

FIGURE 11.8 Corrosion fatigue crack growth rates for 4340 steel in 3 percent NaCl solution [10] (reprinted by permission of the American Society for Testing and Materials).

11.1.4 Protection against Corrosion Fatigue

The principal way we can reduce corrosion fatigue problems is to choose materials that resist corrosion in the expected environment. Increased corrosion fatigue resistance can also be accomplished through various surface treatments, such as shot-peening, cold working, and nitriding, which induce desirable surface compressive self-stresses. Anodic coatings have usually been beneficial, while cathodic coatings have been detrimental. Zinc and cadmium coatings are anodic to steels and have produced improved corrosion fatigue resistance. Zinc coatings have provided the better improvements. Chromium and nickel are cathodic to steels, and electrolytic plating with these metals produces undesirable tensile self-stresses, hairline surface cracks, and possibly hydrogen embrittlement.

11.2 Fretting Fatigue

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Surface coatings such as paint, oil, polymers, and ceramics can protect against corrosive air and liquid environments if they remain continuous. However, under service conditions for many components and structures it is difficult or maybe impossible for these coatings to retain complete continuity. Broken or disrupted coatings can eliminate the beneficial effects.

Oxide coatings can be beneficial to corrosion fatigue resistance. Cladding of higher strength aluminum alloys with a pure aluminum surface layer (alcladding) has caused substantial increases in corrosion fatigue resistance of the base alloy. They often decrease air fatigue resistance, however. Shot-peening in conjunction with oxide coatings has caused even greater increases in corrosion fatigue resistance. In fact, shot-peening alone is quite beneficial to corrosion fatigue resistance, as well as to air fatigue resistance.

Corrosion inhibitors that form an adherent corrosion resistant chemical film on the metal surface have been somewhat successful. Chromates and dichromates have been widely used.

11.1.5 Dos and Don'ts in Design

1. Do consider that materials are susceptible to stress corrosion cracking under static loads when stress intensity values are greater than K_{ISCC} , which varies from about 0.1 to 1.0 times K_{Ic} .
2. Don't relate water or salt water corrosion fatigue resistance of steels to ultimate tensile strength. Many carbon and low alloy steels have similar corrosion fatigue strengths in water and salt water and thus high strength steels may not be advantageous unless surface compressive self-stresses and/or protective coatings are used. Long-life corrosion fatigue strengths in water and salt water can vary from about 5 to 40 percent of the ultimate strength.
3. Do obtain better corrosion fatigue resistance by choosing a material that exhibits low corrosion in the service environment.
4. Do consider stainless steels for better corrosion fatigue resistance; but their resistance is reduced relative to fatigue resistance in air.
5. Don't overlook the deleterious effects of humidity on fatigue resistance, particularly in aluminum alloys.
6. Do consider the many factors that can improve corrosion fatigue resistance, such as shot-peening, surface cold working, nitriding, anodic coatings cadmium and zinc, cladding, paint, oil, ceramic and polymeric coatings, and chemical inhibitors.

11.2 FRETTING FATIGUE

The nature of fretting-induced fatigue failures is not well understood and the terms used to describe the phenomena are not universal. Terms such as fretting, fretting corrosion, fretting fatigue, fretting corrosion fatigue, and

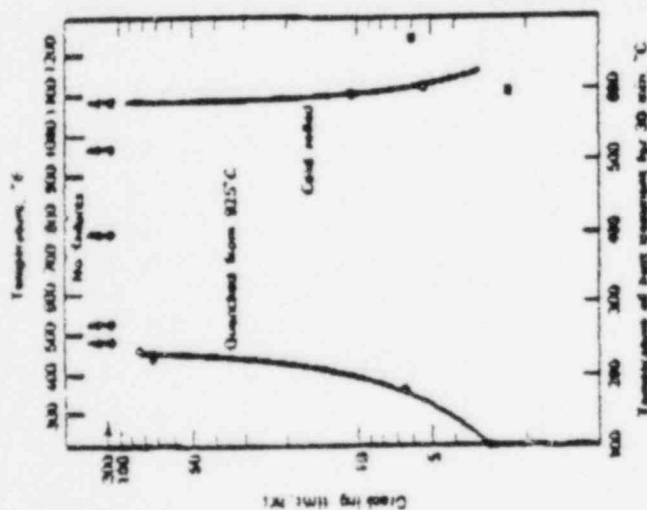


Fig. 4. Effect of heat treatment of mild steel after quenching or cold rolling (40% reduction of thickness) on resistance to stress corrosion cracking in boiling nitrate solution.

cracking. Iron ($>0.002\%$ C)¹¹ or mild steel (0.04% C) quenched from about 925°C contains a sufficient concentration of carbon atoms along the grain boundaries to induce susceptibility. Low-temperature heating, (e.g., 250°C for one-half hr) randomly nucleates iron carbides, which rub the grain boundaries of carbon, accounting for increased resistance or immunity. Longer heating, or at higher temperatures (e.g., 70 hr at 445°C) allows slow moving lattice imperfections within the grain to migrate to the grain boundaries, transporting carbon atoms with them, and the steel again becomes susceptible. Cold working, on the other hand, produces immunity by destroying continuous grain-boundary paths, and, more important, by generating imperfections that have high affinity for carbon and deplete any continuous paths along which carbon atoms tend to segregate. Measures for the production of crack-sensitive paths by carbon atoms localized at grain boundaries are discussed later on. Remedial measures to avoid s.c.c. of steel in nitrate solutions, and probably also in alkalies for which the mechanism of cracking appears

¹¹ M. Long and H. Uhlig, *J. Electrochem. Soc.*, 113, 664 (1966).

to be similar, include the following:

1. *Severe Cold Working.* Cold rolling to $>50\%$ reduction of thickness is found to impart relative immunity to a stressed mild steel in boiling nitrate solution. The resistant state is predicted to persist at low temperatures, e.g., 100 to 200°C (200–400°F) for thousands of hours.
2. *Heat Treatment.* Mild steel slowly cooled from 900 to 950°C (1650–1740°F), or quenched from this temperature range and then tempered at about 250°C (480°F) for one-half hr, or at higher temperatures for shorter times, is resistant. This resistance is temporary and short-lived (200 hr) at temperatures in the order of 400°C (750°F), but it is predicted to reach the order of thousands of hours at 300°C (570°F) or below.¹²

3. *Surface Packing or Shot Blasting.* Compressive stresses are produced at the surface of the metal which are effective in avoiding damage so long as the compressive layers are continuous, remain intact, and are not dissolved by general corrosion.

4. *Cathodic Protection.* Schneider and Besh¹³ found that cathodic polarization of steel stressed in hot sodium hydride-sodium silicate solution greatly delayed or prevented cracking. Parkins¹⁴ found similar protection in hot nitrate solution. Bohnerkamp¹⁵ reported maximum susceptibility of various carbon steels (0.003–0.11% C) in 33% NaOH boiling at 123°C at -0.66 to -0.75 V (s.s.c.) with orders of magnitude longer life at potentials 0.1 V either more noble or active to this range. Anodic as well as cathodic protection was found to be effective.

5. *Special Alloys.* Steels containing small alloying additions of aluminum, titanium, or niobium ("dry tantalum," which reacts preferentially with carbon and nitrogen, exhibit improved resistance to s.c.c. but are not immune.

6. *Use of Inhibitors.* Sodium nitrate has already been mentioned as a practical inhibitor for steel exposed to boiler waters. Crude quebracho extract and waste milbik liquor are also used. Buffer ions such as PO_4^{3-} are useful, because they avoid high concentrations of OH^- in concentrated boiler water.

In accelerated tests, the addition of 3% NaCl or 3% sodium acetate to boiling 60% $\text{Ca}(\text{NO}_3)_2$ + 3% NH_4NO_3 at 100°C, was found to inhibit cracking (>200 hr)¹⁶ of mild steel.

¹² B. Parkins, *J. Iron Steel Inst.*, 172, 149 (1952).

¹³ M. Bohnerkamp, *Proc. Fundamental Aspects of Stress Corrosion Cracking*, p. 216, Nat. Amer. Corros. Congr., Houston, Texas, 1966.

¹⁴ E. Bohnerkamp and W. Hirsch, *Steel + Eisen*, 73, 263 (1953).

¹⁵ V. Agarwal, M. S. thesis, Dept. of Metallurgy and Materials Science, M.I.T., 1966.

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