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Scope for High Temperature Coatings in the Nuclear Field

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Coatings are widely used in a variety of fields to increase wear and/or corrosion resistance, reduce friction, alter optical and thermal properties, etc. A wide range of coatings to protect or enhance specific properties of the substrate are presently available and the industrial processes to apply the coatings are well established but surprisingly, use of coatings in the nuclear field has received very little attention. This presentation will highlight the scope for using high temperature coatings in the nuclear field.

The nuclear field includes all stages of the nuclear fuel cycle. It ranges from uranium mining, its purification and enrichment, fuel fabrication, the power or research reactor where the fuel is burnt, reprocessing or long term storage of the spent fuel and radioactive waste management. Even though a vast array of metallic components and structures in the nuclear field can be protected with coatings, due to space and time constraints, I will focus only on fuel claddings and reactor components.

The most common type of nuclear reactor, accounting for two-thirds of current installed generating capacity worldwide, is the Pressurised Water Reactor (PWR) followed by the Boiling Water Reactor (BWR). Other reactor types are the Pressurized Heavy Water Reactor, the Advanced Gas Cooled Reactor and the Soviet design RBMK Reactor. All components and structures inside the reactor's pressure vessel are exposed to very high levels of irradiation at high water/steam pressures and temperatures. Qualification of materials for use as reactor components and structures is a very long process and could take from 10 to 20 years. Despite the caution exercised during material selection for fuel cladding or reactor components, degradation brought about by changes in mechanical properties under irradiation has been the primary cause for unplanned outages in the nuclear industry. Qualification of a coated material is further complicated because two different materials are involved, besides the interface, and is the main reason for scant use of coatings in the nuclear field.

Some situations where coatings can be used:

Prevention of accelerated corrosion of zircaloy at high temperature (accident situation) is extremely important to avoid generation of hydrogen (which was the cause of the hydrogen explosions that occurred in the BWRs 1, 2 and 3 of the Fukushima I Nuclear Power Plant in Japan). Had the zircaloy cladding been coated with, say a FeCrAl alloy, the explosions could have been averted by delaying H diffusion through the alumina layer and gaining time to take other preventative measures.

Even at normal reactor operating temperatures, the zircaloy fuel cladding reacts with the water and liberates hydrogen. It has been shown that approximately 16 % of these hydrogen atoms are picked up by the cladding in PWR conditions and between 5-10 % (of deuterium) in CANDU reactors. The zirconium hydrides that form in the cladding cause blisters, delayed hydride cracking and embrittlement. These effects are accelerated considerably in accident conditions. When a fuel cladding fails, leading to water ingress, hydrogen forms and is absorbed from the inner wall of the cladding. These effects can be mitigated by the use of plasma coatings with low hydrogen permeability and surface treatments.

Hydrogen (or tritium) diffusion barriers are essential to prevent hydrogen embrittlement. The ZrO_2 on the surface of Zr alloys is a diffusion barrier, but it is not completely crack-free and has some pores. This can be overcome by using a PVD ZrO_2 that is uniform, crack and pore free.

Fretting-wear of PWR fuel rods against structural grid supports is due to repeated cyclic rubbing between two surfaces caused by flow induced vibrations. This is difficult to avoid and use of a coating or (local) hardening of the fuel cladding could be an elegant and effective method to avoid this type of degradation.

When fuel swells during irradiation with fission product build up in the space between the cladding and the fuel, intermetallic phases with poorer mechanical properties are formed and these severely compromise the reliability of the cladding. Even though several methods have been proposed to prevent fuel-cladding interactions, one option is to coat the inner walls of the cladding with a TiN-based coatings.

Presently Generation III and III+ reactors are in use. Generator IV reactor designs promise higher efficiencies but their service conditions will be even more severe. Hence development and qualification of materials as well as coatings resistant to higher irradiation levels, higher temperatures and more aggressive media will be the key stages before a Gen IV reactor is constructed.

Besides the few instances mentioned above where coatings can be used to mitigate degradation in nuclear reactors, other potential applications for coatings in nuclear power plants will be presented and discussed.