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Influence of corrosion and mechanical loads on advanced ceramic components

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Abstract

Advanced oxide ceramics are prospective materials for severe application conditions, including corrosion, particularly, in oxygen-rich environments, combined with the action of mechanical loads. The corrosion behavior and mechanical strength decrease of oxide ceramics, such as high alumina, alumina–mullite and zirconia-based ceramics, were studied in water steam supercritical conditions (elevated temperatures and pressures). The strength decrease under the action of the studied aggressive environment is mostly dealt with the glassy phase dissolution and intergranular corrosion for alumina–mullite and high alumina ceramics, while degradation of zirconia-based ceramics is also dealt with the phase transformation. The influence of structure defects related to processing of the ceramics on corrosion is considered.

Keywords: C. Corrosion; C. Strength; D. Al_2O_3; D. ZrO_2

1. Introduction

Advanced ceramics are highly prospective engineering materials for severe application conditions, including corrosion, particularly, in oxygen-rich environments, combined with the action of mechanical, thermal and electrical loads [1–6]. However, the degradation of non-oxide advanced ceramics occurs rather fast in wet oxygen-rich atmospheres at elevated temperatures due to their oxidation [3,6–10]. In opposite, oxide ceramics have a high potential in these situations. Among a variety of applications, where the mentioned conditions may exist, these materials can be successfully used in energy generation, nuclear power plants and reactors, mineral, mining, oil&gas and chemical processing. In particular, special types of oxide ceramics are strong to corrosive attacks in harsh environments such as high-temperature water steam at elevated pressures and acidic and basic aqueous solutions of high concentrations, especially if the action of corrosive agents occurs at mechanical, thermal and electrical loads.

For example, these severe conditions take place in nuclear power plant and reactors where high-temperature and high-pressure steam is used as the heat processing source. Electrical insulators (e.g. feedthroughs for electrical cables installation, structural and electrical insulating components in nuclear reactors and others), as well as valve and mechanical seals, made of alumina and alumina–mullite ceramics are successfully used there due to high mechanical and electrical strength, corrosion and radiation resistance [1,2,5,11–14]. As another example, water steam of high temperatures and pressures is also used in oil processing; steam injection is a common method of extracting of heavy oil. This method is considered as an enhanced oil recovery method, and it is used as the main process of thermal stimulation of oil reservoirs. It includes ‘‘cycle steam stimulation’’ and ‘‘steam flooding’’ where steam is injected into a well for a certain period of time to heat the oil in the surrounding reservoir to the conditions when oil flows. The steam-assisted gravity drainage (SAGD) is one of the ‘‘advanced’’ oil recovery methods, particularly used in oil sands in Canada, where the conditions are even more severe for the processing equipment components due to the combination of corrosion, abrasion, erosion, mechanical and thermal loads. It is clear

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that only advanced materials can survive in these conditions with minimal degradation, and oxide ceramics based on alumina and zirconia may be very good candidates for manufacturing of different valves, seats, mechanical seals, bearings, pistons, impellers, lining for pump volutes, nozzles, turbo drill components and many others [15,16]. Severe corrosion conditions also take place in the "modified" Claus sulphur recovery units in oil&gas and chemical processing where "water-wall" boilers are used utilizing high-velocity oxygen-rich air as the oxidant and where steam and acids at high temperatures attack the structural components and lining. High alumina ceramics is one of the mostly used materials in these units.

In general, during exposure of ceramics in corrosive environment or, moreover, under joint attack of corrosive and abrasive–erosive environment, the bonds between grains in polycrystalline ceramics become weaker. In some cases, it is accompanied by the formation of micro-cracks, which then propagate to the visual cracking, and by the leaching of the material from the surface. This weakening, of course, depends on the kind of corrosive–erosive medium and service conditions, and it results in the strength reduction of ceramics.

At the development and manufacturing of advanced ceramic materials and components designated for the service in corrosive environment and structural and wear protection applications, many factors have to be taken into consideration. They include the design of the components and general assembling into devices; the features of their applications, such as mechanical, thermal and electrical loads and how these loads are applied, duration of their actions; types and compositions of corrosive and abrasive media, their parameters, e.g. temperature and pressure of corrosive media, hardness and size of particles of abrasive media, flow velocity, duration and cycling, etc. Also the manufacturing features and capability of the ceramics have to be taken into account, e.g. ability to produce particular shapes and sizes, ceramic microstructure, capability to joint ceramic materials and components with other components of the devices.

The information related to the influence of corrosion in water steam environments on mechanical properties of oxide ceramics is limited; particularly, with minimal amounts of recent publications. In this paper, the features of the corrosion of advanced engineering ceramics, mainly alumina- and zirconia-based materials, in water steam of "supercritical" parameters (elevated pressures and temperatures) used in some industrial applications are considered and summarized based on the extensive studies conducted during the years. The influence of these corrosive environments on the mechanical strength and joint action of corrosion and mechanical loads was evaluated as the studied materials have to serve under mechanical loads. Some technological factors affecting reliability, mechanical properties and corrosion resistance of ceramics were reviewed. Many factors affecting corrosion process of ceramics in water steam environments, including when mechanical loads are also the part of the service conditions, may be spread out for the integrity of ceramics and corrosion situations in other environments.

2. Features of the water steam as the corrosive media

Water steam being at high temperatures and pressures (200–400 °C and 4–40 MPa, respectively) is a highly corrosive environment, and the corrosion process in these conditions may be very strong when the exposure occurs during a long period of time. Basically, water molecules have the–O–H bonds with the length of about 0.1 nm and the hydrogen bonds H…O- with the length of about 0.176 nm. The "aggressiveness" of the water steam is dealt with the fact that, at high temperatures and pressures, hydrogen bonds between molecules of water are weakened and broken, and it results in significant decrease of viscosity and surface tension of water and increase of its penetration into the pores of solid bodies. At these severe conditions, water partially dissociates to hydrogen and hydroxyl ions:

$$H_2O \rightarrow H^+ + OH^- \text{ and } 2\,H_2O \rightarrow H_3O^+ + OH^-$$

The constant of dissociation and, hence, the activity and reaction ability of the hydrogen and hydroxyl ions in the gaseous phase are increased with the increase of temperature and pressure. The influence of temperature increase may be expressed by the van't Hoff equation $d(lnK)/dT = -U/RT^2$, where K—constant of water dissociation, T—temperature, R—universal gaseous constant, U—heat of dissociation. The pressure increase also results in the destruction of the bonds in the water structure and hence promotes the activity of the formed ions. The pressure dependence may be expressed as $(dlnK_x/dP)_T = \Delta V/RT$, where ΔV—partial molar volume, x—mole fraction, P—pressure. These ions have very small sizes, and, because of this, they can easy penetrate through micro-pores of the ceramic surface and the grain boundaries and defects of the ceramic structure destroying the grains after a long exposure. Due to the small sizes of these ions, their penetration into the crystalline lattice of the surface grains may take place. The interaction of metal oxide with water steam, in general, occurs through the formation of hydroxide:

$$Me_xO_y + H_2O \rightarrow Me(OH)_z$$

$$Me(OH)_z \rightarrow Me(OH)^{+}_{z\text{–}1} + OH^- \rightarrow Me(OH)^{+}_{z\text{-}2} + 2OH^- \rightarrow \text{finally to } Me^{Z+}$$

$$Me(OH)_z \rightarrow HMeO_z^- + H^+$$

In some cases, the "impurities" to water steam make this environment even more "aggressive".

Generally, the most corrosion resistant ceramic materials usually have microcrystalline structures formed by the thermodynamically stable phases with minimal amounts of a glassy phase and impurities and with zero open porosity. If the ceramics consist of different oxides, the interaction with water steam or with the products of its dissociation will occur