CORROSION FATIGUE

M. O. Speidel

Swiss Federal Institute of Technology, ETH Zurich, Switzerland

ABSTRACT

The goal of high corrosion fatigue resistance can be reached only by alloys which exhibit both, high resistance to pitting corrosion and high mechanical strength. These two simultaneous requirements are difficult to achieve with steels. One possible solution is given by the two-phase austenitic-ferritic "duplex" stainless steels. This paper presents several other solutions as well, e.g. titanium alloys and precipitation-hardened nickel base superalloys. Finally an overview is presented concerning the corrosion fatigue strength which may be achieved with many other alloy systems.

KEYWORDS

Corrosion fatigue, fatigue strength, pitting corrosion, alloy development, stainless steels.

CORROSION FATIGUE AND MECHANICAL STRENGTH

The fatigue life of a component can be considered to consist of the number of load cycles to nucleate a crack plus an additional number of load cycles to propagate the crack to a size where the component fails. The number of load cycles to crack initiation is often measured by S - N curves where the applied cyclic stress is plotted versus the number of load cycles leading to the failure of small axially loaded, smooth specimens. The residual number of load cycles to failure of precracked components is often evaluated from fracture mechanics corrosion fatigue crack growth rate data. The present paper concentrates upon the nucleation of corrosion fatigue cracks and consequently the results of corrosion fatigue tests with smooth specimens, i.e. S - N curves are discussed.

Consider the fatigue of two carbon steels in air, figure 1. The two steels have extremely different strength levels and, consequently, extremely different fatigue strengths in air, as indicated by the dashed lines in figure 1. In aerated water, however, the corrosion fatigue strengths of both carbon steels become equally low at 10^7 and higher load cycles to failure, as indicated by the solid lines in figure 1. This then indicates that under the conditions shown in figure 1, increasing the strength level alone cannot increase the corrosion fatigue resistance. The data presented in figure 2 permit the same conclusion to be drawn for a large number of carbon steels whith widely differing strength levels.

CORROSION FATIGUE AND PITTING CORROSION

The huge difference between fatigue strength and corrosion fatigue strength at all mean stress levels seen in figure 3 originates from the role of corrosion pits which act as crack starters as shown in figure 4. In order to achieve higher corrosion fatigue resistance in steels it will therefore be necessary to improve the resistance to pitting corrosion. Figures 5, 6, and 7 indicate how this can be achieved. The pitting potential of iron in aqueous solutions depends on alloy composition, chloride concentrations and temperature. Chromium and molybdenum additions are particularly effective in shifting the pitting potential into the desired direction and thereby preventing pitting corrosion and thus corrosion fatigue crack nucleation. However for the most aggressive concentrated hot chloride solutions, 12% to 16% chromium are not sufficient to prevent pitting corrosion and thus corrosion fatigue as indicated in figures 8 and 9. Higher chromium contents than 12% to 16% are possible in modern straight chromium ("super"-) ferritic steels. Such steels however cannot form martensite, and have thus relatively low mechanical and fatigue strengths, as indicated in figures 10 and 11.

HIGH CORROSION RESISTANCE AND HIGH STRENGTH COMBINED

While the chromium content of martensitic stainless steel is limited, it is apparent from the Shaeffler-diagram shown in figure 12 that much higher chromium equivalents are possible with single phase (super-) ferrites and single phase austenites as well as with two-phase ("duplex") stainless steels of austenitic-ferritic microstructure. The single phase stainless steels have low mechanical strengths in both, the ferritic and the austenitic types. This translates also to low fatigue and corrosion fatigue strength, as indicated in figure 13. All the more remarkable is the high fatigue and corrosion fatigue strength of the duplex austenitic-ferritic stainless steels shown in figures 13 and 14. This class of steels has the capability of being further strengthened either by precipitation hardening or by solid solution hardening.

A second approach to high corrosion resistance and high strength and thus, corrosion fatigue strength, is indicated in figure 15. Here it is shown that precipitation hardening of corrosion resistant Ni-Cr-Fe-Mo fcc solid solutions can result in remarkably high corrosion fatigue strength.

Yet another solution to the corrosion-fatigue problem is presented by titanium alloys, such as Ti-6Al-4V, shown in figure 16. Since titanium alloys are extremely pitting corrosion resistant, their fatigue resistance in air is

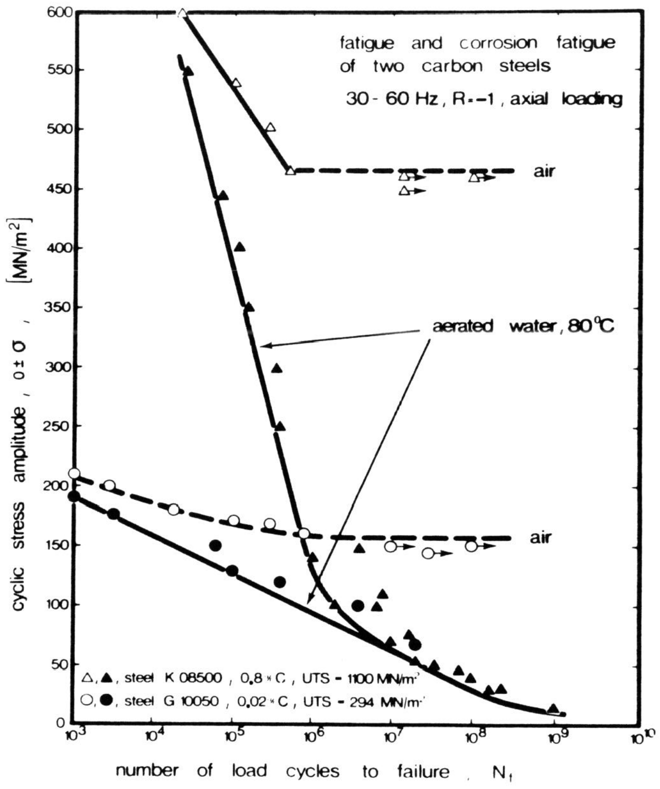


Fig. 1 Fatigue S-N surves of a low strength and a high strength carbon steel in air and in water. Endurance limits in air are significantly different, but the corrosion fatigue strength of both steels are identical and extremely low.

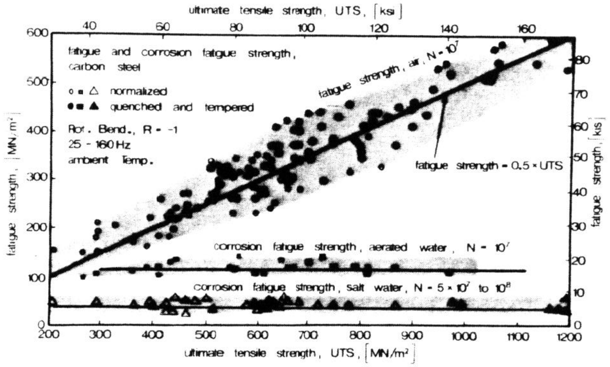


Fig. 2 The fatigue strength of carbon steels in air increases with increasing tensile strength, but the corrosion fatigue strength is equally low for all carbon steels in environments which cause pitting corrosion.

practically identical to their corrosion fatigue resistance in hot concentrated chloride solutions. Care must be taken, however, not to increase the strength of the titanium alloys to the range where they become susceptible to stress corrosion cracking.

CORROSION FATIGUE RESISTANCE OF MANY ALLOY SYSTEMS COMPARED

Figures 2 and 17 indicate the maximum corrosion fatigue strength level which can be achieved with carbon steels or aluminum alloys in salt water. This maximum level of corrosion fatigue resistance is compared for many alloy systems in figure 18. Note that cobalt alloys and titanium alloys permit some of the best corrosion fatigue strength levels to be obtained. This is one reason why materials from these groups are used not only in modern high technology but also where their corrosion fatigue resistance is most immediately felt - as implants in the human body.

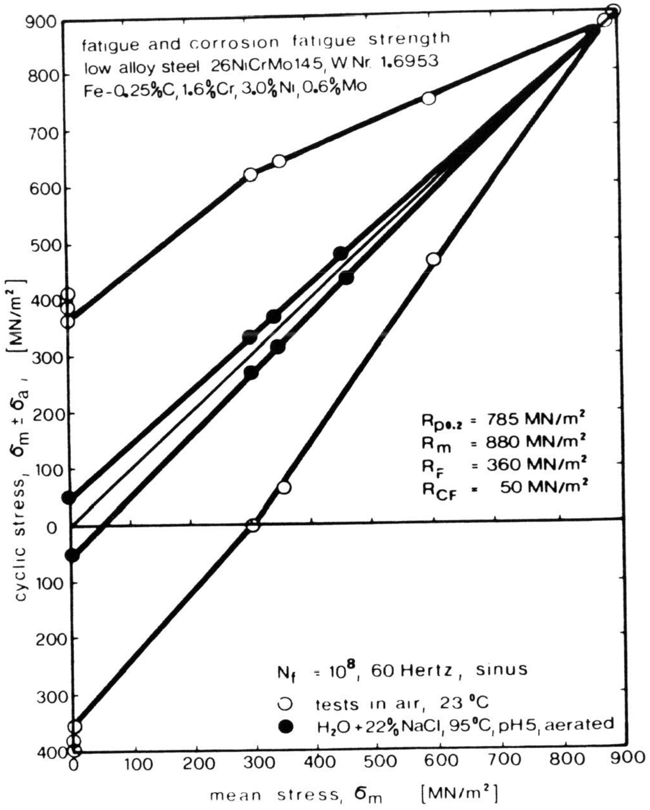


Fig. 3 Fatigue and corrosion fatigue strength at 10^8 cycles for a low alloy steel subjected to different mean stresses in two different environments.

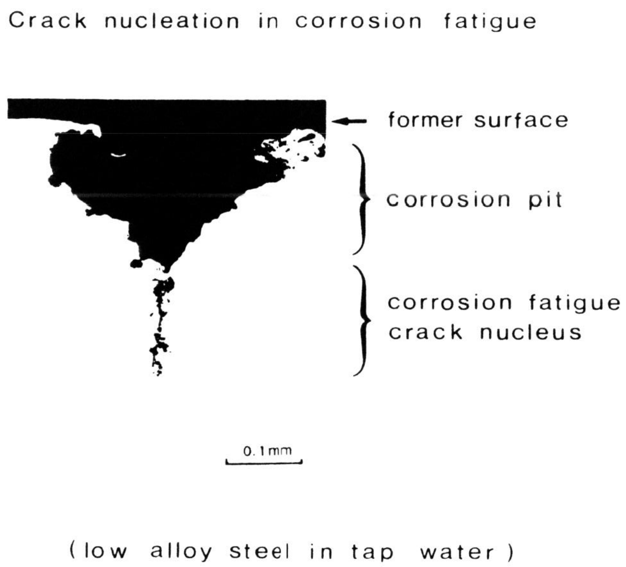


Fig. 4 Corrosion pit as the nucleus of a corrosion fatigue crack. In order to prevent corrosion fatigue, the most important step is to prevent pitting corrosion. This can be done by alloying, surface protection, inhibiting the environment, or potential control.

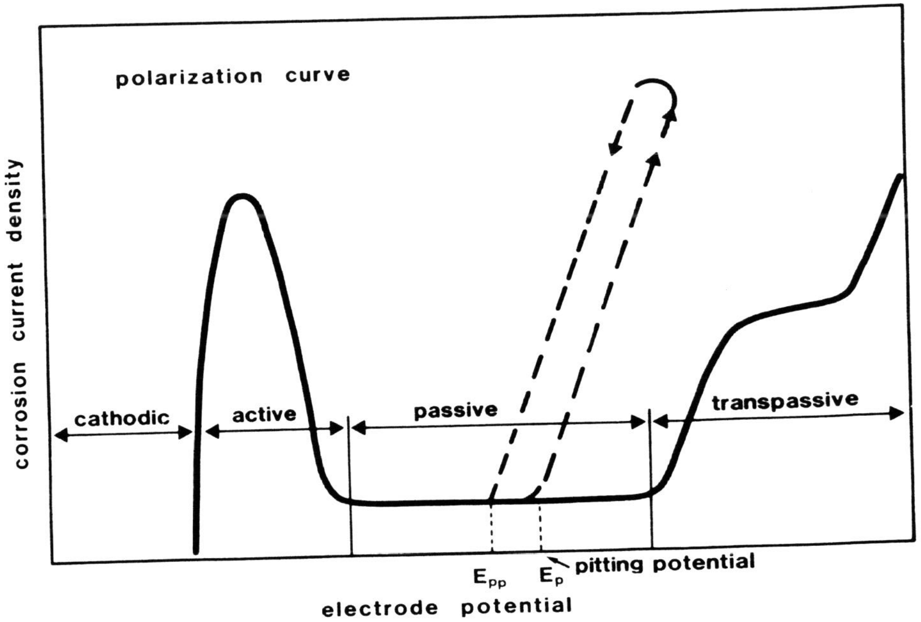


Fig. 5 Pitting corrosion occurs in material-environment combinations where the material passivates by the formation of a protective oxide layer. Pitting can be described as the localized destruction of such protective layers. The onset of pitting with increasing electrode potential is defined by the pitting potential. Desirable alloying additions would shift the pitting potential to higher values.

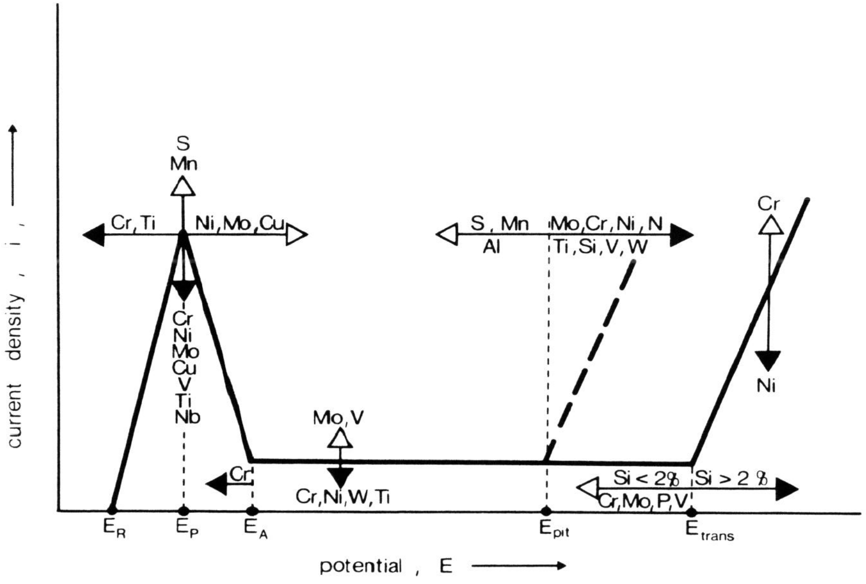


Fig. 6 In steels, chromium, molybdenum, and nitrogen, as well as nickel, titanium, silicon, vanadium and wolfram are alloying elements which shift the pitting potential in the desirable direction.

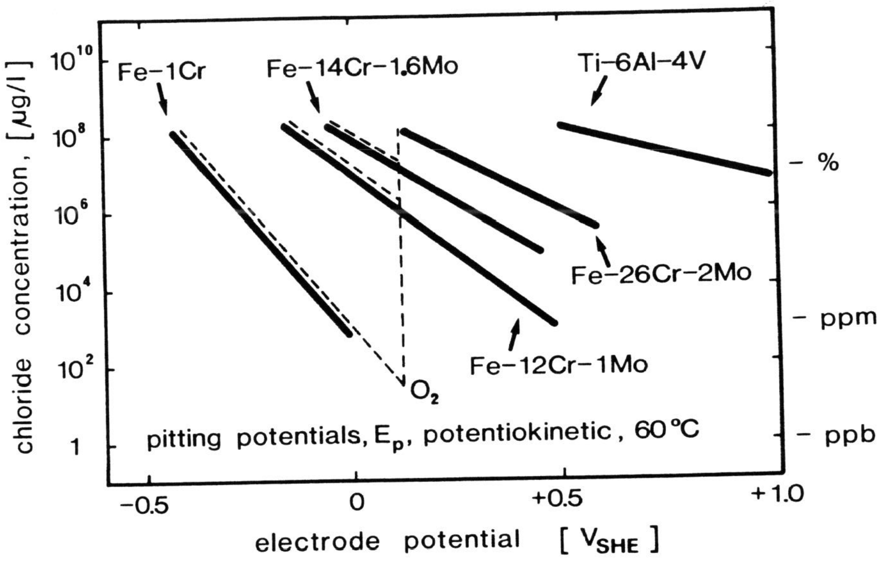


Fig. 7 Ranking of steels and titanium alloys with respect to pitting corrosion resistance. Low alloy steels are least resistant, chromium steels (stainless steels) are better, and titanium alloys are best. The pitting potentials depend strongly on the chloride concentration present in the aggressive aqueous solutions.

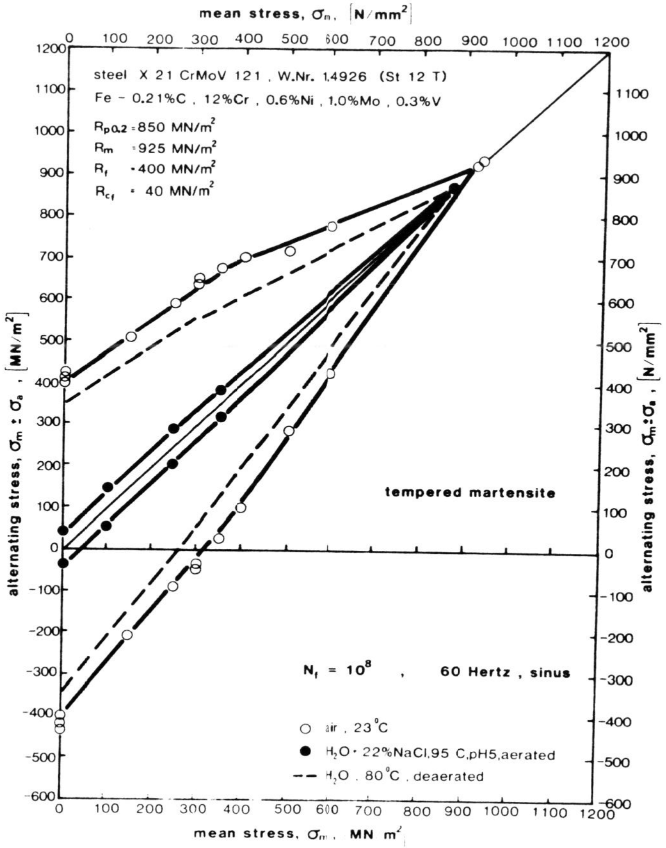


Fig. 8 Fatigue and corrosion fatigue of a 12% chromium steel. Note that the deaerated water causes only a minor reduction of the fatigue strength. Aerated hot chloride solutions however lower the corrosion fatigue resistance dramatically.

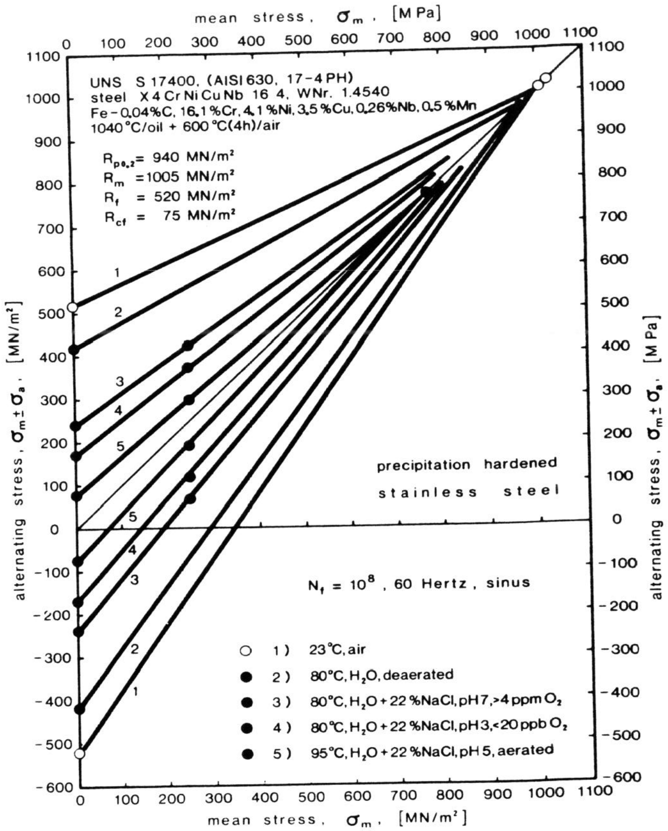


Fig. 9 Fatigue and corrosion fatigue strength as a function of mean stress for a precipitation hardenable stainless steel with 16 percent chromium.

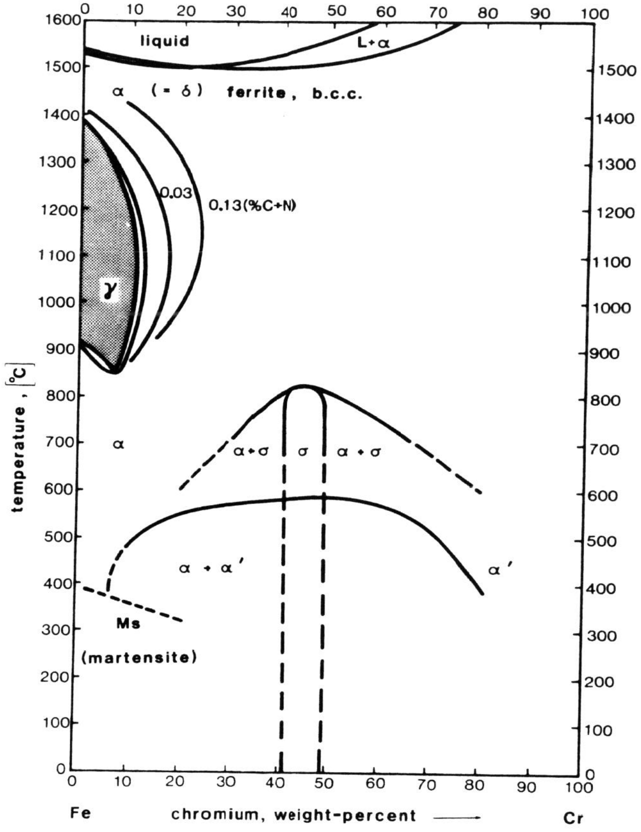


Fig. 10 Martensite formation (and thus the high strength of quenched and tempered steel) is in straight-chromium stainless steels possible only up to chromium concentrations which do not lead outside the gamma-loop. Straight-chromium stainless steels with 18 to 28 percent chromium are now commercial "superferrites" but they exhibit no useful phase transformation and may also embrittle due to the precipitation of undesirable phases at lower temperatures.

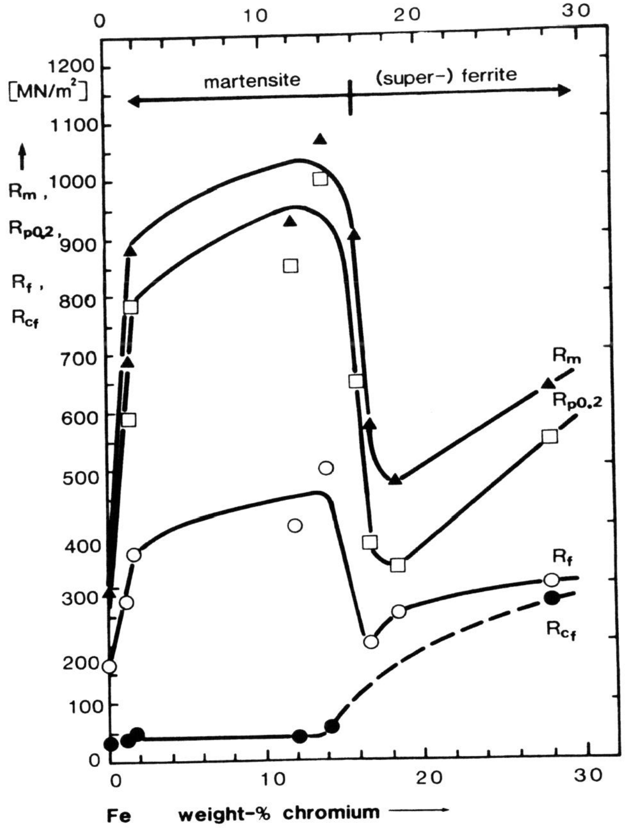


Fig. 11 Strength, fatigue strength and corrosion fatigue strength of straight-chromium steels. Note that the corrosion fatigue strength is particularly low where the mechanical strength is particularly high. Superferrites have good corrosion-fatigue strength but only moderate yield and tensile strength.

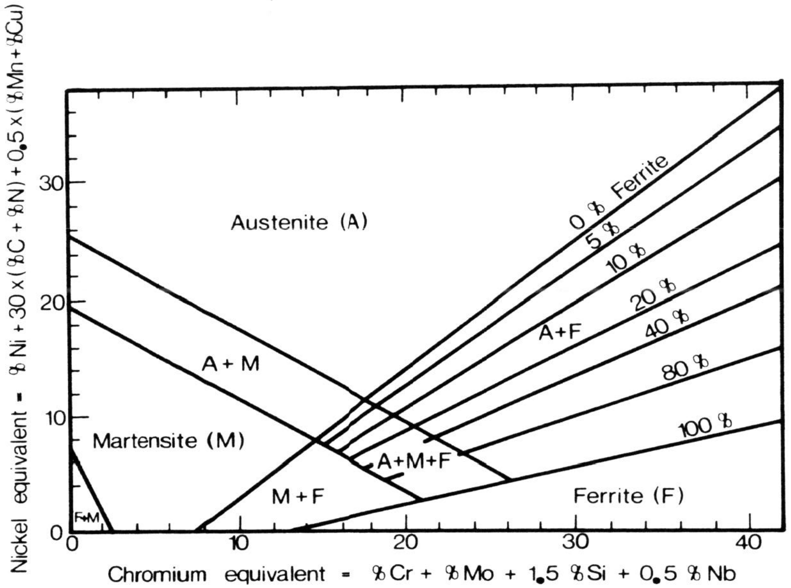


Fig. 12 The chromium content of martensitic stainless steels is limited. Higher chromium equivalents are possible with (super-)ferrites, austenitic and duplex (austenitic-ferritic) steels. The two-phase austenitic-ferritic stainless steels have both, high corrosion fatigue resistance and higher strength levels than single-phase ferrites or austenites of similar chromium content.

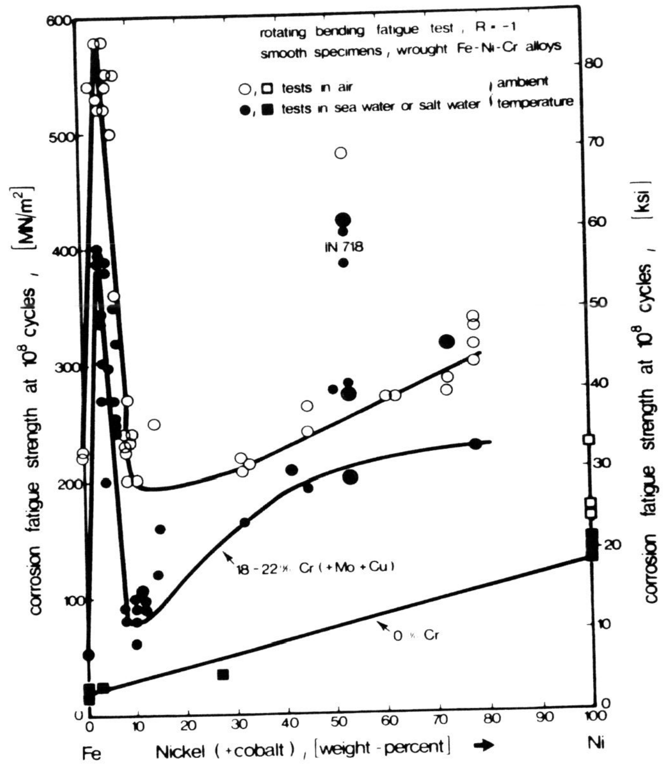


Fig. 13 Increasing nickel contents in Fe-Ni-Cr alloys with about 20% chromium lead from the ferritic stainless steels to duplex stainless steels to austenitic stainless steels and finally to the nickel base fcc solid solutions. The exceptionally high fatigue strength and corrosion fatigue strength of the duplex stainless steels is readily apparent.

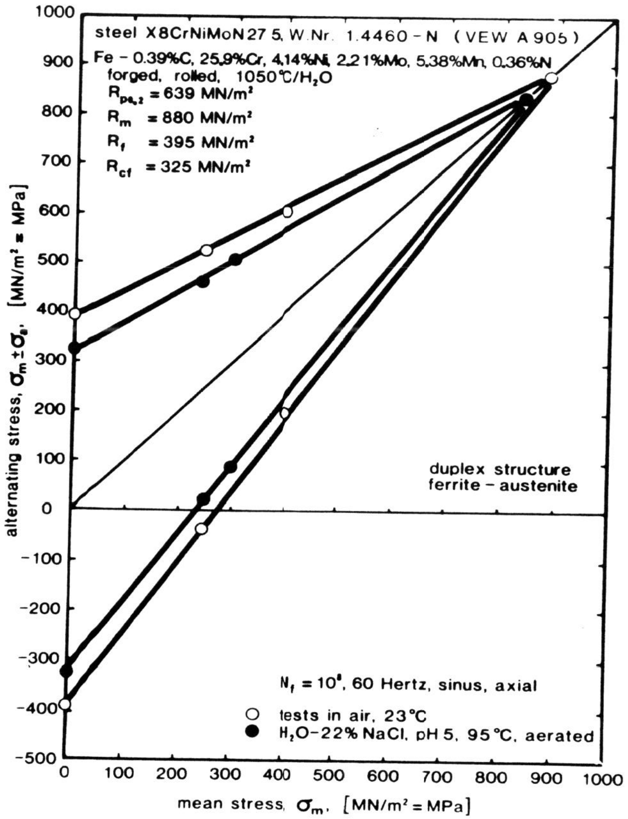
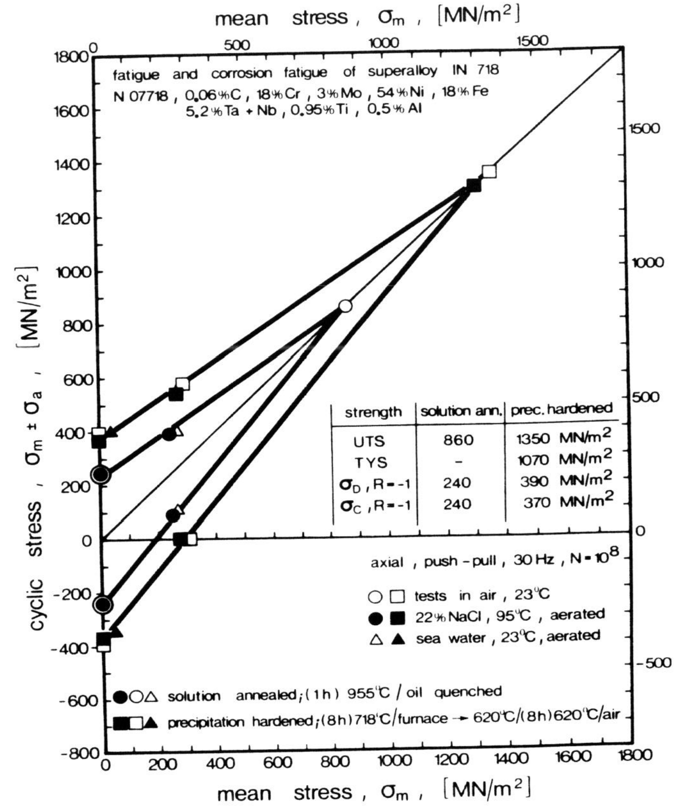


Fig. 14 A high-chromium stainless steel with a duplex ferrite-austenite microstructure has an unusually high corrosion fatigue resistance Note the very modest environmental degradation of the fatigue strength at all mean stress levels.



strength	solution ann.	prec. hardened
UTS	860	1350 MN/m^2
TYS	-	1070 MN/m^2
σ_D, R = -1	240	390 MN/m^2
σ_C, R = -1	240	370 MN/m^2

Fig. 15 Nickel base alloys containing enough chromium and molybdenum may develop a very high corrosion resistance. If this is combined with high mechanical strength (by precipitation hardening) a very high corrosion fatigue strength may be obtained.

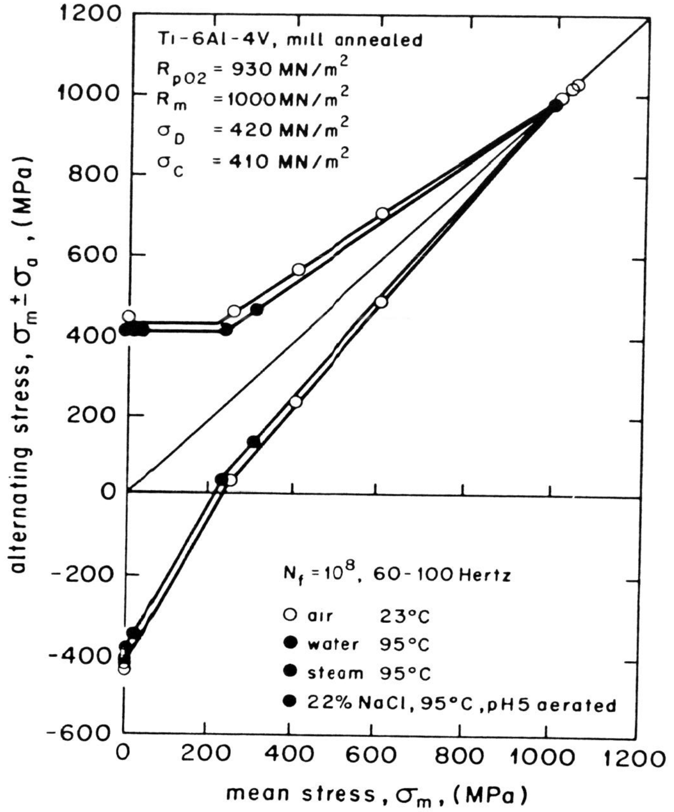


Fig. 16 Titanium alloy Ti-6Al-4V has a remarkable fatigue and corrosion fatigue resistance at zero mean stress. However, at higher mean stresses, such as may occur in service, the fatigue strength of this alloy is less than that of 12% chromium steel (Fig. 8).

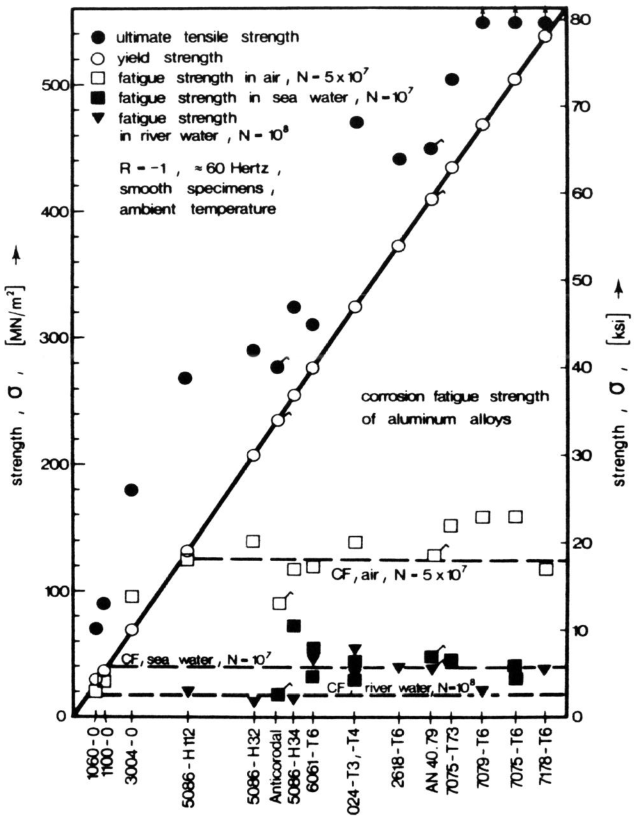


Fig. 17 Aluminum alloys, arranged according to their yield strength. Independent of the strength level, the corrosion fatigue strength is equally low for aluminum alloys if pitting corrosion is allowed to occur. Compare the constant low corrosion fatigue strength level of aluminum alloys shown in this figure with the parallel behaviour of steels shown in figure 2.

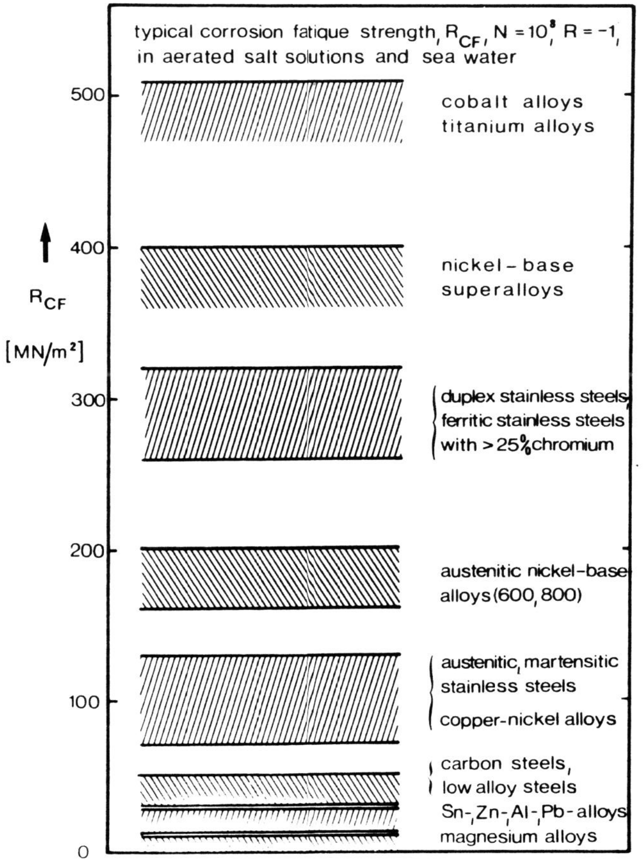


Fig. 18 Corrosion fatigue strength levels which may be reached with given alloy systems. This figure sums up data of the kind shown in figures 2 and 17, but for many more alloy systems.