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Metallic Materials COMMENTARY

Insights into stress corrosion cracking from recent studies on grain boundary structure and hydrogen effects for material life extension

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STRESS CORROSION CRACKING (SCC) AS A COUPLED MECHANICAL-CHEMICAL PHENOMENON

SCC in high-temperature water remains one of the most persistent and least mechanistically resolved degradation problems in austenitic alloys for pressurized water reactors in power plants. The difficulty in establishing a definitive mechanism lies in the strong coupling of multiple factors, including high temperature oxidation, corrosion, grain boundary (GB) structure, local stress and strain, hydrogen, etc. All these processes happen at the same time during service, which has made it difficult for a long time to clearly identify what causes SCC initiation and propagation.

Among these factors, oxidation is particularly important as the resistance to SCC often depends on whether a compact and protective oxide layer was formed and the integrity of the GB during the process. Oxidation often proceeds via selective oxidation, where only specific alloying elements oxidize preferentially, enhancing local chemical and structural heterogeneity. The development of GB oxidation can be strongly influenced by several factors, including microstructure and hydrogen (Figure 1). As a result, the failure mechanism remains difficult to clarify despite decades of study. Hydrogen inherently originates from power-plant structural components in high-temperature water environments. However, hydrogen can diffuse into the matrix and interact with internal defects such as dislocations and GBs; under complex stress states, this coupling promotes hydrogen embrittlement and accelerates material degradation. To better decouple these contributions, well-controlled experiments are needed to separately quantify the roles of mechanical, chemical, and hydrogen-related effects, thereby improving the reliability assessment of SCC in infrastructures. Two recent studies provide complementary insights into this issue. One focuses on the role of GB structure in Alloy 690 exposed to hydrogenated water,[1] while the other examines the effect of diffusive hydrogen (DiffH) in 316L stainless steel using a carefully designed in-situ H-charging method.[2] Together, these works advance SCC research by explicitly decoupling the roles of chromium transport, diffusion-induced grain boundary migration (DIGM), preferential intergranular oxidation (PIO), and hydrogen.

GB STRUCTURE EFFECTS ON SCC

The study on solution annealed Nickel-base alloy 690 by Kuang and Was demonstrates that chromium transport along GBs is strongly controlled by GB structure.[1] Using advanced microscopy, the authors show that random high angle GBs and transformed twin boundaries support fast chromium diffusion, leading to the formation of a continuous chromium-rich surface oxide and a clear DIGM zone beneath the surface. In contrast, coherent twin boundaries exhibit very limited outward chromium diffusion, no detectable GB migration, and instead show intergranular chromia penetration similar to internal oxidation in the grain matrix. Incoherent twin boundaries display intermediate behavior, with some chromium depletion but no measurable GB

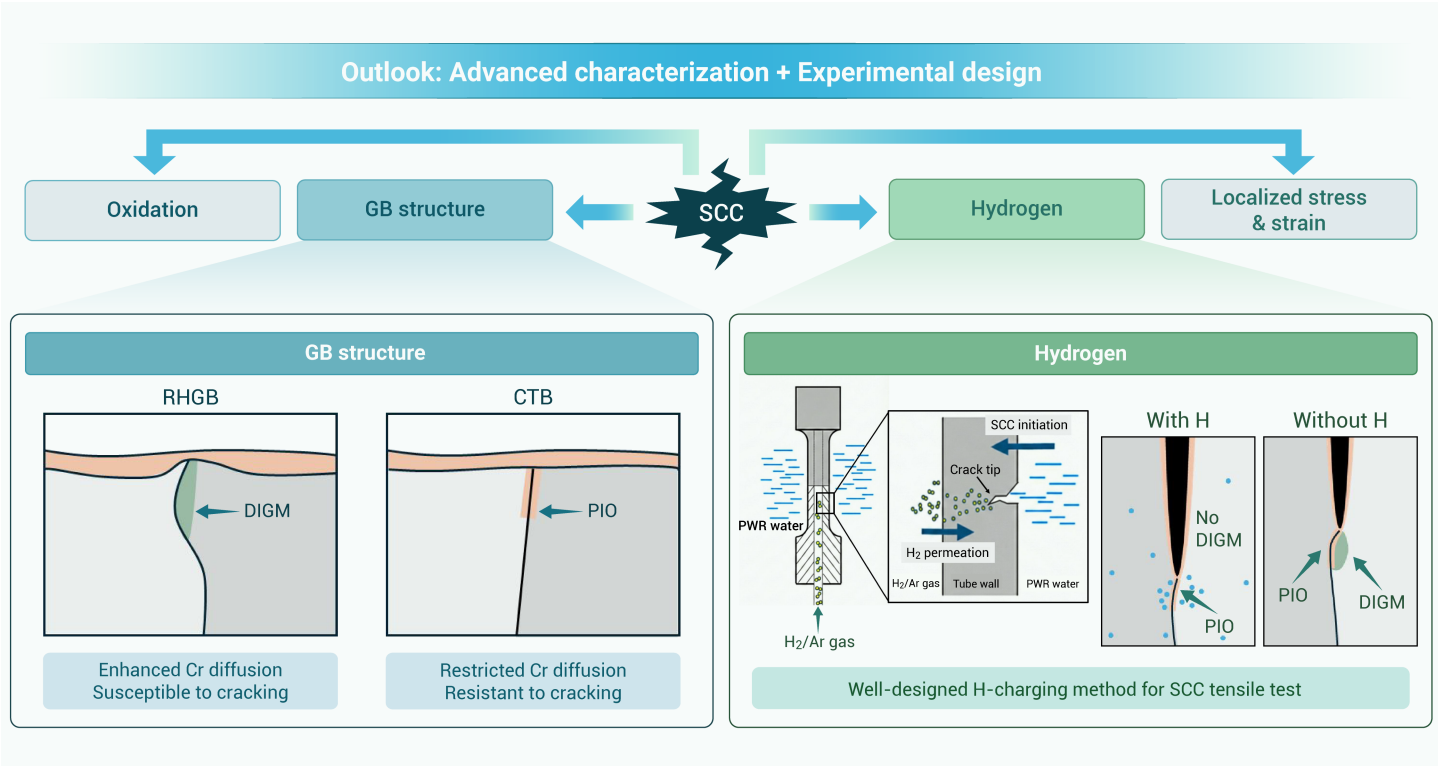

Figure 1. Schematic illustration of the coupled effects of material structure and hydrogen on SCC mechanisms in Ni-based alloys used in power plants.

migration.

These results place chromium diffusion at the center of intergranular degradation in Alloy 690, while also revealing its strong GB structure dependence. The density of coincident sites in the GB plane controls vacancy-mediated solute diffusion, such that increasing boundary coherency suppresses chromium mobility. Importantly, this finding demonstrates that the crack resistance of Alloy 690 does not stem from the absence of oxidation at GBs. Instead, it arises from the formation of a structurally ordered and semi-coherent chromia–metal interface that remains mechanically robust under dynamic straining. While defect-mediated processes such as dislocation motion and vacancy-assisted diffusion may locally enhance mass transport, the semi-coherent interface constrains collective GB migration, thereby stabilizing the GB structure against mechanically driven decohesion. This finding provides a chemically and physically grounded explanation for the intergranular fracture and SCC resistance, and sheds light on predicting the service life of materials under extreme conditions.

ROLE OF HYDROGEN IN SCC

In contrast, hydrogen is another important factor that governs the oxidation of GB. Hydrogen inevitably originates from the power-plant structural system. Among the various forms, dissolved hydrogen (DH) in the coolant and DiffH, which enters and migrates through the metal lattice of components, are considered the most significant. First, DiffH strongly alters vacancy formation and stabilization, which in turn governs mass transport and dislocation mobility. Second, DH is believed to influence SCC primarily through electrochemical effects. It is difficult to address hydrogen in experimental design. The key contribution of this study lies in separating the effect of DiffH from DH during SCC. Wang et al.'s study on 316L stainless steel employs an innovative hollow tensile specimen to introduce DiffH in-situ during SCC testing at 325 °C.[2] The consideration is that hydrogen exhibits different functional roles depending on its location.[3,4] The experimental design in Wang et al.'s study enables isolation of the hydrogen effect from other environmental variables. DIGM is generally considered essential for the onset of intergranular oxidation. However, the results show that, in the presence of DiffH, DIGM at the crack tip is strongly suppressed, while hydrogen charging still promotes crack initiation. Moreover, the study makes delicate use of electron energy loss spectroscopy, indicating that although DIGM is not observed in the presence of DiffH, Cr is still oxidized due to its substantially lower corrosion potential compared with Ni and Fe. Consequently, preferential intergranular oxidation can persist in the absence of GB migration. This finding challenges the previous assumption that DIGM is a necessary precursor to intergranular oxidation.

Based on the experimental evidence from the two studies, the roles of GB structure, hydrogen, and Cr transport in SCC in austenitic alloys can be more clearly defined. In Alloy 690, when the effects of hydrogen are not independently isolated, GB structure primarily governs Cr diffusion. GBs that permit rapid outward Cr transport exhibit DIGM and the formation of continuous chromia surface oxides. In contrast, coherent twin boundaries suppress chromium diffusion and migration. As a result, these GBs display a high resistance to cracking owing to the formation of semi-coherent chromia–metal interface. In Wang et al.'s study, the in-situ introduction of DiffH significantly suppresses DIGM. Despite this suppression, preferential intergranular oxidation and crack initiation persist and are further enhanced. Overall, these results demonstrate that Cr diffusion is a key factor influencing SCC. However, its behavior may be controlled either by GB structure or by chemical fields such as DiffH. Ultimately, SCC susceptibility is determined by the structural order and mechanical integrity of the oxidized GB region.

FUTURE OUTLOOK

The advanced characterization techniques and well-controlled experimental designs employed in the above studies demonstrate clear advantages in elucidating the mechanisms of SCC and DIGM.

SCC in high-temperature water does not originate from a single dominant mechanism. Rather, it arises from the coupled evolution of GB structure, mechanical deformation, and the surrounding chemical environment, reflecting its inherently complex multi-physics and multi-chemistry nature. A major barrier to mechanistic understanding has been the difficulty of separating the influence of individual factors under realistic conditions. The two studies discussed here provide clear examples of how this challenge can be addressed through deliberate decoupling. One isolates GB structure through advanced materials processing and atomic resolution characterization, while the other isolates hydrogen effects through precise experimental design and in-situ control. Together, they offer a methodological template for future SCC research.

Further progress in mechanistic understanding and materials life extension will rely on continued development along the two directions outlined above. First, in-situ characterization techniques that integrate heating, mechanical loading, and environmental control with scanning transmission electron microscopy enable direct observation of atomic-scale structural evolution under corrosive environments, providing critical insights for early diagnosis and remaining life assessment of SCC. Besides the structure characterization, in-situ and operando electrochemical techniques with high spatial and temporal resolution have become a major focus. Unlike conventional ex-situ microscopies that require high vacuum and limit observation of dynamic corrosion, methods such as scanning electrochemical microscopy and scanning electrochemical cell microscopy enable simultaneous mapping of morphology, chemistry, and electrochemical activity under realistic conditions, offering the potential to reveal localized corrosion dynamics.[5] Second, precise experimental design that allows key variables to be independently controlled is critical for establishing causality in SCC. By integrating diffusion, oxidation, mechanics, and hydrogen effects within a unified multiscale description, these approaches provide a quantitative basis for interpreting experimental results and offer predictive guidance for both experimental design and alloy development.

CONCLUSION

In summary, these two studies resolve long standing ambiguities surrounding the roles of Cr diffusion, DIGM, and intergranular oxidation by independently isolating the effects of GB character and DiffH. These two studies collectively demonstrate that decoupling strongly coupled variables is essential for achieving a genuinely mechanistic understanding of SCC. They further underscore the critical importance of developing and integrating advanced experimental approaches together with state-of-the-art materials characterization techniques for advancing mechanistic insight into SCC.

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DECLARATION OF INTERESTS

The authors declare no competing interests.