅 (NS) 和高硅 (HS) 含量的高纯模型合金在 290°C 下用 3 MeV 的 Ni²⁺ 离子辐照至 0.8 dpa。采用 IPM 法发现，在高硅样品中存在 Ni 团簇和 Si 团簇，而在无硅样品中也存在镍团簇。此外，无硅样品中 Ni 团簇的数量密度较低且半径较小。采用改进的局部浓度法分析溶质偏聚情况，结果显示，添加 Si 显著增强了 Ni 和 Cr 的偏聚，其中 S 的偏聚最为明显。此外，对通过 IPM 识别出的团簇应用最近邻距离 (NND) 法，对不同类型团簇间的空间分布进行了分析。结果表明，Ni-Si 存在共团簇化趋势，同时有证据表明镍团簇存在均匀形核现象，暗示可能存在双重形核机制。这种多方法研究途径为辐照下的早期团簇过程提供了新的见解。

关键词

不锈钢；离子辐照；三维原子探针；溶质团聚

Abstract

Radiation-induced solute clustering plays a critical role in the degradation of stainless steels used in nuclear reactors. However, the early-stage nucleation mechanisms of Ni-Si clusters remain incompletely understood. This study investigates the initial clustering behavior of Ni and Si in ion-irradiated 316L stainless steel using atom probe tomography. High-purity model alloys with no Si (NS) and high Si (HS) content were irradiated with 3 MeV Ni²⁺ at 290°C to 0.8 dpa. Ni clusters and Si clusters were found in the HS samples, while Ni clusters were found in the NS samples, using the iso-position method (IPM). Moreover, the number density of Ni clusters in the NS samples was low and the radius was small. A modified local concentration method was used to analyze solute segregation, revealing significant Ni and Cr segregation enhanced by Si addition, with Si exhibiting the most pronounced segregation. Complementarily, the nearest neighbor distance (NND) method, applied to clusters identified via the IPM, provided spatial distribution analysis between different types of clusters. The results indicate a tendency for Ni-Si co-clustering, alongside evidence of homogeneous nucleation of Ni clustering, suggesting a dual nucleation mechanism. This multi-method approach offers new insight into early-stage precipitation under irradiation.

Keywords

Stainless steel; Ion irradiation; Atom probe tomography; Solute clustering

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