

Paper No.
16705



A Review of Hydrogen Embrittlement of Nickel-Based Alloys For Oil and Gas Applications

Thierry Cassagne
TOTAL SE
CSTJF, Avenue Larribau
F-64018 Pau
France

Thiago Mesquita
TOTAL Gabon
Blvd Hourcq
Port-Gentil
Gabon

Hervé Marchebois
TOTAL SE
CSTJF, Avenue Larribau
F-64018 Pau
France

ABSTRACT

After a number of failures in the Oil and Gas industry research works on hydrogen embrittlement (HE) of nickel-based alloys has been quite significant. Much work had been done previously in other industries, nuclear and aeronautic in particular. Despite this work, a lot remains to be understood. Among them, precipitation-hardened (PH) nickel alloys UNS N07718 has been significantly studied and its HE resistance is now better assessed based on its microstructure. Less work has been performed on some of the other PH nickel alloys, although, their HE resistance is better appreciated from recent literature data. The results published at NACE Corrosion 2019 from a large JIP study indicated that PH nickel alloys could be split in three families with less susceptible alloys, like UNS N07718, UNS N09925 and UNS N09935, more susceptible alloys like UNS N07725 and UNS N07716, while alloy UNS N09945 had variable susceptibility. Besides PH nickel alloys, other solution-annealed or cold worked alloys are used in environments where hydrogen can be present. As PH alloys they are also susceptible to HE, but published studies are scarce. This paper is a review of internal and published work setting the base of our current understanding on the HE resistance of various PH, solution annealed and cold worked nickel-based alloys. Consequences on the use of these alloys are discussed for Oil and Gas applications.

Key words: Hydrogen Stress Cracking, mechanisms, nickel alloys, precipitation hardened nickel alloys, Oil and Gas, microstructure, cold work, plastic strain

INTRODUCTION

A literature survey and results of internal studies have been used to summarize our knowledge concerning hydrogen embrittlement (HE), also called HSC (hydrogen stress cracking) or HISC (hydrogen-induced stress cracking) of nickel-based alloys, specifically alloys in use in the upstream Oil and Gas industry. Since the first major failure reported in an HPHT well in early 2000's a number of studies have completed previous work primarily on UNS⁽¹⁾ N07718 in the nuclear and aeronautics and space industries. Other alloys have since been developed specifically for the upstream Oil and Gas production, while others were already in use. The objective of these alloys is to be resistant to internal corrosion in severe sour conditions, where carbon and low alloy steels cannot be used, and be also resistant to HSC in case hydrogen charging occurs in wells and subsea components. This means these alloys must be listed in NACE⁽²⁾ MR0175/ISO 15156 Standard with high sour limits and they should have the highest possible resistance to HSC. This paper only deals with HSC and attempts to give an update on the current knowledge on the resistance of nickel-based alloys to HSC and how they can be used in the field to avoid failures.

BACKGROUND

Precipitation-hardened (PH) nickel alloys are used in the nuclear, aeronautics and space industries, as well as, in the Oil and Gas sector. Among the various alloys, the UNS N07718 has had a particular focus because of its high strength, high temperature resistance and corrosion resistance. In the Oil and Gas production PH nickel alloys are used for high strength downhole applications in sour corrosive conditions, often as forged components like hangers or valves and subsea for high strength fasteners when sour service resistance is required under insulation. Several high profile failures of downhole and subsea components have been published since 2003.¹⁻⁵ These have triggered renewed interest on one hand for attempting to better understand the cracking mechanism in the presence of hydrogen, and on the other hand to develop API⁽³⁾ specifications to prevent/limit the use of susceptible materials. This paper starts with a (non-exhaustive) review of the work done since the 50's to understand hydrogen stress cracking (HSC) in pure nickel and nickel alloys and to see how this knowledge can be used to prevent the occurrence of failures in the future. It primarily focuses on nickel-based alloys but works on other materials like (low alloy and stainless) steels are also relevant to these alloys, since the proposed failure mechanisms are the same. The objective is to summarize and bring to light important aspects of what is known so far, questions yet to be answered, consequences on material selection and eventually give directions for future works to use these materials as safely as possible. In the course of this paper new information is given where relevant to highlight specific aspects. Single phase alloys are also discussed to remind that these alloys are also susceptible to HSC under severe loading conditions.

UNDERSTANDING HYDROGEN STRESS CRACKING

This first part is dedicated to summarizing our understanding of the HSC phenomenon addressing key features in relation with the main proposed mechanisms. Mechanistic work has

⁽¹⁾ Unified numbering system

⁽²⁾ National Association of Corrosion Engineers

⁽³⁾ American Petroleum Institute (API), 1220 L St, N.W. Washington DC 20005-4070.

been performed on more simple materials like pure nickel, iron-silicon and many materials with either a body centered cubic (BCC) structure like steels or a face centered cubic (FCC) structure like nickel alloys. Although there must be differences between low alloy steels, stainless steels and nickel alloys, the same mechanistic approach has been taken for all these materials. We will focus here on nickel alloys, but some reference work will deal with other materials when relevant. Johnson is cited as the first one to recognize the embrittlement of iron through a decrease in toughness and breaking strain of iron immersed in hydrochloric acid and sulfuric acid in 1875.⁶ The importance of this phenomenon was not really recognized until the 40's when hydrogen embrittlement failures occurred. A number of reviews have been published over the years by well recognized researchers in this field. Some of them are mentioned here. Troiano summarized his views on this topic in 1959.⁷ He stated that for low alloy steel a critical hydrogen concentration was required in the high triaxial stress zone ahead of the main crack, to produce further embrittlement. He also mentioned that the same brittle behavior was observed in nickel and nickel-based alloys when heavily charged with hydrogen. Later on, Oriani at NACE Corrosion 1987 focusing on steels discussed the decohesion model and the localized slip model giving the basis for further mechanistic work.⁸ Birnbaum in 1989 advocated the HELP (hydrogen enhanced localized plasticity) mechanism, "hydrogen embrittlement being a shear localization by hydrogen".⁹ He also discussed hydrogen induced decohesion as being another possible failure mechanism. Lynch discussed the various mechanisms at NACE Corrosion 2007 where he summarized his views concerning his model of adsorption-induced dislocation emission (AIDE) and those of other workers who advocate hydrogen enhanced decohesion (HEDE) and HELP.¹⁰ Gerberich performed an extensive review in 2012 and summarized the chronology of proposed mechanisms, including those which had been dismissed over the years.¹¹ In 2015 Robertson and coworkers summarized the main findings based on detailed microscopic work using focused ion beam and transmission electron microscopy (TEM).¹² After a detailed review of microscopic evidence the authors concluded that Beachem model of embrittlement induced by localized plasticity was demonstrated for transgranular (TG) and particularly for intergranular (IG) cracking in the presence of hydrogen.¹³ More recently UNS N07718 as well as UNS N09945 and UNS N09946 have been the focus of detailed work using advanced microscopic and analytical techniques.¹⁴⁻²¹ The authors advocated also the HELP mechanism for the HSC of these alloys.

General observations

Before going further into the details of these mechanisms and how they may apply to HSC major features of HSC of nickel alloys are summarized below.

It is well known that unlike more susceptible materials, like low alloy steels or martensitic stainless steels, plasticity is required for HSC to occur in nickel-based alloys. In general, all nickel alloys are susceptible to HSC (even pure nickel) but some alloys are more susceptible than others. This is the case of precipitation-hardened (PH) nickel alloys when compared to solution annealed alloys.^{22, 23} Concerning the cracking mode, typically TG cracking occurs when alloy susceptibility to HSC is low to moderate. The cracking mode becomes IG when the alloy becomes more susceptible as will be discussed later. Intergranular cracking is typically associated with the presence of precipitation at grain boundaries (GB). Hence heat treatments favoring IG precipitation (δ , σ , NbC ...) are detrimental for HSC resistance.^{1, 2, 23-25} In the absence of IG precipitation the precipitate free zone and the strengthening phases γ' and especially γ'' are expected to play a detrimental role.²³ Some alloys such as UNS N07725 and

UNS N07716 have been shown to be more susceptible than other PH alloys like UNS N07718 and UNS N09945.²⁶ This is presumably associated with a continuous IG precipitation inherent to these alloys.^{26, 27} We will see that cold work may not be detrimental when considering the resulting high strength of these strain-hardened alloys.²⁸

The role of plasticity

Among the major findings concerning HSC the interaction of hydrogen with dislocations and plasticity has been particularly studied. The literature is quite lengthy on this topic and only selected references are mentioned here to illustrate the main observations. Bastien and Azou were certainly among the first to mention the embrittling role of hydrogen entering the lattice as protons and being entrained by dislocations during plastic deformation in iron and steel.^{29,30} The sudden increase of tritium desorption at the onset of plastic deformation during straining was shown by Louthan et al. and Donovan in pure iron, AISI 304L, an aluminum alloy and Alloy 718 (Figure 1).^{31,32} The very fast degassing was similar for different materials. Later on, Lecoester et al. observed the same behavior in Alloy 600 (Figure 2).³³ Since nothing happened in the elastic range this was interpreted as the sweeping of hydrogen by dislocations emerging at the material surface during plastic straining. They studied the effect of temperature and strain rate and observed that HSC decreased with increasing temperature and increasing strain rate. The fracture mode transition brittle to ductile was also dependent on microstructure. They concluded that hydrogen transport by mobile dislocations was a necessary step for hydrogen embrittlement.

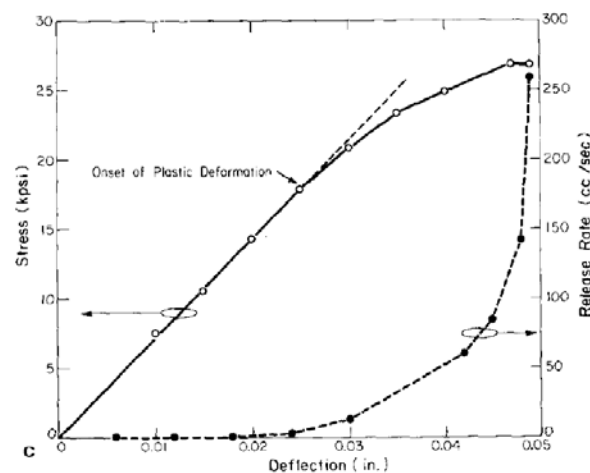


Figure 1: Alloy 718 tritium release from charged tensile specimens during yielding from³¹

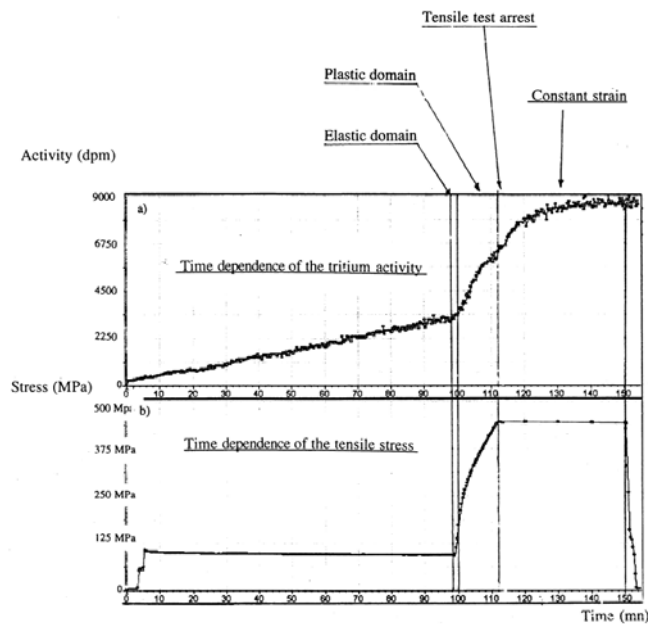


Figure 2: Alloy 600 tritium release from charged tensile specimens strained at 10^{-4} s^{-1} from³³

Other observations on a Superalloy single crystal indicated that only one slip system was activated when plastically strained under cathodic charging, while two slip systems were activated in the absence of hydrogen charging.³⁴ This indicated that hydrogen transport was not only enhanced by plasticity but that hydrogen also localized deformation on specific slip planes. Earlier Hicks and Altstetter had observed fracture on $\{111\}$ planes in aged Alloy 718 with localized deformation in the vicinity of the fracture surface.³⁵ Lynch observed a similar behavior in pure nickel [36] at GB. Louthan et al. observed that low stacking fault energy (SFE) stainless steels were more embrittled by hydrogen.³¹ They also suggested that hydrogen could also lower the SFE and hinder cross slip as shown for pure nickel.³⁷ Birnbaum et al. concluded that hydrogen decreases the flow stress and strain hardening, and solid solution hardening.⁹ It was advocated to result from an elastic shielding decreasing interaction between dislocations and obstacles in the temperature range where hydrogen embrittlement occurs. One of the most demonstrative observation illustrating the effect of hydrogen on dislocations is the high voltage TEM work performed by Birnbaum and colleagues and later by Robertson then summarized by Robertson et al..^{38,39,12} They observed that dislocations were moving when hydrogen was introduced in the TEM environmental chamber (Figure 3a) and that dislocation velocity was increasing with hydrogen pressure (Figure 3b). This effect was also reversible and reproducible. Consistent with these observations enhanced slip activation and coarser slip were observed with increasing hydrogen content in AISI 310 SS and pure nickel as shown in Figures 4 and 5, respectively.^{36,40}

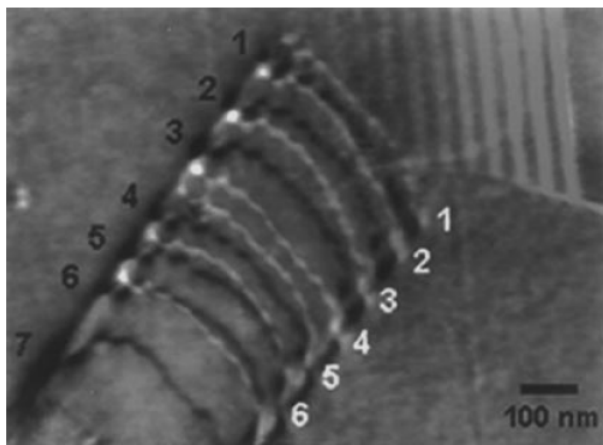


Figure 3a: Moving dislocations (from black to white positions) after introduction of 95 torr of hydrogen from⁴¹

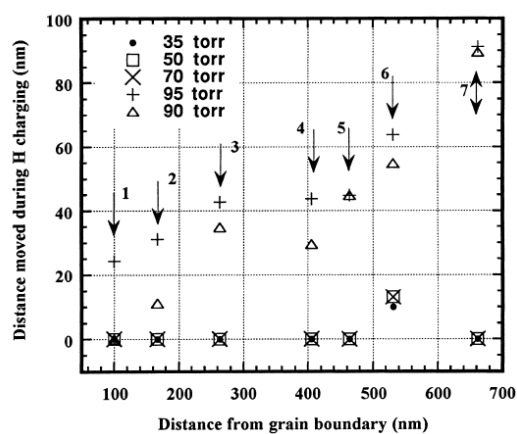


Figure 3b: Dislocation motion versus distance from GB and as a function of hydrogen gas pressure from⁴¹

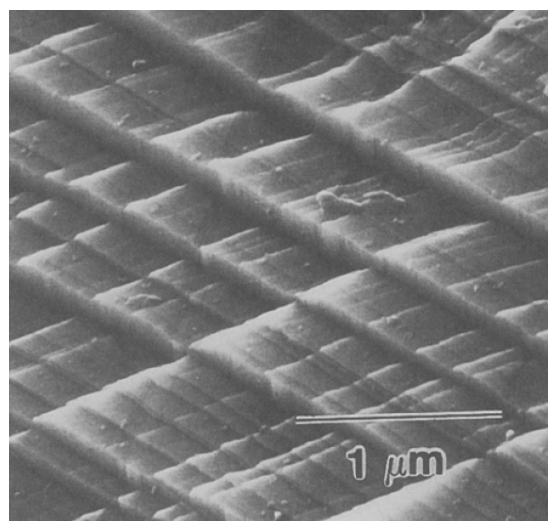
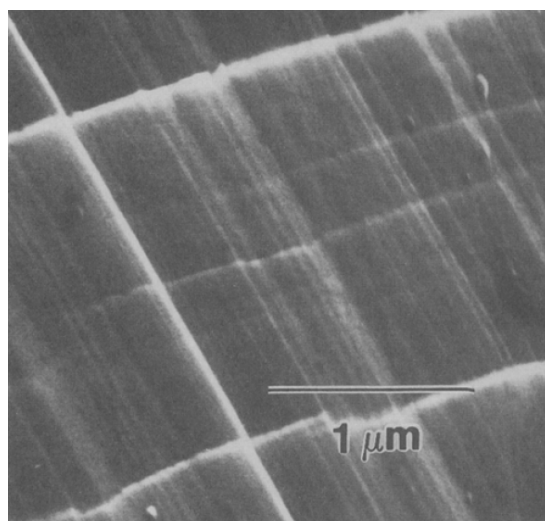


Figure 4: Slip bands observed on 310 SS during slow crack growth from⁴⁰

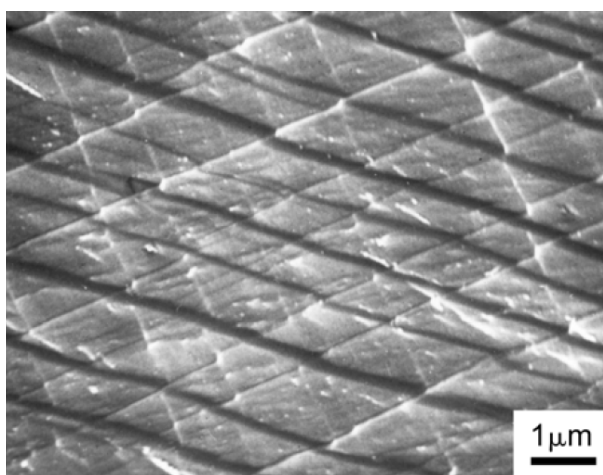


Figure 5 Slip bands observed on pure nickel GB during slow crack growth from³⁶.