Electrochemical Microprobes Reveal Irradiation Damage in Nuclear Alloys

Xin Chen, Sina Shahrezae, Gaurav N. Sant, Marta Pozuelo
University of California, Los Angeles

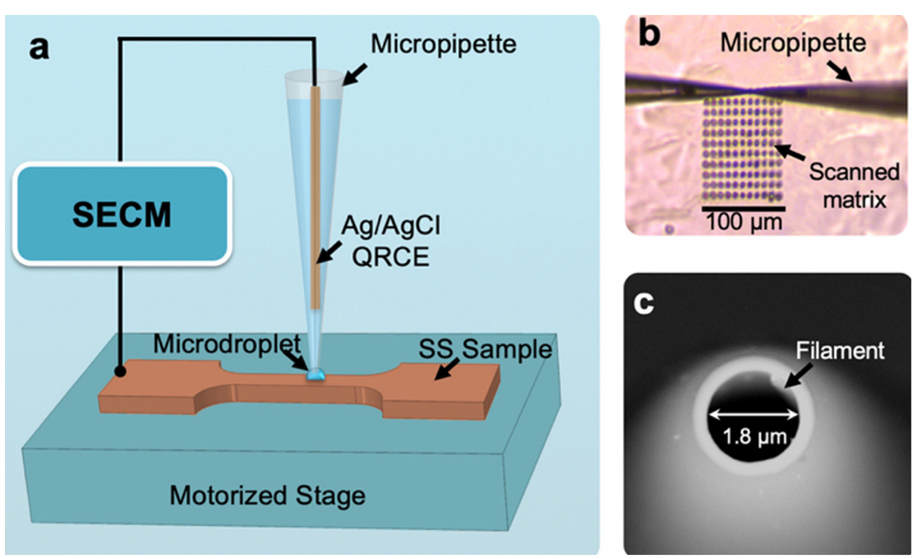
Yongqiang Wang
Los Alamos National Laboratory

Materials Research Pathway

Alloys have been developed to function in aggressive environments, such as nuclear power plants, nuclear waste disposal facilities [1], and others. In such environments, alloys may experience corrosion [2], irradiation, and deformation across scales [3, 4], or more uniquely, stress corrosion cracking (SCC) and irradiation-assisted stress corrosion cracking (IASCC) [5, 6]. Transformative damage detection technologies are needed not only to predict and prevent catastrophic failure in nuclear constituents, but also to screen next-generation alloys that are resistant to complex and aggressive environments.

Under the work scope of the materials research pathway, the University of California–Los Angeles (UCLA) has developed glass microprobes with nano-to-micrometer openings and filled them with electrolyte and filament electrodes, as observed in Figure 3. The microprobes were used to perform scanning electrochemical microscopy (SECM) and to profile corrosion activity in nuclear alloys. This technique, most significantly, discloses regions subjected to SCC and IASCC in scans take only seconds to minutes. For instance, as observed in Figure 4(a) and Figure 4(b), the microprobe resolved strain-induced microstructures and their enhanced corrosion activity; features that in general can lead to SCC initiation. Moreover, the microscope can also reveal irradiated microstructures that are of reduced corrosion resistance.

Figure 3 (a) A schematic of the microprobe setup developed using SECM. (b) An optical photo showing the matrix of microdroplets during a scan in progress. (c) A scanning electron microscopy (SEM) image of the filamented borosilicate micro-pipette used in this study.



In other words, it is discovered that the more an alloy has been exposed to radiation, the less resistant to corrosion it is. Therefore, the technique can be used to forecast IASCC initiation in alloys that are deformed and damaged under irradiation, as observed in Figure 4.

Currently, the team has been pushing the resolution limit of this microprobe technique to interrogate nanoscale features, such as grain boundaries and dislocation channels, as indicated in Figure 4(c) and Figure 4(d). By doing so, very early stage irradiation-induced damage and cracking can be resolved. Furthermore, due to the high-throughput and high-resolution nature of this technique, in-reactor probes to survey reactor components during maintenance shutdowns are being developed. Finally, the microprobe technique can be used to provide accurate corrosion examinations with fast turnaround times, as well as to screen next-generation nuclear alloys for new, advanced reactor designs.

References:

1. Cattant, F., and D. Crusset, 2008, "Corrosion issues in nuclear industry today," Materials Today, 11(10), 32–37.
2. Chen, X., M. Gussev, M. Balonis, M. Bauchy, and G. Sant, 2021, "Emergence of micro-galvanic corrosion in plastically deformed austenitic stainless steels," Materials & Design, 109614.
3. Gussev, M. N., and K. J. Leonard, 2019, "In Situ SEM-EBSD analysis of plastic deformation mechanisms in neutron-irradiated austenitic steel," Journal of Nuclear Materials, 517, 45–56.
4. Gussev, M. N., K. G. Field, and J. T. Busby, 2014, "Strain-induced phase transformation at the surface of an AISI-304 stainless steel irradiated to 4.4 dpa and deformed to 0.8% strain," Journal of Nuclear Materials, 446 (1–3), 187–192.
5. Matsubara, N., T. Kobayashi, K. Fujimoto, Y. Nomura, N. Chigusa, and S. Hirano, 2011, "Research programs on SCC of cold-worked stainless steel in Japanese PWR NPP," In International Symposium Fontevraud, Vol. 7, p. A099.
6. Takakura, K., K. Nakata, M. Ando, K. Fujimoto, and E. Wachi, 2007, "Lifetime evaluation for IASCC initiation of cold-worked 316 stainless steels' BFB in PWR primary water," In Proceedings of the 13th Int. Conference on Environmental Degradation of Materials in Nuclear Power Systems.
7. Was, G. S., D. Farkas, and I. M. Robertson, 2012, "Micromechanics of dislocation channeling in intergranular stress corrosion crack nucleation," Current Opinion in Solid State and Materials Science, 16(3), 134–142.

Figure 4. The scanning microprobe technique reveals: (a) strain localization; and (b) corrosion susceptibility in a deformed nuclear alloy. (c)-(d) The same technique was applied to predict IASCC susceptible regions [7] in a nuclear alloy that was deformed and damaged under irradiation. The scale bars are 20 µm in length.