

UNS N08034 – A High-Performance Solution for Corrosive, High-Stress Conditions

Philipp Hübner
VDM Metals International GmbH
Kleffstr. 23
58762 Altena
Germany

Julia Botinha
VDM Metals International GmbH
Kleffstr. 23
58762 Altena
Germany

Michael Dodge
The Welding Institute Ltd.
Granta Park
Cambridge, CB21 6AL
United Kingdom

David Martelo
The Welding Institute Ltd.
Granta Park
Cambridge, CB21 6AL
United Kingdom

Helena Alves
VDM Metals International GmbH
Kleffstr. 23
58762 Altena
Germany

ABSTRACT

In the oil and gas and petrochemical industries, different parts and components can be prone to Hydrogen Embrittlement (HE). This is a critical phenomenon, where the diffusion of atomic hydrogen into metallic materials severely diminishes ductility and load-bearing capacity, leading to premature brittle fracture. Challenges include the susceptibility of high-strength materials to aggressive environments, often exacerbated by cathodic protection systems in subsea environments. Especially high-strength materials under heavy loads, such as fasteners and bolts, need to be carefully selected. Finding materials with enhanced resistance to hydrogen absorption and cracking is paramount to ensure the long-term integrity, safety, and reliability of critical infrastructure, not only on already established applications, but especially as hydrogen gains traction as a clean energy carrier.

When in its cold-worked condition, UNS¹ N08034, a bridging alloy between 6-Mo stainless steels and the highly alloyed nickel based alloys of the C-family, represents an optimum choice between mechanical strength, corrosion resistance and resistance against HE. In this paper, a variety of investigations using cold-worked UNS N08034 are to be displayed, proving that the material is extremely resistant even under very challenging conditions of application.

Key words: Alloy 31 Plus, Nickel based alloys, Hydrogen embrittlement, UNS N08034, Cold work, Corrosion resistance, Fasteners, Bolting

¹ Unified Numbering System

INTRODUCTION

For the global economy, the oil and gas industry as well as the chemical process industry have been foundational since the Industrial Revolution in the 19th century. These sectors have been some of the main promoters for scientific and technological progress not only by providing the well-needed raw materials but also by providing new challenges for engineers and scientists to overcome.^{1, 2}

Some of those challenges originate from the goal, to optimize the efficiency of processes and to reduce carbon emissions by enhancing the cleanliness of exhaust gases. Others simply arose from the so-called “resource curse”, which mainly refers to the limited availability of raw resources as for example gas and oil. This fact made it necessary to start the exploration process towards fields with more limited accessibility and more critical conditions, increasing the application requirements. As a result, new drilling methods such as the horizontal drilling and hydraulic fracturing have been introduced and thereby enabled a significant increase in oil and gas availability and supply.^{1, 2, 3}

By definition, the oil and gas industry as well as the chemical process industry reveal harsh application conditions for materials in use, which makes the material selection process very important. The service conditions reach from “sweet” to “sour”, meaning that highly acidified and toxic gases such as hydrogen sulfide (H₂S) are common atmospheres in contact with the components in use. Seawater at different temperatures and compositions in terms of chloride content and biological activity makes an additional threat for material performance.^{1, 3, 4}

As corrosive environments are a critical factor for the applied materials in the oil and gas industry, one corrosion prevention technique is cathodic protection. This technique involves the application of a suitable potential to the components, thereby achieving immunity. However, by applying cathodic protection, in contact with liquid water, hydrogen can be produced at the surface of the parts through electrochemical reactions. The subsequent adsorption and absorption of atomic hydrogen can lead to hydrogen embrittlement, particularly in high-strength materials subjected to heavy loads, which are more prone to this degradation mechanism.^{5, 6} Beyond that, the presence of hydrogen sulfide mentioned above leads to an additional and more easy intake of hydrogen, hence sulfur acts as an inhibitor for the recombination of atomic hydrogen and thereby enables the hydrogen absorption.^{7, 8, 9, 10}

The mechanisms behind hydrogen embrittlement are complicated and only understood in part. Several theories have been proposed during the past 50 years, including Hydrogen Enhanced Decohesion (HEDE) and Hydrogen Enhanced Localized Plasticity (HELP).¹¹ At first, atomic hydrogen is adsorbed to the metal surface and then absorbed by the metal matrix. When the atomic hydrogen is inside the metal, it can move by diffusion rapidly through the lattice structure. Lattice defects such as dislocations, grain boundaries and phase boundaries can act as traps for the hydrogen atoms, hindering it from further moving forward. An accumulation of hydrogen at these traps in combination with elevated mechanical loads can further cause the material to lose ductility and crack. The HEDE-theory describes the weakening of atomic bonds and the mechanical strength of the material is significantly reduced. Intergranular crack progression is often associated with this theory. According to the HELP-theory, hydrogen increases the mobility of dislocations, leading to a local increase of plasticity. Thereby, crack initiation and propagation in such areas is significantly accelerated and typically associated with trans-granular crack propagation.

To provide the best possible protection against hydrogen induced failures, the material selection process is of absolute importance. Figure 1 was extracted from a technical memorandum from NASA¹² and shows a correlation between nickel content and vulnerability to hydrogen embrittlement. The authors define the term “Hydrogen Environmental Embrittlement” (HEE), which was used to describe the degradation of mechanical properties under the influence of an applied stress and intentionally exposed to gaseous

hydrogen environment. The HEE Index, a property ratio for testing in hydrogen environment as compared to inert environments, is used as an initial material screening tool to evaluate the severity of hydrogen embrittlement effects. HEE Indexes comprise values from 1 to 0, where maximum HE resistance is achieved at values as close to unity as possible.

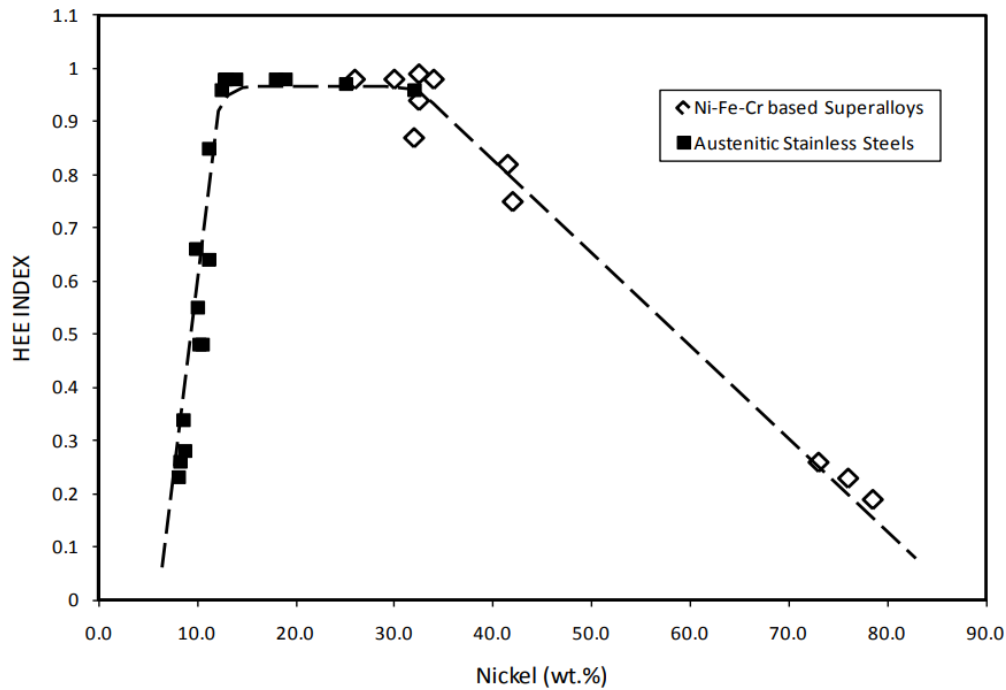


Figure 1: Hydrogen Environmental Embrittlement (HEE) index for Fe-Ni-Cr super alloys and stainless steels as a function of Ni content in wt.%.¹²

HE becomes negligible when nickel contents are from 12.5 % to 34 %. Nickel contents greater than 34 wt.% start showing a vulnerability for hydrogen embrittlement under critical application conditions.

Materials such as UNS N07718 and UNS N07725 are widely used in the oil and gas industry. Both are precipitation hardenable (PH) alloys and each has its pros and cons. UNS N07718 is the most used PH-Nickel-Alloy in the oil and gas industry and provides very high mechanical strength in combination with acceptable localized corrosion resistance. UNS N07725 is a more recent development that combines high mechanical strength with high localized corrosion resistance. Despite their interesting combination of properties, PH-nickel-alloys may be highly susceptible to hydrogen embrittlement in oil and gas environments, especially UNS N07725, as seen in the most recent reported failures.^{13, 14, 15}

The combination of requirements for high localized corrosion resistance, high mechanical strength and resistance against hydrogen embrittlement suggests the optimized selection of high-strength medium level nickel alloys that bridge the gap between stainless steels and highly alloyed nickel-based alloys. One material to be considered at this point is the UNS N08034, a fully austenitic nickel-based alloy with the chemical composition listed in Table 1.

Table 1: Main chemical composition of UNS N08034 in weight percent.¹⁶

UNS	Chemical composition in wt.%					
	Fe	Ni	Cr	Mo	C	Others
N08034	Balance	34	26.5	6.5	< 0.01	Cu, N

Its single phase austenitic microstructure, as depicted in Figure 2, is stabilized by a nickel content of 34 wt.% and the intentional alloying with nitrogen and manganese. The well-balanced composition of this alloy leads to a good thermal stability and excellent corrosion resistance against general surface corrosion in oxidizing as well as in reducing media according to Behrens et al.¹⁷ Further, the material has proven an outstanding resistance against localized corrosion phenomenon such as pitting and crevice corrosion in the solution annealed condition, as shown in Table 2.

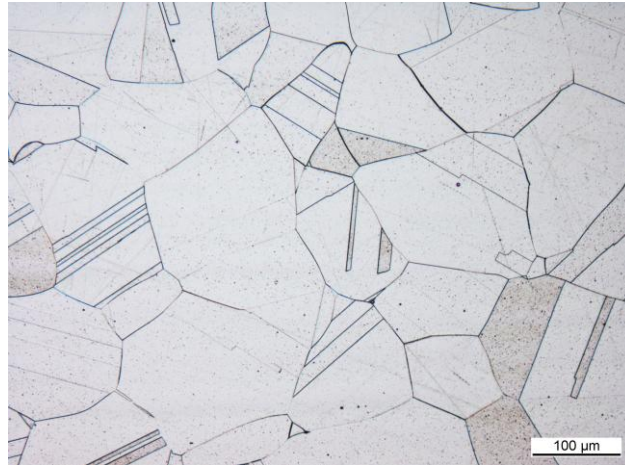


Figure 2: Homogeneous austenitic microstructure of UNS N08034 in the solution annealed condition.

Studies by Botinha et al.^{18, 19} have shown that an adapted manufacturing process involving work hardening can achieve yield strengths up to 160 ksi with sufficient remaining ductility, as depicted in Figure 3, where the achieved mechanical properties as a function of the amount of work-hardening is shown.¹⁴ Also, previous investigations of Hübner et al.²⁰ demonstrated that the material retains its marked resistance to localized corrosion when in the work-hardened condition, comparably to the solution annealed state, as depicted in Table 2. Table 2 also presents literature data available for UNS N07718 and UNS N07725 for comparison.

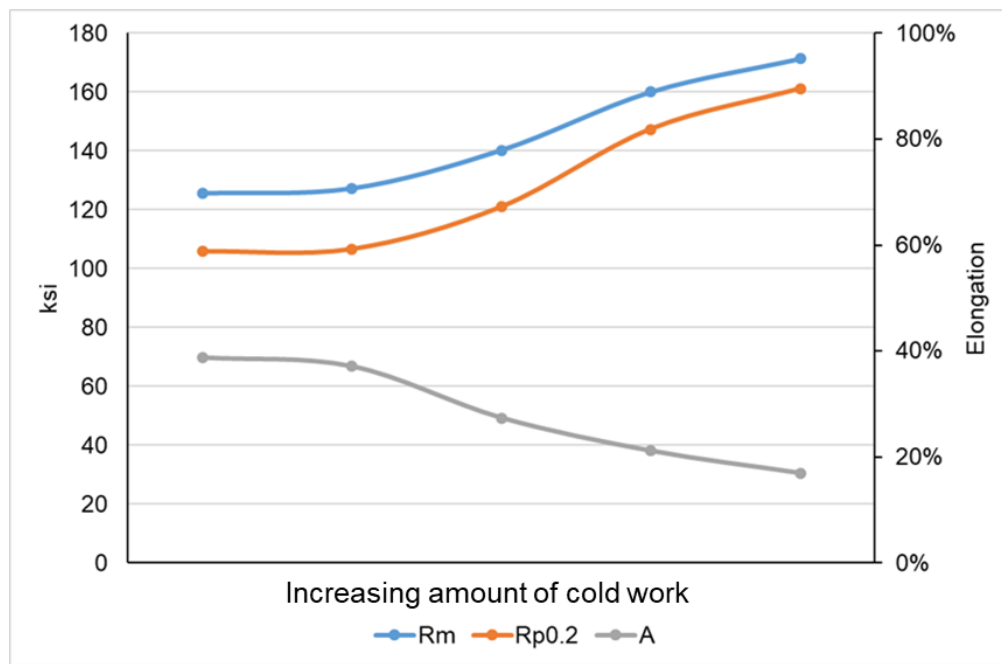


Figure 3: Achieved mechanical strength levels of UNS N08034.²⁰ Here Rm stands for ultimate tensile strength, $R_{p0.2}$ stands for yield strength at 0.2 % elongation and A stands for elongation.

Table 2: The corrosion resistance of UNS N08034 in work hardened condition in standardized media in comparison to solution annealed UNS N08034 ²⁰ and with PH-Nickel Alloys UNS N07718 ²¹ and UNS N07725 ²¹.

	Solution annealed UNS N08034	Work hardened UNS N08034	UNS N07718	UNS N07725
ASTM G28, Method A ^{*1}	0.22 mm/a 24 h exposure time	0.11 mm/a	-	-
ASTM G48, Method C ^{*2}	90 °C	90 °C	45 °C	>85 °C
ASTM G48, Method D ^{*3}	70 °C	65 °C	<10 °C	25 °C
^{*1} : 50 wt.% H ₂ SO ₄ + 42 g/l Fe ₂ (SO ₄) ₃ x 9 H ₂ O, boiling, 120 h ^{*2} : 6 wt.% FeCl ₃ + 1 wt.% HCl, 72 h intervals ^{*3} : 6 wt.% FeCl ₃ + 1 wt.% HCl, 72 h intervals				

In terms of hydrogen embrittlement susceptibility, investigations were carried out by Dhillon et al. ²². The authors have carried out slow strain rate tests on UNS N08034 and proven that the material shows no evidence of susceptibility to HE, as shown in Figure 4. These results place UNS N08034 as a very promising material alternative to PH-Nickel alloys like UNS N07718 and UNS N07725.

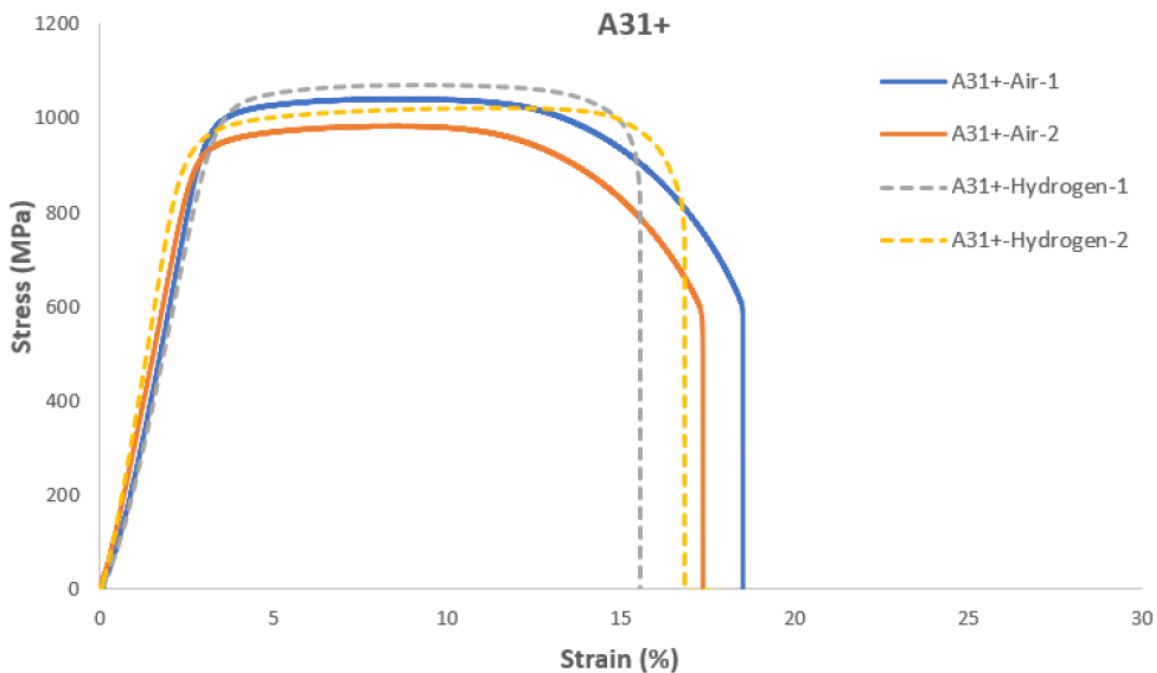


Figure 4: No susceptibility of UNS N08034 to HE. ²²

EXPERIMENTAL PROCEDURE

This paper takes a closer look at examining the UNS N08034 in its work-hardened condition, focussing on its suitability for use as fasteners. Herein, the materials' resistance against hydrogen embrittlement under constant load is investigated at The Welding Institute (TWI Ltd.), in the UK.

Fabrication of sample material

For the intended investigations, an industrial heat has been manufactured. After the primary melting step, a vacuum treatment has been conducted to ensure low levels of sulfur, phosphorus, carbon and oxygen in the material. Additionally, electro slag remelting has been conducted, followed by a homogenization heat treatment, thereby ensuring a homogeneous distribution of elements more prone to segregation. The material was then hot forged to intermediate dimension and finally solution heat treated in order to obtain a fully recrystallized microstructure free of intermetallic precipitates. In the final forming step, the intended work hardening level was set.

Initially, the manufactured material was characterized in terms of mechanical strength. For that, tensile tests and hardness measurements were conducted to validate the comparability to the mechanical strength levels to UNS N07718 and UNS N07725.

In order to determine the hydrogen embrittlement susceptibility relevant to subsea fasteners, an experimental procedure was carried out at TWI in the UK. First, a finite element analysis (FEA) was conducted to map the stress and strain distributions within a full-scale fastener under typical service loads, identifying critical stress concentrations. Based on this model, small-scale round notched tensile (RNT) specimens were fabricated. The notch geometry was designed to replicate the fasteners' thread profile and stress concentration factor (SCF), ensuring mechanical comparability. The depth and root radius were 0.06 mm and 0.26 mm respectively, with a flank angle of 60°. The specimens were subjected to constant loading while fully immersed in a 3.5% NaCl solution under cathodic polarisation to replicate hydrogen-charging conditions representative of a subsea environment. A linear variable differential transformer (LVDT), positioned within the test solution, was employed to measure small-scale displacements across the specimen's length. The experimental set-up is shown in Figure 5. A matrix of tests was performed at various load levels, defined as percentages of the materials' yield strength, ultimate tensile strength, or the notch root plastic strain. The primary objective was to identify the threshold stress required to initiate failure. Post-test fractographic analysis by scanning electron microscopy was used to characterize the failure mechanisms. This methodology shall establish a direct correlation between applied load and the probability of cracking, providing critical data for integrity assessments of subsea fasteners.

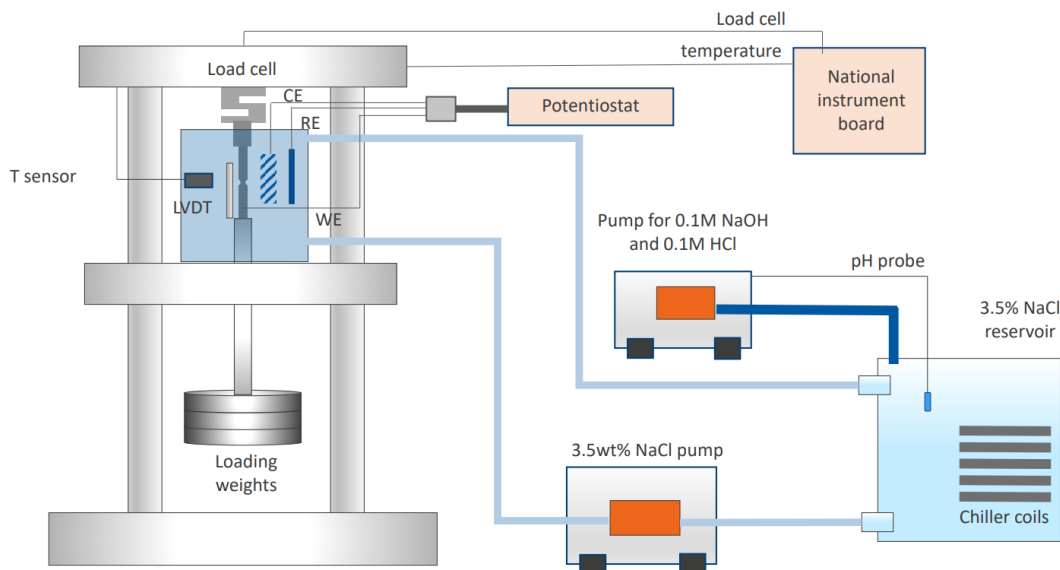


Figure 5: Schematic concept of the testing facility for the constant load tests at TWI.

RESULTS AND DISCUSSION

Mechanical testing

Tensile tests according to ASTM E8/E8M ²³ at room temperature were carried out to compare the mechanical properties of UNS N08034 to the PH-Nickel Alloys UNS N07718 and UNS N07725. Results are presented in Table 3 and show that work hardened UNS N08034 fulfils the mechanical requirements set by the API 6ACRA ²⁴ Standard for the material it is intended to replace.

Table 3: Tensile properties of work hardened UNS N08034 compared to UNS N07718 and UNS N07725

Alloy	Yield Strength [ksi]	Tensile Strength [ksi]	Elongation [%]
UNS N08034	143	159	23
UNS N07718*	120-145	> 150	> 20
UNS N07725*	120-150	> 150	> 20

*Tensile requirements acc. to API 6ACRA

Finite Element Analysis

Snapshots of the FEA calculations at 23 % of the notch root plastic strain are shown in Figure 6 as a representation of the behaviour of the notched sample in comparison to the fastener. The results confirm that the SCF of the notched specimen is representative of the fastener.

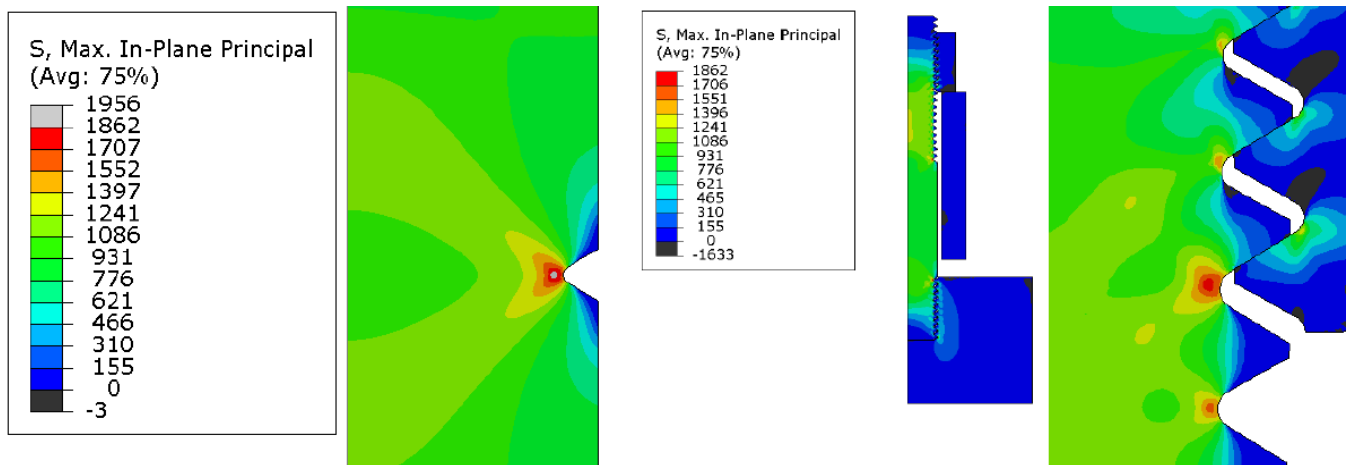


Figure 6: Snapshot of FEA calculations at 23% of notch root plastic strain showing the maximum principal in-plane stresses in MPa in the specimen (left) and fastener (right).

Constant load testing

Samples were tested at load levels equivalent to about 100 % actual yield strength (AYS) based on gross section stress (i.e. major diameter). These load levels are equivalent to about 130-135 % AYS based on net section stress. The time vs load and time vs displacement diagrams are shown in Figure 7. Figure 8 and Figure 9 show the fractography of a tested specimen that presents a ductile overload fracture surface without evidences of hydrogen cracking.

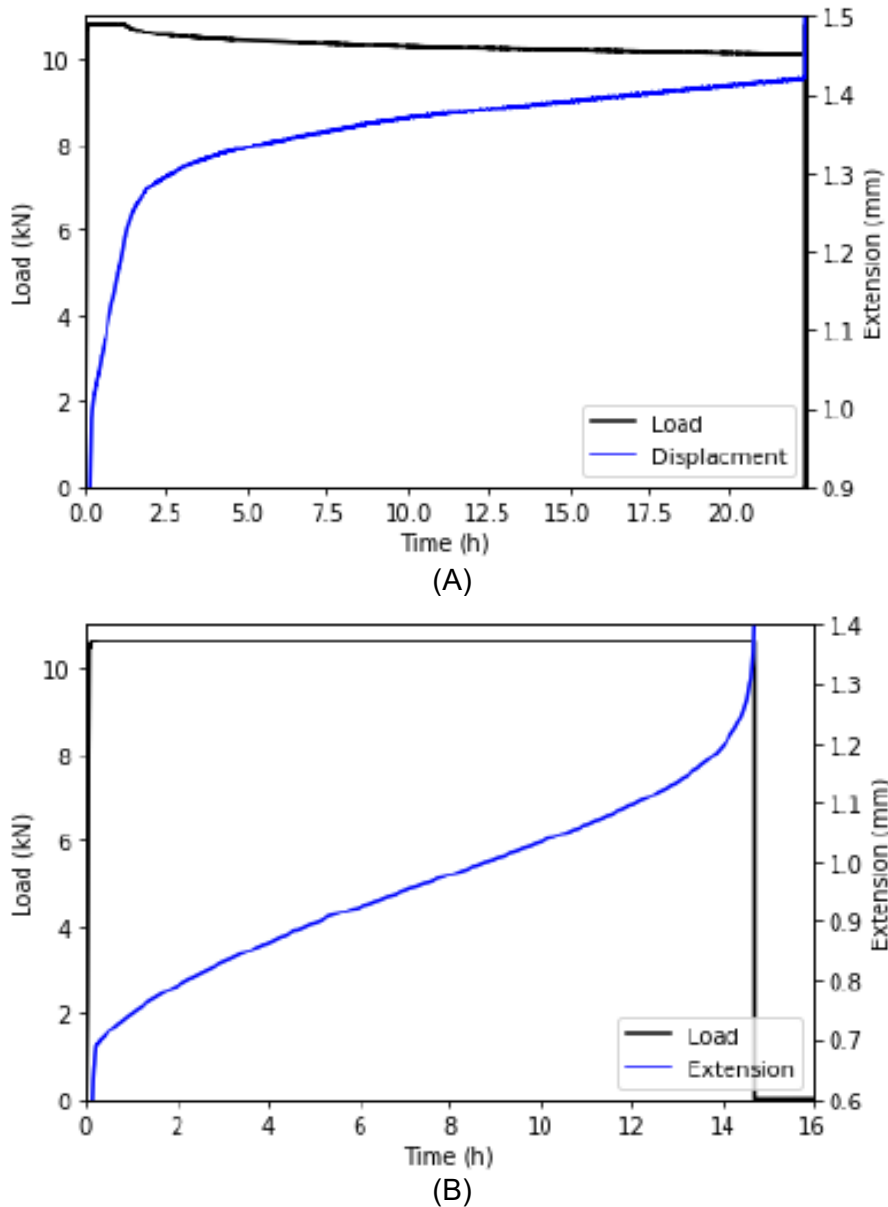


Figure 7: Time vs load and displacement diagrams generated by constant load testing at 100 % of AYS based on gross section stress. (A) 37% plastic strain at the notch root and (B) 24% plastic strain at the notch root.

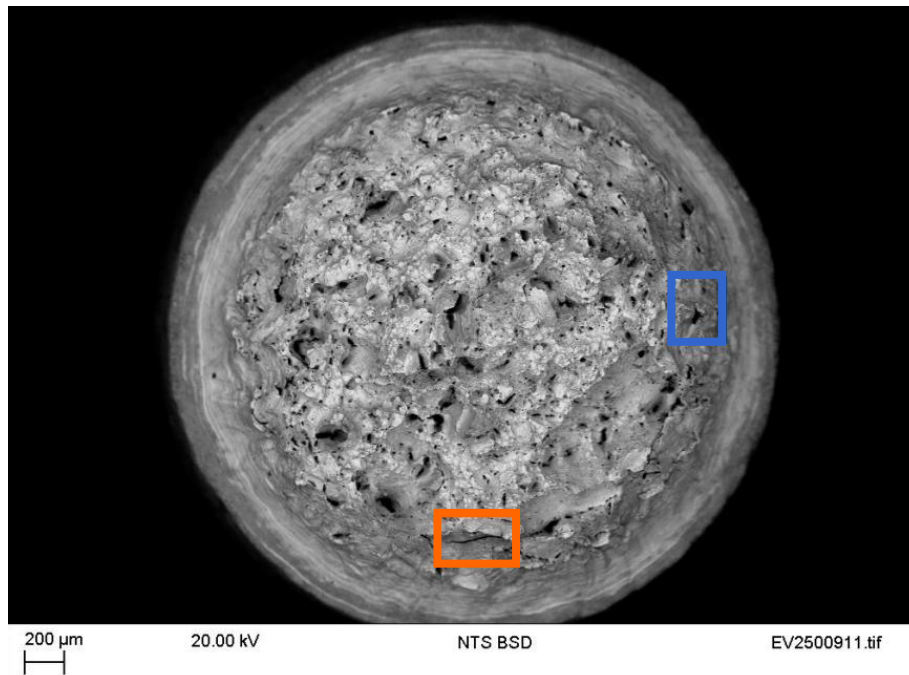


Figure 8: Fractography of tested specimen.

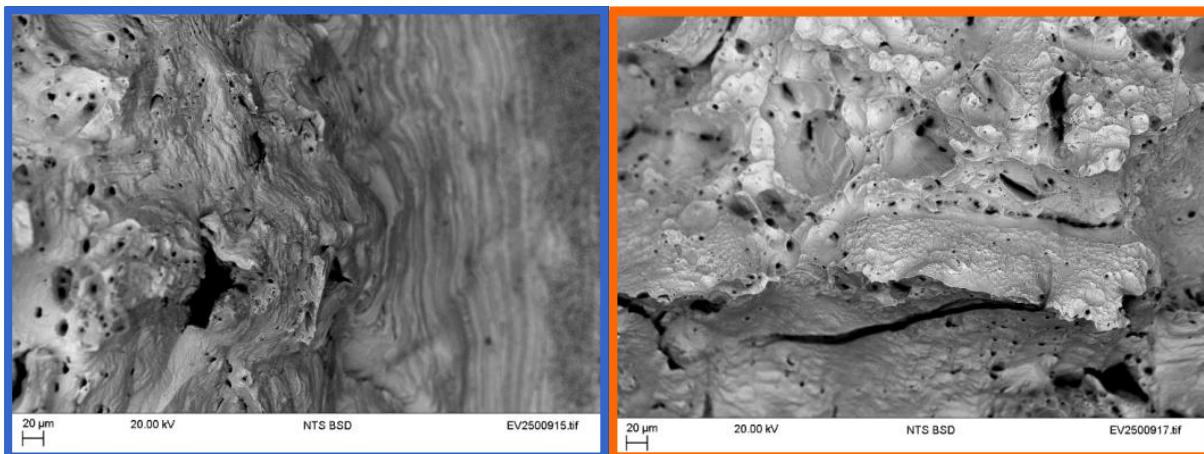


Figure 9: Detailed analysis of the fractured interface. No evidence for hydrogen embrittlement was found.

When reducing the applied load levels to 83 % of AYS based on gross section stress, which produced an applied stress of 111 % of AYS based on the net section, the time vs displacement diagram is as shown in Figure 10. The test was stopped after 720 hours with no failure. The sample showed a creep behaviour, which is similar to the behaviour presented by many materials when loaded above the yield strength, including ASTM A320 Grade L7. The bottom of the notch has been investigated in SEM (Figure 11) and presents no evidence of hydrogen cracking.

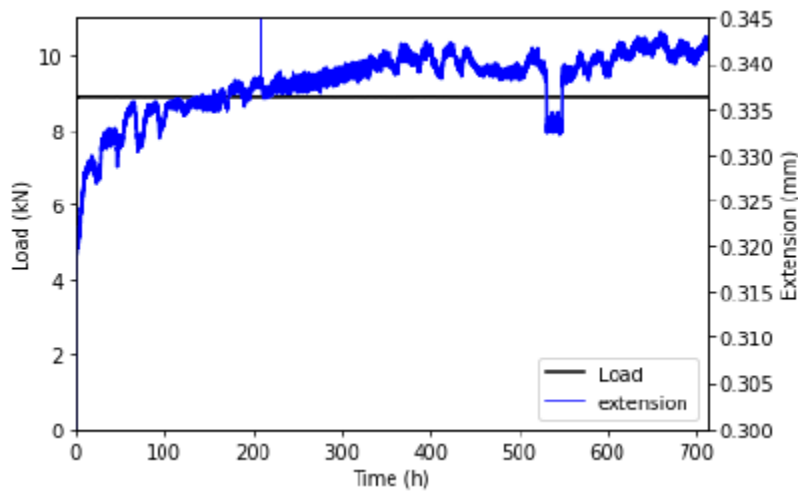


Figure 10: Time vs load and displacement diagrams generated by constant load testing at 83 % of AYS based on gross section stress, corresponding to 6.8 % plastic strain at the notch root.

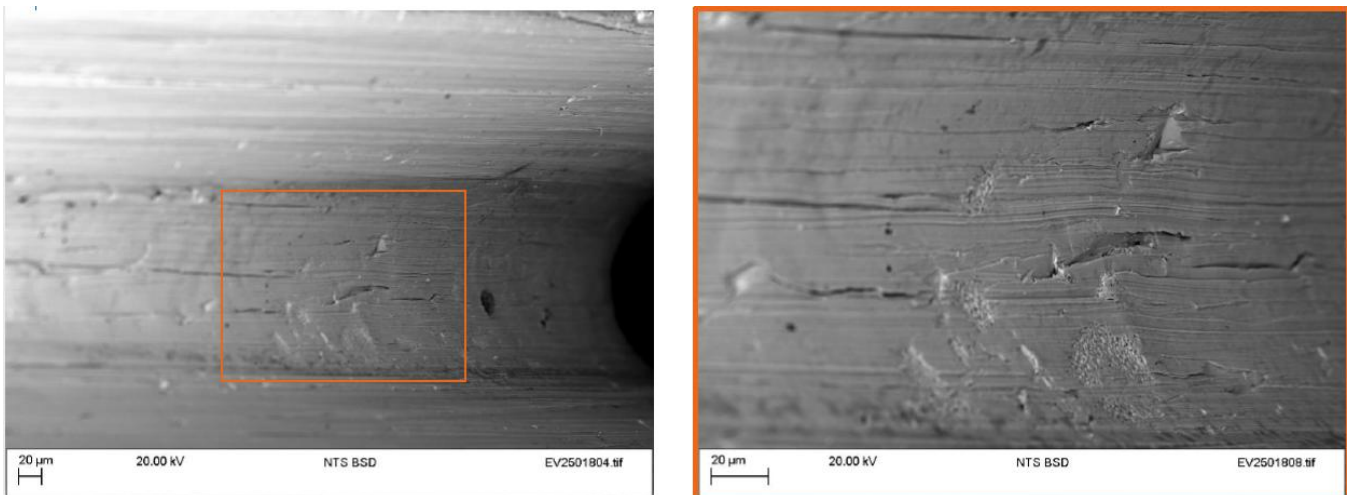


Figure 11: SEM post-test inspection on the bottom of the notch of sample tested at 83% AYS shows no evidence of hydrogen cracking.

CONCLUSIONS

- It has been proven that through a controlled manufacturing process, UNS N08034 will achieve mechanical properties comparable to UNS N07718 and UNS N07725.
- Under extreme loading scenarios (above the yield strength), the UNS N08034 material shows stress relaxation behaviour and good tolerance to hydrogen from cathodic protection.
- Work hardened UNS N08034 did not fail by hydrogen embrittlement, even at very high equivalent fastener loads.

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