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# Environmentally Assisted Cracking of Nickel Alloys – A Review

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## **Abstract**

Nickel can dissolve a large amount of alloying elements while still maintaining its austenitic structure. That is, nickel based alloys can be tailored for specific applications. The family of nickel alloys is large, from high temperature alloys (HTA) to corrosion resistant alloys (CRA). In general, CRA are less susceptible to environmentally assisted cracking (EAC) than stainless steels. The environments where nickel alloys suffer EAC are limited and generally avoidable by design. These environments include wet hydrofluoric acid and hot concentrated alkalis. Not all nickel alloys are equally susceptible to cracking in these environments. For example, commercially pure nickel is less susceptible to EAC in hot concentrated alkalis than nickel alloyed with chromium (Cr) and molybdenum (Mo). The susceptibility of nickel alloys to EAC is discussed by family of alloys.

*Keywords:* Environmentally Assisted Cracking, Nickel Alloys, Alkalis, Wet Hydrofluoric Acid.

## **1. Introduction**

Environmentally Assisted Cracking (EAC) is a general term that includes events such as stress corrosion cracking (SCC), hydrogen embrittlement (HE), sulfide stress cracking (SSC), liquid metal embrittlement (LME), corrosion fatigue (CF), etc. EAC refers to a phenomenon by which a normally ductile metal loses its toughness (e.g. elongation to rupture) when it is subjected to mechanical stresses in presence of a specific corroding environment. For EAC to occur, three affecting factors must be present simultaneously. These are: (1) Mechanical tensile stresses, (2) A susceptible metal microstructure and (3) A specific aggressive environment. If any of these three factors is removed, EAC will not occur. That is, to mitigate the occurrence of EAC, engineers may, for example, eliminate residual stresses in a component or, limit its application to certain non-aggressive chemicals (environment). The term environment not only includes the chemical composition of the solution in contact with the component but also other variables such as temperature and applied potential.

Nickel alloys are in general more resistant than stainless steels to EAC. Austenitic stainless steels (such as S30400) suffer SCC in presence of hot aqueous solutions containing chloride ions. Since chloride ions are ubiquitous in most industrial applications, the use of stainless steels components containing sometimes only minimal residual stresses is seriously limited because of the chloride cracking. On the other hand, nickel alloys (such as C-276) are to all intents and purposes immune to SCC in presence of hot chloride solutions and therefore an excellent alternative to replace the troubled austenitic stainless steels. Nickel alloys may be prone to EAC in other environments such as hot caustic and hot wet hydrofluoric acid [1]. Nevertheless, the conditions where nickel alloys suffer EAC are more specific than for austenitic stainless steels and therefore avoidable by the proper design of the industrial components.

## **2. The Family of Nickel Alloys**

### *2.1. Properties*

Nickel-based alloys are solid solutions based in the element nickel (Ni). Even though Ni based alloys in general contain a large proportion (sometimes up to 50%) of other alloying elements, nickel alloys still maintain the face centered cubic lattice structure (FCC or gamma) from the nickel base element. As a consequence of the FCC structure, nickel based alloys have excellent ductility, malleability and formability. Nickel alloys are also readily weldable. There are two large groups of the commercial Ni-based alloys. One group was designed to withstand high temperature and dry or gaseous corrosion while the other is mainly dedicated to low temperature (aqueous) applications. Nickel based alloys used for low temperature aqueous or condensed systems are generally known as corrosion resistant alloys (CRA) and nickel alloys used for high temperature applications are known as heat resistant alloys (HRA) or high temperature alloys (HTA). The practical industrial boundary between high and low temperature nickel alloys is in the order of 500°C (or approximately 1000°F). Most of the nickel alloys have a clear use either as CRA or HRA; however, a few alloys can be used for both applications (e.g. alloy 625 or N06625).

### *2.2. Heat Resistant Alloys*

Unlike CRA, which are mostly selected for their capacity to resist corrosion in a given environment, most HRA need to play a dual role. Namely, besides their capacity to withstand the corrosive aggressiveness of the environment, HRA also need to keep significant strength at high temperatures. In many instances, for example near and above 1000°C, alloy selection is dominated by how strong the alloy is in this temperature range. There are many different industrial high temperature environments. In general, practical use has divided these environments according to the most common causes of failure of a component in service. The most common failures are associated to the attack by a specific element such as oxygen (which causes oxidation), carbon (carburization and metal dusting), sulfur (sulfidation), halogen (e.g. chlorination) and nitrogen (nitridation). Other modes of failure such as molten metal attack and hot corrosion, are less specific. Detailed description of the mode of attack in these different environments is given elsewhere [2,3]. The most common high temperature degradation mode is oxida-

tion and the protection against oxidation in general is given by the formation of a chromium oxide scale. In many instances, the presence of a small amount of aluminum or silicon in the alloy may improve the resistance against oxidation of a chromia-forming alloy. Attack by other elements such as chlorine, sulfur, etc. will depend strongly on the partial pressure of oxygen in the environment [3]. Due to their application, failures of HTA in service are not usually associated with environmentally assisted cracking since they may not be in contact with a condensed phase promoting cracking. A few HTA are used in the handling of liquid metals (such as in liquid Zn galvanizing) and therefore may suffer embrittlement by liquid metal.

### *2.3. Chemical Composition and Corrosion Behavior of Corrosion Resistant Alloys*

Nickel alloys are highly resistant to corrosion, and in most environments nickel alloys outperform the most advanced stainless steels. One of the reasons is because nickel can be alloyed more heavily than iron. That is, large amounts of specific elements can be dissolved purposely into nickel to tailor the alloy for a particular environment. In general, industrial environments can be divided into two broad categories, reducing and oxidizing. These terms refer to the range of electrode potential that the alloys experience, which is controlled by the cathodic reaction in the system. Thus, a reducing condition is generally controlled by the discharge of hydrogen from a reducing acid such as hydrochloric acid. An oxidizing environment has a potential that is higher than the potential for hydrogen discharge. This potential may be established by cathodic reactions such as reduction of dissolved oxygen ( $O_2$ ) from the atmosphere, chlorine gas ( $Cl_2$ ), hydrogen peroxide ( $H_2O_2$ ), chromates or chromic acid ( $CrO_4^{2-}$ ), nitrates or nitric acid ( $NO_3^-$ ) and metallic ions in solution such as ferric ( $Fe^{3+}$ ) and cupric ( $Cu^{2+}$ ). Nickel alloys, the same as other alloys, may suffer two main types of corrosion, uniform corrosion and localized corrosion. Uniform corrosion may happen under reducing conditions in the active region of potentials and also under oxidizing conditions in the form of a slow passive corrosion. Localized corrosion such as pitting and crevice corrosion generally occurs under oxidizing conditions. Stress corrosion cracking (SCC) or environmentally induced cracking could occur at any electrochemical potential range.

From the chemical composition point of view, corrosion resistant Ni-based alloys can be grouped as: (1) commercially pure nickel, (2) Ni-Cu alloys, (3) Ni-Mo alloys, (4) Ni-Cr-Mo alloys and (5) Ni-Cr-Fe alloys. Table 1 gives the approximate chemical composition and the typical mechanical properties of the most familiar commercial wrought nickel based alloys. A brief description of the corrosion behavior and application of each group of alloys is given below. More extended analyses are given elsewhere [4,5]. The main widely accepted application of commercially pure nickel is the handling of highly concentrated caustic solutions (alkalis). Nickel has lower corrosion rates in hot caustic solutions than alloyed nickel since alloying elements such as Cr and Mo dissolve preferentially in hot caustic solutions. Nickel can also tolerate well cold reducing acids because of the slow discharge of hydrogen on its surface. Hot reducing acids and oxidizing acids corrode pure nickel rapidly. The main application of Ni-Cu alloys (or Monel alloys) is in the handling of pure hydrofluoric acid. However, if oxidants such as oxygen are present in hydrofluoric acid, Ni-Cu alloys may suffer intergranular attack [6]. Ni-Cu alloys are slightly more resistant to general corrosion than Ni-200 in hot reducing and oxidizing acids such as sulfuric acid and nitric acid. Ni-Mo alloys, com-

Table 1: Approximate Chemical Composition, Typical Mechanical Properties (MPa) and Applications of Corrosion Resistant Nickel Alloys. Mechanical Properties at Ambient Temperature for Annealed Plates.

Alloy	UNS	Approximate Composition	YS (0.2%)	UTS	ETF (%)	RH	Applications
Commercial Nickel							
Ni-200	N02200	99Ni-0.2Mn-0.2Fe	190	450	50	60 B	strong caustic
Ni-301 <sup>A</sup>	N03301	93Ni-4.5Al-0.6Ti	860	1170	25	35 C	fasteners, springs
Ni Cu Alloys							
Monel 400	N04400	67Ni-31.5 Cu-1.2Fe	270	540	43	68 B	hydrofluoric acid
Monel K-500 <sup>A</sup>	N05500	63Ni-30Cu-3Al-0.5Ti	700	1020	28	30 C	fasteners, springs
Ni-Mo Alloys							
B-2	N10665	72Ni-28Mo	407	902	61	94 B	hot hydrochloric
Hastelloy B-3	N10675	68.5Ni-28.5Mo-1.5Cr-1.5Fe-	400	885	58	NA	reducing acids
Nimofor 6629 (B-4)	N10629	65Ni-28Mo-4Fe-1Cr-0.3Al	340	755	40	NA	hydrochloric, sulfuric
Ni Cr Mo Alloys							
C-276	N10276	59Ni-16Cr-16Mo-4W-5Fe	347	741	67	89 B	versatile CPI and pollution control
Inconel 625	N06625	62Ni-21Cr-9Mo-3.7Nb	535	930	45	95 B	Aerospace, pollution control
Hastelloy C-22	N06022	59Ni-22Cr-13Mo-3W-3Fe	365	772	62	89 B	Resistant to localized corrosion
Hastelloy C-2000	N06200	59Ni-23Cr-16Mo-1.6Cu	345	758	68	NA	CPI, oxidizing and reducing, sulfuric
Nicrofer 5923hMo (59)	N06059	59Ni-23Cr-16Mo-1Fe	340	690	40	NA	oxidizing and reducing acids, CPI
Inconel 686	N06686	46Ni 21Cr-16Mo-4W-5Fe	364	722	71	NA	oxidizing and reducing acids, CPI
Ni-Cr Fe Alloys							
Inconel 600	N06600	76Ni-15.5Cr-8Fe	275	640	45	75 B	nuclear power
Incoloy 825	N08825	43Ni-21Cr-30Fe-3Mo-2.2Cu-1Ti	338	662	45	85 B	oil and gas, sulfuric, phosphoric
Hastelloy G-30	N06030	44Ni-30Cr-15Fe-5Mo-2Cu-2.5W-4Co	317	689	64	NA	nitric, phosphoric
Nicrofer 3033 (33)	R20033 <sup>D</sup>	31Ni-33Cr-32Fe-1.6Mo-0.6Cu-0.4N	380	720	40	NA	phosphoric acid

YS = Yield Stress (MPa), UTS = Tensile Strength (MPa), ETF = Elongation to Failure, RH = Rockwell Hardness, CPI = Chemical Process Industry, A = Annealed and Aged Bar, NA = Not Available, D = UNS starts with an R because it classified as Cr based alloy.

monly known as Hastelloy B type alloys, were specifically developed to withstand reducing HCl at all concentrations and temperatures. Besides more expensive materials

such as tantalum, Ni-Mo alloys are the best alloys for hot hydrochloric acid [4,7,8]. Ni-Mo alloys are also used in the handling of other corrosive reducing environments such as sulfuric, acetic, formic, hydrofluoric and phosphoric acids. B-2 has the lowest corrosion rate in boiling 10% sulfuric acid. However, Ni-Mo alloys perform poorly in oxidizing acids or, for example, in hydrochloric acid contaminated with ferric ions [7]. There are many commercially available Ni-Cr Mo alloys today. All these alloys were derived from the original C alloy (N10002), which was introduced to the market in cast form in 1932. The more advanced Ni-Cr Mo alloys are Inconel 686, Nicrofer 5923 and Hastelloy C-2000 [8]. However, the more common Ni-Cr Mo alloy in industrial applications is Hastelloy C-276, which was introduced in the market in the mid 1960s. Ni-Cr Mo alloys are the most versatile nickel alloys since they contain molybdenum for protection against corrosion under reducing conditions and chromium, which protects against corrosion under oxidizing conditions [7,8]. C-276 has low corrosion rates both in reducing conditions (boiling 10% sulfuric acid) and oxidizing conditions (boiling 10% nitric acid). One of the major applications of Ni-Cr Mo alloys is in presence of hot chloride containing solutions. Under these conditions, most of the stainless steels would suffer crevice corrosion, pitting corrosion and stress corrosion cracking. However, Ni-Cr Mo alloys are highly resistant if not immune to chloride induced attack in most industrial applications [4]. The last group of nickel-based CRA is the group of Ni-Cr Fe alloys. These alloys also may contain smaller amounts of molybdenum and/or copper. Ni-Cr Fe alloys in general are less resistant to corrosion than Ni-Cr Mo alloys; however, they could be less expensive and therefore find a wide range of industrial applications. The corrosion rate of alloy 600 in sulfuric acid is higher than the corrosion rate of alloy 825. The latter contains small amounts of molybdenum and copper (Table 1), which are beneficial alloying elements for resistance to sulfuric acid. Also, alloy 825 has lower corrosion rate in nitric acid since it contains larger amount of chromium. One of the most common applications of Ni-Cr Mo alloys such as alloy 33 and Hastelloy G-30 is in the industrial production of phosphoric acid and in highly oxidizing media such as nitric acid.

Table 2. Environments that may cause EAC in nickel alloys

Nickel Alloys	Example UNS	Environments which may produce EAC
Commercial Nickel	N02200	Not especially susceptible. Molten Metals
Ni-Cu Alloys	N04400	Hydrofluoric acid (especially in the vapor phase containing oxygen), mercury salts, ammonia
Ni-Mo Alloys	N10675	Cathodic and anodic acidic solutions (especially near welds), Wet HF solutions
Ni-Cr Mo Alloys	N10276, N06022	Hot Caustic, SCWO, Hot Aqueous HF solutions
Ni-Cr Fe Alloys	N06600, N08825	Hot water, Hot Caustic, high chloride high temperature, high temperature mercury

### 3. Environments that Cause Cracking in Nickel Alloys

The main limitation in the application of nickel alloys is not EAC, because nickel alloys are less prone to suffer EAC than the more widely used austenitic stainless steels. In general, mill annealed nickel CRA have tensile strengths lower than 1000 MPa (Table 1) and large elongation to failure (>50%), that is, for example, they are not especially susceptible to failure mechanisms associated to hydrogen uptake. Two of the specific environments that would cause EAC in nickel CRA are hot caustic and hot wet hydrofluoric acid [1]. These environments also produce EAC in austenitic stainless steels. Table 2 lists the different family of nickel alloys and the environments that were shown to cause embrittlement of nickel alloys.

#### 3.1 Commercial Nickel

Commercially pure nickel is not susceptible to stress corrosion cracking, except in the heavily cold worked conditions in the presence of high temperature (>250°C) concentrated caustic solutions and liquid metal. Commercial nickel is not susceptible to hydrogen embrittlement since the solubility and diffusivity of hydrogen in nickel are low and this material has low mechanical strength.

#### 3.2 Nickel-Copper Alloys

As in the case of Ni 200, alloy 400 is not highly susceptible to stress corrosion cracking (SCC) probably because it has low mechanical strength (Table 1). Alloy 400 was found to be susceptible to SCC in acidic solutions containing mercury salts, in liquid mercury, in hydrofluoric acid and in fluosilicic acid [9]. In hydrofluoric acid the cracking is transgranular and the highest susceptibility occurs in the vapor phase, especially in the presence of air [10]. Reduction of aeration reduces the susceptibility to cracking in hydrofluoric acid. Using U-bend specimens, it has been reported that the crack propagation rate in Alloy 400 exposed to the vapor phase of 20% HF for 240 h decreased as the temperature increased from 66°C to 93°C, probably because less oxygen was available in the vapor phase as the temperature increased [11]. In the same study, U-bends of Alloy 400 were found free from cracking while immersed in the liquid portion of 20% HF [6,11]. It has also been reported that highly stressed alloy 400 suffers SCC in ammonia vapors at 300°C [12]. Heat treatments that eliminate residual stresses and cold worked microstructures greatly reduce the susceptibility of alloy 400 to all types of environmentally induced cracking.

#### 3.3 Ni-Mo Alloys

Ni-Mo alloys are resistant to chloride induced cracking in boiling magnesium chloride solutions [13]. When B-2 alloy and, to a lesser extent B-3 alloy, are exposed to temperatures in the range 550°C to 850°C, they lose ductility due to a solid phase transformation which forms ordered intermetallic phases such as Ni<sub>4</sub>Mo. The precipitation of these ordered phases changes the deformation mechanisms of the alloys making them susceptible to EAC such as hydrogen embrittlement [14,15]. In B-2 alloy, the precipitation of intermetallic phases can occur in the heat-affected zone (HAZ) during welding.

It has been reported that B-2 alloy failed by intergranular stress corrosion cracking of the HAZ when exposed to organic solvents containing traces of sulfuric acid at 120°C [16]. It has also been reported that B-2 alloy was prone to transgranular stress corrosion cracking in the presence of hydroiodic acid (HI) above 177°C [17].

Stress corrosion cracking studies of B, B-2 and B-3 alloys in acidic solutions were carried out under laboratory and plant conditions [18]. The effects of the electrochemical potential, cold work produced by drilling, and two different aging processes (that would simulate welding and the subsequent cooling cycle) were investigated. At anodic potentials (200 mV above the free corrosion potential) Nakahara and Shoji found transgranular fissuring in all three alloys both for mill annealed and aged materials. At cathodic potentials (100 mV and 400 mV below the free corrosion potential) they found intergranular cracking only for the aged (sensitized) alloys. Since the amount of intergranular brittle cracking increased at the lower applied cathodic potential, this environmentally induced cracking was attributed to hydrogen embrittlement [18].

U-bend specimens of mill annealed B-3 (N10675) alloy were found to suffer stress corrosion cracking in the presence of vapor and liquid phase of a 20% HF solution at 66°C, 79°C and 93°C [12]. The cracking susceptibility of N10675 increased with the temperature and the liquid portion of 20% HF solution was more aggressive than the vapor phase.

### *3.4 Ni-Cr-Mo Alloys*

One of the major limitations of stainless steels is that these alloys are susceptible to chloride induced localized attack such as crevice corrosion, pitting corrosion and stress corrosion cracking. Ni-Cr Mo alloys are the most resistant Ni based alloys to the classic chloride induced localized corrosion that troubles the stainless steels. In some cases SCC was reported in high strength materials; however, cracking only occurred in very aggressive conditions, such as temperatures higher than 200°C, pH lower than 4 and presence of hydrogen sulfide [19]. U-bend specimens of C-2000, C-22 and C-276 alloys were not susceptible to cracking in boiling (154°C) 45% MgCl<sub>2</sub> solution after 1008 h of testing [11]. C-276 and C-4 alloy were free from cracking in a 25% NaCl solution at 232°C; however, these alloys were susceptible to cracking in a MgCl<sub>2</sub> solution of same chloride content at the same temperature [14]. C-22 alloy was immune to SCC in 20.4% MgCl<sub>2</sub> solution up to 232°C, even in the 50% cold reduced condition and in the 50% cold reduced plus aged at 500°C for 100 h condition [11].

Laboratory testing using U-bend specimens (ASTM G 30) had shown that Ni-Cr Mo alloys such as C-276, C-22 and C-2000 alloy were susceptible to SCC in wet HF at both in the liquid and vapor phase (Figure 1) [11,12]. The most resistant of the Ni-Cr Mo alloy to cracking in wet HF was C-2000 (N06200) probably because the beneficial effect of 1.6% Cu content. Just in opposite behavior to Ni-Cu Alloy 400, Ni-Cr Mo alloys were less susceptible to cracking in the vapor phase than in the liquid phase, suggesting that the presence of Cr is beneficial for HF vapor phase applications [12].

Nickel based alloys are known to be susceptible to caustic cracking. Under slow strain rate conditions, C-276 alloy was susceptible to transgranular cracking in 50% NaOH at 147°C [20]. On the other hand, mill annealed and aged for 24 h at 677°C C-shape specimens (ASTM G 39) of C-22 alloy did not exhibit cracking after immersion in 50% NaOH solution at 147°C for 720 h [21].



Figure 1: SCC of Alloy C-276 (N10276) U-bend specimen immersed in a 20% HF solution at 93°C for 240 h. Magnification X100.

When Ni-Cr Mo alloys are aged at temperatures higher than 600°C for long time, long range ordering reactions and precipitation of tetrahedrally close packed (TCP) phases ( $\mu$ , P,  $\sigma$ ) may take place. The presence of the TCP phases produced by thermal aging may greatly reduce the ductility of Ni-Cr Mo alloys. For example, for annealed C-276 alloy, the yield stress (YS) at room temperature is 360 MPa, the ultimate tensile stress (UTS) is 807 MPa, the elongation to rupture is 63%; however, for a C-276 alloy that was aged for 16,000 h at 760°C, the YS increases to 476 MPa, the UTS increases to 894 MPa and the elongation to rupture decreases to 10%. It has been reported that thermally aged C-276 alloy was susceptible to hydrogen induced cracking in environments containing hydrogen sulfide ( $H_2S$ ) [22,23].

Ni-Cr Mo alloys were also found to suffer environmentally induced cracking in conditions associated to super critical water oxidation (SCWO). It has been reported that both C-276 (N10276) and Alloy 625 (N06625) suffered intergranular cracking when exposed to various aqueous solutions in the vicinity of the critical point of water (374°C) [24,25,26].

Because of its excellent resistance to stress corrosion cracking and other types of localized corrosion, C-22 (N06022) was selected by the Department of Energy (U.S.A.) to fabricate the outer shell of the high level nuclear waste containers to be disposed permanently at the Yucca Mountain site [27,28,29]. C-22 has been extensively tested for its susceptibility to SCC in a variety of environments, mainly at GE Global Research, Southwest Research Institute and Lawrence Livermore National Laboratory (LLNL). This alloy was found extremely resistant to EAC in many different solutions at the corrosion potential, at all the tested temperatures from ambient 110°C [30,31,32,33]. Tests were carried out using cyclic loading, constant load, constant deformation and slow strain rate tests in solutions from 14 molal  $MgCl_2$ , to simulated concentrated ground waters from pH 3 to 13. U-bend specimens of C-22 (N06022) and

other nickel alloys such as C-4 (N06455), G-3 (N06985), 825 (N08825) and 625 (N06625) were being used to characterize their stress corrosion cracking susceptibility in a variety of environments [34]. Gas Tungsten Arc Welded (GTAW) and non-welded U-bend specimens were exposed for more than 5 years at the corrosion potential to the vapor and liquid phases of three different solutions (pH 2.8 to 10) simulating up to 1000 times the concentration of ground water both at 60°C and 90°C. None of these alloys suffered any indication of environmentally induced cracking [34].

Alloy C-22 was found susceptible to EAC when SSRT was performed on mill annealed specimens in hot simulated concentrated water (SCW) at anodic applied potentials [33,35,36]. SCW is a multi-ionic alkaline solution approximately 1000 times more concentrated than a Yucca Mountain ground water. It is likely that the small amount of fluoride ions present in this solution (1400 ppm) contributed to the cracking of C-22 [36]. The susceptibility to cracking of C-22 was strongly dependent on the applied potential and the temperature of the solution. The highest susceptibility to EAC was found at around 90°C at +400 mV in the saturated silver chloride (SSC) electrode scale (Figure 2). At the corrosion potential, C-22 was free from EAC even at 90°C. Similarly, at anodic applied potentials, C-22 was free from EAC at ambient temperatures and as the temperature increased the time to failure in the tests decreased (Figure 3).

It has also been reported that Alloy C-22 (N06022) may suffer some embrittlement when it is slow strained under cathodic applied potentials (or currents) [36,37,38]. The maximum susceptibility to cracking under cathodic conditions seemed to occur at ambient temperatures suggesting a hydrogen related failure mechanism.

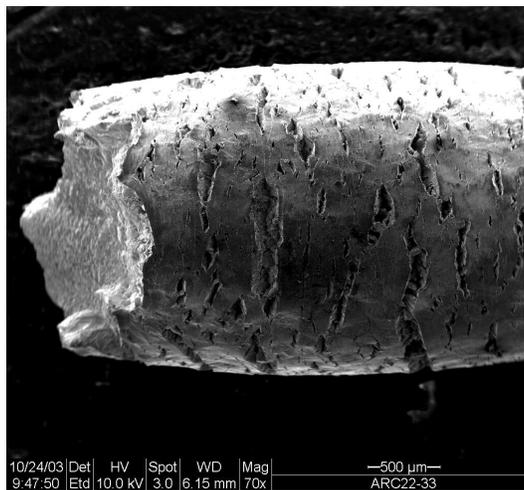


Figure 2: Alloy N06022 strained in SCW solution at 86°C. Applied +400 mV SSC.

### 3.5 Ni-Cr-Fe Alloys

This is one of the largest groups of nickel-based alloys since it covers Inconel 600 (N06600), Incoloy 825 (N08825) and 800 (N08800) and Hastelloy G-30 (N06030) type

alloys. Since Alloy 600 has been used to fabricate the tubes of steam generators in nuclear power plants, it has been by far the most studied nickel alloy regarding its stress corrosion cracking behavior, especially in hot water and in caustic solutions. Alloy 600 has been found to suffer stress corrosion cracking in high temperature pure water (> 300°C) both in service and in the laboratory. Due to its importance for the nuclear industry, the stress cracking of alloys 600 and 690 in pure water and in caustic solutions has been extensively researched in the last three decades [39,40] and more than one thousand technical papers have been published in this subject. The susceptibility to cracking of alloys 600 and 690 depend strongly on environmental factors such as temperature, level of tensile stresses, deformation rate, presence of hydrogen gas, solution pH and electrochemical potential, and metallurgical factors, such as presence of minor alloying elements (impurities), the amount of cold work and heat treatment (intragranular or intergranular carbides). Cracking in alloy 600 could be intergranular or transgranular.

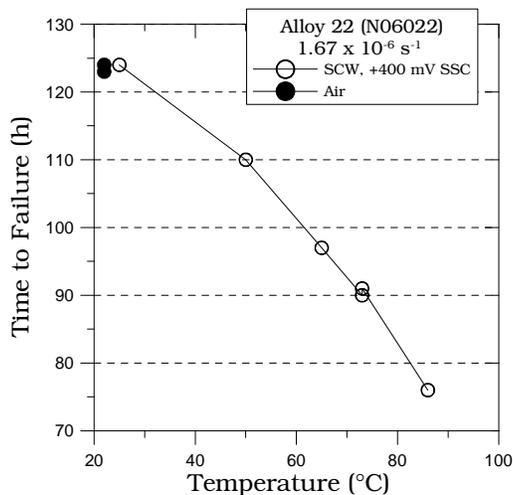


Figure 3: Effect of temperature on the SCC susceptibility of N06022 in SCW solution at an applied potential of +400 mV.

Alloy 600, like other nickel based alloys, also suffers stress corrosion cracking in hot caustic solutions (150°C-200°C). Alloy 690, which has double the amount of chromium in Alloy 600 has been found to be more resistant than Alloy 600 to high temperature cracking in pure water and in caustic solutions. Due to its high content of nickel (76%), alloy 600 is resistant to stress corrosion cracking in chloride containing solutions; however, Alloy 600 was susceptible to localized attack in hydrofluoric acid containing environments [10].

Alloy 800 is also used in the nuclear power generation. It was shown that Alloy 800 (N08800) was susceptible to caustic cracking [41] and even more susceptible than Alloy 690, probably because of the higher Cr content of the latter [42].

Alloy 825 is more resistant to stress corrosion cracking than for example 316 stainless steels due to its higher content of nickel. Slow strain rate tests and U-bend tests have

shown that alloy 825 was susceptible to transgranular stress corrosion cracking in 45%  $\text{MgCl}_2$  solutions at temperatures above 146°C. Alloy 825 is used extensively in the oil and gas production in sour wells, performance of other nickel alloys such as C-276 and G-50 (N06950) is still superior of that of 825 [43]. These nickel alloys are used mainly in the cold worked condition for increased strength. The corrosion society (NACE International) provides guidelines (MR0175) on the maximum allowable hardness. For example, the maximum hardness for cold worked Alloy 825 is 35 HRC (the annealed hardness is 85 HRB, Table 1). Environmental factors that may affect the stress cracking performance of Alloy 825 (and other alloys) in oil and gas wells include temperature, amount of chloride and the presence of hydrogen sulfide gas [43].

Data on the stress corrosion cracking behavior of G-30 alloy is scarce. It has been reported that G-30 components used in the industrial production of hydrofluoric acid suffered cracking [11]. U-bend specimens of G-30 alloy did not crack after exposure for 500 h in 45%  $\text{MgCl}_2$  solution at 154°C. It has been found that G-30 as well as other nickel alloys would suffer cracking in the aggressive conditions encountered in super critical water oxidation (SCWO) treatments.

#### 4. Concluding Remarks

Nickel alloys are more resistant than stainless steels to environmentally assisted cracking (EAC). Nickel alloys are practically immune to EAC in hot chloride containing solutions. Ni alloys are also resistant to hydrogen assisted cracking. The environments that induce cracking of nickel alloys are highly specific and therefore they may be avoidable by design. Nickel alloys may be prone to EAC in wet HF and in hot alkalis. Ni-Cu alloys (e.g. Alloy 400) are more resistant to cracking in wet HF than Ni-Cr Mo alloys (e.g. C-276). Similarly, commercially pure Ni such as Ni-200 is more resistant to cracking in hot alkalis than Ni-Cr Mo alloys.

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