STRESS CORROSION CRACKING OF NICKEL-BASE AND COBALT-BASE ALLOYS

Narasi Sridhar and Gustavo Cragnolino
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
San Antonio, TX

OUTLINE

Nickel-base alloys are often used because their resistance to stress corrosion cracking (SCC) is superior to stainless steels, especially in chloride environments. However, these alloys are susceptible to SCC in various environments. It is the purpose of this article to review the state of knowledge regarding the combination of environmental and material parameters that may lead to cracking in these alloys. In this respect, SCC has been broadly interpreted to include some aspects of hydrogen embrittlement not only because hydrogen embrittlement forms part of the spectrum of environmentally-induced cracking, but also because hydrogen embrittlement has been suggested to be the mechanism in some SCC phenomena. Cobalt-base alloys are used in many instances because of their strength and resistance to wear and high temperature corrosion. Cobalt-base alloys are included in this review because many similarities exist in the SCC behavior of cobalt-base alloys and nickel-base alloys, although there is a paucity of data for the former.

The chapter will be divided into several sections. An outline of the physical metallurgy of Ni and Co-base alloys will be provided in the first section. The focus will be on those factors that influence the stress corrosion cracking resistance. Such factors include stacking fault energy, coherent precipitation, order-disorder transformations, sensitization due to carbide or intermetallic precipitation, and segregation of metalloid impurities to grain boundaries.

While the number of environments found to stress corrosion crack Ni and Co-base alloys have increased with time, there are many specific combinations of alloy and environment. The types of environments that have been shown to cause SCC in Ni-base alloys range from high-purity water in nuclear power generation to concentrated brine containing sulfur species found in oil and gas production. While the cause of SCC in high-purity water is still debated, the SCC in H_2S + chloride environments at high temperatures has been better established to be due to anodic dissolution processes. In the case of Ni-Cr-Fe-Mo alloys, the addition of sulfur containing species (H_2S, S, S_2O_3 etc) has been shown to exacerbate cracking. In other alloy systems such as the Ni-Mo alloys, SCC has been found to be specific to certain environments (e.g., iodides cause greater embrittlement in these alloys than chlorides or fluorides). While Ni-Cr-Fe-Mo alloys have been shown to be more resistant to SCC in chloride environments than the stainless steels, cracking has been observed in these environments once a certain temperature has been exceeded. SCC occurs in the Ni-base alloys in certain potential regions, although the corrosion potential has not been measured in many cases where SCC has been observed.

In some cases (e.g., alloy 600 in steam generator tubing, alloy 825 in oil and gas tubing), SCC is observed under crevices. Galvanic coupling may have a beneficial or detrimental effect on SCC. For example, coupling to steels in room temperature Cl^- + H_2S environment can exacerbate cracking of certain Ni-base alloys because the mechanism is one of hydrogen embrittlement. On the other hand, the same coupling can cause a reduction in SCC in the same environment at high temperatures. The effect of environmental parameters such as the type of anions and cations and their concentrations, temperature, applied or open-circuit potential, presence of crevices, and galvanic coupling on SCC will be reviewed in the next section. Examples from many industrial applications will be presented.

The mechanical factors in SCC including applied or residual stress levels, strain rate, and presence of defects inducing locally elevated stresses will be examined in the third section. Strain rate has been shown to be an important variable in the SCC of many alloys. However, the range of strain rate that can result in SCC appears to differ in various environments, probably depending on the underlying rate controlling processes. The effect of notches or cracks on SCC has been studied in many systems. Because of the well-defined stress and strain conditions at crack tips, models have been developed for crack growth phenomena, and these will be briefly reviewed as they apply to Ni-base alloys.

In the following section, the effect of material variables on SCC, such as chemical composition, grain size, stacking fault energy, presence of second-phase particles, short- and long-range ordering, and segregation of metalloid elements, will be reviewed. The effect of alloy chemical composition on SCC is dependent on the environment under consideration. For example, in chloride solutions, Ni seems to be the most beneficial element, whereas, when sulfur species are present in the chloride solutions, Cr and Mo also have important beneficial effects. The effect of alloying elements such as Al, Nb(Cb), and Ti depend on the solubility of other alloying elements such as Cr and Mo in the coherent phases formed by the former. The effects of alloying elements also depend on the applied potential. For example, in caustic solutions, Cr may be beneficial in one potential regime and have no effect in another. Minor alloying elements such as S, P, and Sb may have detrimental effects due to their segregation to grain boundaries. Stacking fault energy and, hence, deformation mode has a profound effect on SCC. The addition of Co to Ni lowers the stacking fault energy, promotes planar deformation mode, and, hence, increases the susceptibility to SCC. Short- and long-range ordering occurs in many Ni-Cr-Mo alloys upon exposure to temperatures in the range of 200 - 500°C and have somewhat similar effect as lowering the stacking fault energy. Curiously, however, the ordering reactions seem to have a greater effect on hydrogen embrittlement than on SCC. Presence of coherent particles after age-hardening treatments also can result in planar deformation modes and increase cracking. Grain boundary precipitation, resulting in regions depleted in alloying elements, can have adverse or beneficial effects depending on the environment and applied potential. For example, in caustic solutions, sensitization in alloys 600 and 800 has a beneficial effect on SCC when an anodic potential is applied and has a detrimental effect when tested under open-circuit conditions.

An attempt is made to present these diverse observations in a coherent framework of environmental factors and microstructural factors. The industrial examples of SCC will be intertwined within this framework. However, in many cases, quantitative information on the effect of one or more of these factors is not available. The areas needing further systematic investigation will be identified.