Considerations on the Risk of Hydrogen Embrittlement of Pipeline Steel due to Cathodic Overprotection

Hanns-Georg Schöneich, Open Grid Europe GmbH, Essen, Germany

Abstract

The risk of hydrogen embrittlement of pipeline steel due to cathodic overprotection has frequently been described in literature. ISO 15589-1 mentions this risk for pipeline steels with specified minimum yield strength exceeding 550MPa (N/mm^2) and requires to investigate the limiting cp-potential (at the steel/soil phase boundary). Furthermore there is some evidence from literature that a combination of mechanical damage and cathodic overprotection can lead to rapid failure due to hydrogen embrittlement.

On the other hand, however, in case of risks due to alternating current corrosion EN 15280 recommends adjusting the cp on-potential to a sufficiently low level in order to establish a current ratio J_{ac}/J_{dc} < 5 (e.g. measured on probes). Following this it has been found that even at low ac voltage U_{ac}≈5V cathodic dc-current densities (J_{dc}) of some 10A/m_2 may be needed to reduce ac-corrosion rate thus causing the formation of hydrogen on the steel surface.

The paper considers the state of the art regarding the operation of cp-systems of buried pipelines and presents a case history of mechanically damaged pipe surfaces. Results are summarized from different laboratory and full scale investigations that have been performed on this subject considering (simulated) different soil conditions, different mechanically damaged/deformed and non damaged pipeline steel grades and a range of cathodic protection current densities.

Betrachtungen zur Gefährdung von Rohrleitungsstahl durch Wasserstoff-versprödung bei kathodischem Überschutz

Hanns-Georg Schöneich, Open Grid Europe GmbH, Essen, Deutschland

Zusammenfassung

Das Risiko für Wasserstoffversprödung von Rohrleitungsstählen bei kathodischem Überschutz wurde in der Literatur häufig beschrieben. In ISO 15589-1 findet dieses Risiko Beachtung in der Forderung, dass für Rohrleitungsstähle mit einer Mindeststreckgrenze über 550MPa (N/mm^2) das Grenzpotential (an der Phasengrenze Stahl/Erdboden) für den kathodischen Korrosionsschutz untersucht werden soll. Weiterhin existieren in der Literatur Hinweise, dass das Zusammenwirken einer mechanisch beschädigten Stahloberfläche mit kathodischem Überschutz zu einem Schaden durch Wasserstoffversprödung führen kann.

Auf der anderen Seite empfiehlt jedoch EN 15280 im Falle einer Wechselstrom-Korrosionsgefährdung, das Einschaltpotential soweit abzusenken, dass ein Verhältnis der Wechsel- und Gleichstromdichten J_{ac}/J_{dc} < 5 (das z.B. an Probeblechen gemessen werden kann) erreicht wird. Bei Anwendung dieses Kriteriums wurde gefunden, dass schon bei geringen Wechselspannungen U_{ac}≈5V kathodische Stromdichten von einigen 10A/m^2 erforderlich sein können, um die Korrosionsgeschwindigkeit zu vermindern. Bei diesen Stromdichten wird die Bildung von Wasserstoff auf der Stahloberfläche begünstigt.

In diesem Beitrag wird die übliche Vorgehensweise beim kathodischen Korrosionsschutz von erdverlegten Rohrleitungen betrachtet und der Fall einer mechanisch beschädigten Rohrleitung vorgestellt. Die Ergebnisse von verschiedenen Untersuchungen, die bei unterschiedlichen Forschungsstellen durchgeführt wurden, werden zusammengefasst. Die untersuchten Parameter umfassen neben verschiedenen Rohrleitungsstählen unterschiedliche Elektrolytlösungen, nicht- und unterschiedlich aufgehärtetes Probenmaterial sowie einen breiten Bereich kathodischer Stromdichten.

Considérations sur le risque de fragilisation par l'hydrogène de l'acier de canalisation en raison d'une surprotection cathodique

Hanns-Georg Schöneich, Open Grid Europe GmbH, Essen, Allemagne

Résumé :

Le risque de fragilisation par l'hydrogène de l'acier de canalisation en raison d'une surprotection cathodique a fait l'objet de nombreuses descriptions dans la littérature. Les normes EN 12954 et ISO 15589-1 font état de ce risque pour l'acier de canalisation dont la limite d'élasticité dépasse respectivement 550MPa. De plus, il ressort de la littérature qu'une combinaison de dommages mécaniques avec une surprotection cathodique peut conduire à une défaillance rapide due à la fragilisation par l'hydrogène.

D'un autre côté cependant, la norme EN 15280 recommande l'ajustement de la PC au potentiel à courant établi à un niveau suffisamment bas, afin d'établir un rapport des courants de $J_{ca}/J_{cc} < 5$ (par ex. mesuré à l'aide de capteurs). Il a ensuite été découvert que même avec une faible alimentation en courant alternatif $U_{ca} \approx 5$ V, des densités de courant cathodique (courant continu) (J_{cc}) d'environ 10A/m^2 pouvaient être nécessaires pour réduire le taux de corrosion dû au courant alternatif, entraînant donc la formation d'hydrogène sur la surface de l'acier.

Ce document aborde les techniques les plus récentes en matière d'utilisation de systèmes de PC sur des canalisations enterrées et présente des études de cas de surfaces de canalisations mécaniquement endommagées. Les résultats sont extraits de différents examens laboratoires qui ont été effectués dans ce domaine, en se basant sur différentes conditions de sol (simulées), différentes catégories d'acier de canalisation mécaniquement endommagé/déformé et non endommagé et une fourchette de densités de courant de protection cathodique. Des conclusions seront données à propos de l'utilisation de systèmes de PC pour éviter la surprotection cathodique.

1. Cathodic protection and the risk of hydrogen embrittlement

Under cathodic polarization of a steel surface (coating defect of a buried pipeline) in contact with soil the following electrochemical reactions are generally considered:

Oxygen reduction:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (1)$$

Under oxygen-diffusion controlled conditions this reaction dominates at “moderate” on-potential, E_{on}, and in the presence of a sufficient oxygen concentration. It results in shifting the pH at the steel/soil interface to alkaline values [1].

Note: Secondary scale forming reactions, e.g. resulting in calcareous layers on the steel surface due to increase of pH, are not considered.

Decomposition of water and hydrogen evolution:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (2)$$

This reaction is to be considered in case that the supply of electrons exceeds the diffusion controlled oxygen flux to the steel/soil interface.

On closer examination equ. (2) is the result of a series of preceding reactions:

$$2H_2O + 2e^- \rightarrow H_{ad} + H_{ad} + OH^- \text{ (2a1)} \qquad H_{ad} + H_{ad} \rightarrow H_{2,ad} \text{ (2a2)} \quad (2a)$$

Reaction (2a) is known as “Tafel-mechanism”

$$H_2O + e^- \rightarrow H_{ad} + OH^- \text{ (2b1)} \qquad H_{ad} + H_2O + e^- \rightarrow H_{2,ad} + OH^- \text{ (2b2)} \quad (2b)$$

Reaction (2b) is known as “Heyrovsky-mechanism”

Both mechanisms show at first adsorbed hydrogen atoms H_{ad} on the steel surface, followed by a recombination with further H_{ad} to gaseous hydrogen $H_{2,ad}$ (Tafel mechanism) or by a second electrochemical reaction also leading to gaseous hydrogen $H_{2,ad}$ (Heyrovsky mechanism), that may remain adsorbed at the steel surface or form hydrogen bubbles.

It is well known that reactions according to equ. (2a2, 2b2) are competing with

$$H_{ad} \rightarrow H_{ab} \quad (3)$$

indicating the absorption of hydrogen atoms by the steel lattice.

Being absorbed the hydrogen is dissolved in interstitial sites (diffusible hydrogen) and in lattice imperfections (traps, trapped hydrogen), e.g. dislocations, precipitations, phase boundaries etc. Under the impact of internal or external mechanical loads it diffuses towards the zones of stress concentration (expanded lattice) and may induce brittle (delayed) fractures when reaching a critical concentration. The following mechanisms are considered to cause brittle fracture of the steel [2]:

- Buildup of strong pressure from recombination to $H_{2,ab}$, e.g. at inclusions. This mechanism causes hydrogen induced cracks (HIC) - without internal and/or external loads.
- Blocking of dislocations resulting in a reduction of ductility
- Adsorption effects that lower the required critical tension for the formation of the new metal surface at the crack tip
- A lowering of the bonding between the metal atoms by the mutual reaction with the atomic hydrogen is considered by the decohesion theory.

Damages due to absorbed and recombined hydrogen are found as stepwise internal cracks that may connect to adjacent blisters on different planes, generally parallel to the steel surface. Damages due to hydrogen induced stress corrosion cracking occur under the influence of internal/external loads and are generally found as transgranular cracks.

A well known scenario that results in critical hydrogen (H_{ab}) concentration considers the presence of promoters (e.g. sulfide chemical compounds), which act as inhibitors for reactions (2a2, 2b2) and thus favor reaction (3). This effect is well known and it is responsible for HIC phenomena in pipeline steels under sour service conditions [3], i.e. media containing hydrogen sulphide. In case of buried pipelines among the known promoters (phosphorous-, arsenic chemical compounds etc.) only hydrogen sulfide may be considered as being present at the steel/soil interface as a result of microbial (SRB=Sulphate Reducing Bacteria) activity. Measurements regarding the concentration of SRB on steel surfaces under cathodic protection show a significant decrease between -0,87V ($7 \cdot 10^5/cm^2$) and -1,27V ($7 \cdot 10^1/cm^2$) [4] (potential values refer to saturated copper/copper sulphate electrode). In this study hydrogen permeation was found doubled compared to media without SRB. From the low corresponding average hydrogen concentration (<0.7ppm) it was also concluded that SRB do not contribute to enhance the risk for hydrogen induced damages of pipeline steels under conditions of cathodic overprotection. This evaluation is backed by investigations with X70 pipeline steel under high tensile stress (90% SMYS)in a weakly acid buffered medium (pH 5.5) containing sulfide (150mg/l): rupture life is short in the range of -1V but increases remarkably at potentials more negative than -1.2V. This is explained by a deactivation of the promoter by the pH at the steel/medium interface due to cathodic overprotection [5].

In case of media that are free from promoters measured hydrogen activity on the steel surface is low and even for steel grades showing higher tensile strength hydrogen induced damages are generally - even under static load - not to be expected [2]. Some specific scenarios are described in literature and technical guidelines that may favor their occurrence (see also chapter 3):

- Damage is reported regardless the soil and the protective measures in case of hard spots (e.g. inadvertably (rapid cooling, higher carbon content) occurring from the mill process as spots with martensitic microstructure) showing HV>400 [6].
- High strength steels, e.g. tensile strength exceeding 800-1000MPa are sensitive against hydrogen induced cracking in aqueous media without or under constant static load [7].
- Hydrogen induced stress corrosion cracking occurs on pipeline steels under cathodic overprotection during plastic deformation [6].

- High strength pipeline steels, e.g. specified minimum yield strength exceeding 550MPa are assumed to be sensitive against hydrogen induced stress corrosion cracking in case of cathodic overprotection [8, 9]. It is generally noted that cracks are not likely to occur on the non damaged steel surface under static load [6] but some concern exists in case of a damaged pipe surface, e.g. due to the impact of an excavator, combined with varying hoop stress, e.g. due to gas pressure fluctuations.

The last topic is of importance for the operators of high pressure gas pipelines, especially in case of high voltage interference where cathodic overprotection is recommended as a possible measure against alternating current corrosion [10].

2. Cathodic (over-) protection

Cathodic protection (cp) of buried pipelines requires a DC-voltage to be applied between pipeline and ground. This voltage ΔE may be expressed as

$$\Delta E = E_{on} - E_{IR-free} \tag{4}$$

with E_{on}=on-potential, measured between pipeline and remote earth and $E_{IR-free}$=potential at the steel/soil-interface.

The corresponding cathodic current density J_{dc} at a coating defect (area S) is:

$$J_{dc} = \frac{\Delta E}{R_S \cdot S} = \frac{E_{on} - E_{IR-free}}{R_S \cdot S} \tag{5}$$

R_S is the resistance of the coating defect, i.e. the combination of polarization-, pore and spread resistance (any variations of J_{dc} over the steel surface, e.g. edge effects, are neglected). Due to electrochemical polarisation $E_{IR-free}$ is a function of J_{dc}, e.g. as demonstrated by Büchler, fig. 1 [11].

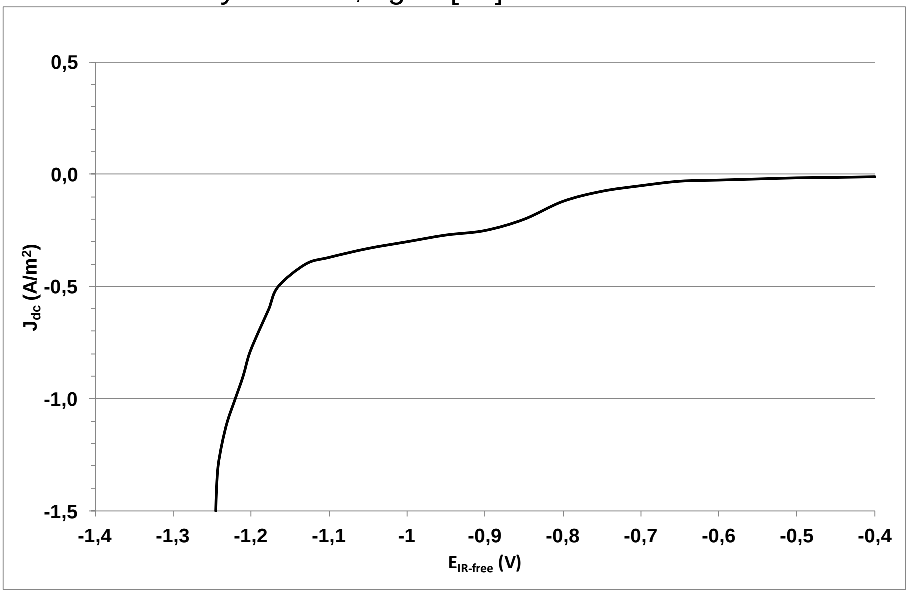


Fig.1: Cathodic polarization of steel in 0.1M NaOH [11]

From fig. 1 it is also concluded that hydrogen evolution is the determining electrochemical reaction at $E_{IR-free}$<-1.2V and J_{dc}<-1A/m^2 but in fact it needs to be stated that even at more positive potentials the accumulation of hydrogen at the steel surface has generally to be taken into account.

Equ. (5) indicates that the cathodic current density in a coating defect, J_{dc}, depends on its area S and resistance R_S and on the adjustment of the cp-on-potential, E_{on}.

- J_{dc} increases (in the following the cathodic current density J_{dc} is considered as a positive value) with decreasing surface area S.
- J_{dc} increases with decreasing resistance R_S of the coating defect. The value of R_S is a complex function of the geometry of the coating defect and the soil resistivity. Furthermore a mutual reaction between J_{dc} and R_S has to be considered; it is well known that R_S may significantly decrease with increasing J_{dc} (resulting in a further increase of J_{dc}) due to the formation of hydroxyl-ions and the migration of cations (e.g. Na+, K+) towards the coating defect. On the other hand R_S may increase, e.g. in case of the formation of calcareous layers on the protected steel surface.

As an example fig. 2 shows the result from measurements on a 1cm^2-coupon that had been electrically connected to a buried pipeline. Cp was provided by a potential controlled rectifier.

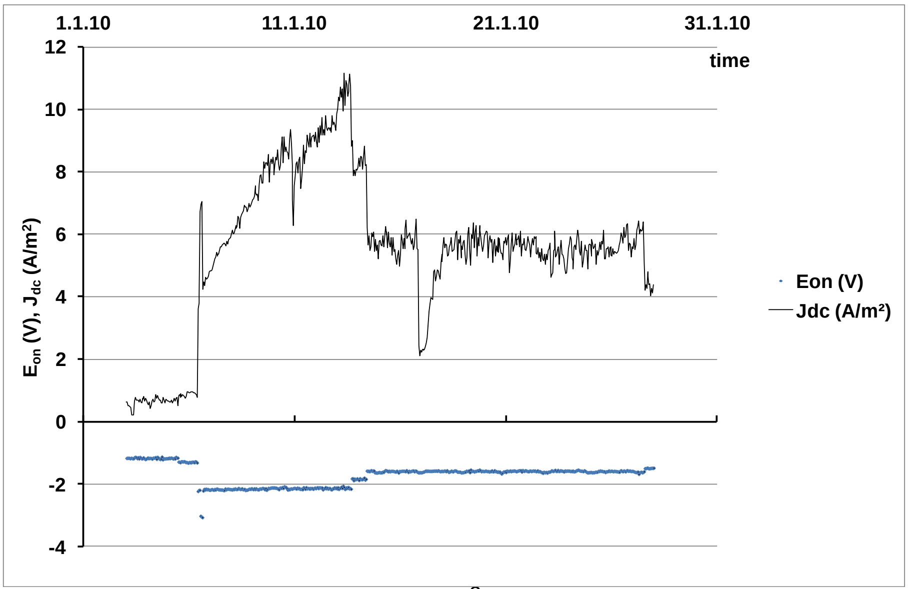


Fig.2: Cathodic protection current density J_{dc} measured on a 1cm^2 coupon at different on-potentials, E_{on}

Starting at E_{on}≈-1,2V (J_{dc}≈0.6A/m^2) the on-potential is adjusted to -2.1V after some days. The current density jumps to 4A/m^2 and continuously increases to 11A/m^2. Adjusting E_{on} to -1.6V results in an average current density of 5.3 A/m^2 (fluctuating variations of J_{dc} are due to a fluctuating ac-voltage on the pipeline). From these measurements it is concluded:

- Assuming only minor variations in the soil around the coupon while adjusting E_{on} from -1.2V to -2.1V and readjusting E_{on} from -2.1 to -1.6V a variation of resistance R_S from 2100Ω to 900Ω respectively can be estimated. It may be assumed, however, that the resistance decreases even more at E_{on}=-2.1V, as J_{dc} still shows a tendency to increase when E_{on} was set to -1.6V.
- A conservative consideration has to take into account that Cp-current at E_{on}<-1.2V mainly initiates the evolution of hydrogen (J_{dc}=10A/m^2 on a 1cm^2 coupon corresponds to a volume of app. 4000cm^3 hydrogen gas per year).

Note: Mechanical damages of the pipe surface, that are due to the impact of an excavator frequently exhibit a longitudinally stretched geometry, e.g. width 1cm, length 10cm. Comparing the resulting cp-current density with J_{dc} on a (circular) 1cm^2 coupon it should be noted:

- Increasing surface area tends to lower the current density
- Increasing ratio length/width (of damaged area) tends to increase the current density [18], but will not compensate the lowering influence of increasing surface area.

Note: From permeation measurements a “critical” current density has been found that initiates cracks and blisters in the near surface steel microstructure, which significantly reduces further hydrogen absorption [12]. This “critical” cathodic current density is app. $500 A/m^2$ and it should be noted that this value is well above the level of cp-current densities that may be expected in coating defects on cathodically protected pipelines.

3. Risk of hydrogen embrittlement of pipeline steel

3.1 Technical guidelines

ISO 15589-1 (2003) [9]
In case of cathodic overprotection ISO 15589-1 (2003) specifies:
For high strength steels (specified minimum yield strength greater than 550 MPa)….
…the limiting critical potential shall be determined with respect to the detrimental effects in the material due to hydrogen formation at the metal surface.
(Note specified minimum yield strength greater than 550 MPa corresponds to grade X80 and higher)
The latest draft revision (March 2014) of this standard states:
To prevent hydrogen embrittlement on high strength non alloyed and low alloyed steels with designed yield strength exceeding 550 N/mm², the critical limit potential shall be documented or determined experimentally.

These notes triggered investigations on X70 pipeline steel material mechanically hardened to yield strength >550MPa. Results are described in chapter 3.4.

EN 12954 (2001) [13]
There is no detailed requirement mentioned in EN 12954 (2001): For non- and low alloyed steel with (actual) yield strength <800MPa no critical potential is mentioned. The statement in the latest draft revision (March 2014) of this standard is analogue to the latest draft revision of ISO 15589-1.

NACE SP 0169 (2007) [14] states:
Polarized potentials that result in excessive generation of hydrogen should be avoided on all metals, particularly higher strength steel….

Following the requirements and recommendations from the technical standards an operator of buried pipelines should be sensitive with regard to the adjustment of cathodic protection in case of steel grades X80 and higher.

3.2 Literature review

A detailed review considering case histories as well as field and laboratory investigations in the field of hydrogen induced damages on pipeline steels had been performed for the European Pipeline Research Group (EPRG, [15]). The main conclusions are as follows:

- Detailed investigations of five separate pipeline incidents have confirmed that a combination of mechanical damage and cathodic overprotection can lead to rapid failure due to hydrogen embrittlement.
- Failures can occur in all pipeline steels subjected to varying levels of mechanical damage if certain environmental and loading conditions are met.
- Fluctuations of pressure in particular those of low frequencies increase the susceptibility of pipeline materials to this failure mechanism.
- Laboratory studies have confirmed that most pipeline steels are susceptible to hydrogen embrittlement under varying conditions of fluctuating load and cathodic overprotection.

Among these very clear conclusions, however, other statements indicate open questions regarding the failure mechanism which has not been successfully simulated in the laboratory–scale test programmes. The studies have not replicated the range of mechanical damage encountered in the field, the typical pressure fluctuations of gas transmission lines and environmental conditions (test environment, hydrogen flux, etc.). Furthermore it is noted that full-scale test–programmes that have attempted to address the issue of hydrogen embrittlement of pipeline steels have generally been inconclusive.

As a result of this review EPRG has launched a full-scale project on the investigation of hydrogen induced stress corrosion on mechanically damaged pipe exposed to fluctuating pressure and cathodic overprotection (see chapter 3.4).

3.3 Case history

The following provides some details on a case history of a buried pipeline (constructed in 1967 / MOP 66bar). The pipe wall (10.75” O.D. (ND 250) x 5.56mm API 5L X 52) was heavily damaged by a trench cutting machine causing gouges. Cathodic protection on potential was -2.86V (fluctuating due to stray current interference). The pipeline was operated at 38 - 41%(55-60bar) SMYS with some pressure fluctuations. From the operation of the pipeline it may be estimated that crack propagation ran over 18 years. Fig. 3 to 6 show the gouges in the pipe wall and results from metallographic investigations:

- Depth of gouges is between 0.21 and 0.92mm and longest circumferential length was 135mm
- Crack length is app. 0.6mm; the boundaries along the crack path are sharp and complementary with no evidence of corrosion.
- Vickers hardness is app. 350 in the altered and hardened material, compared to HV180 of the non altered material. It should be noted that the propagation of the crack does not exceed the transition from the hardened to the non altered material.

These indications suggest that this crack is due to hydrogen induced stress corrosion.

Fig.3: Gouges in the pipe wall of a cathodically protected pipeline

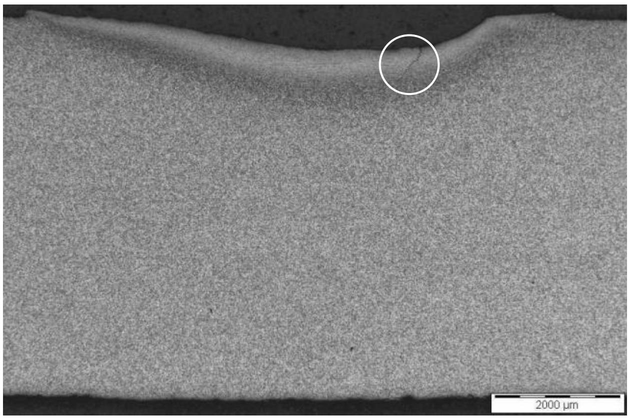


Fig. 4: Crack in the bottom of a gouge; penetration of pipe material is less than 1mm

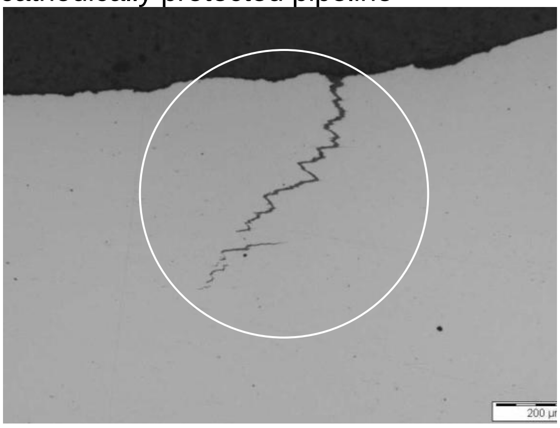


Fig.5: Crack from fig. 4 (magnified)

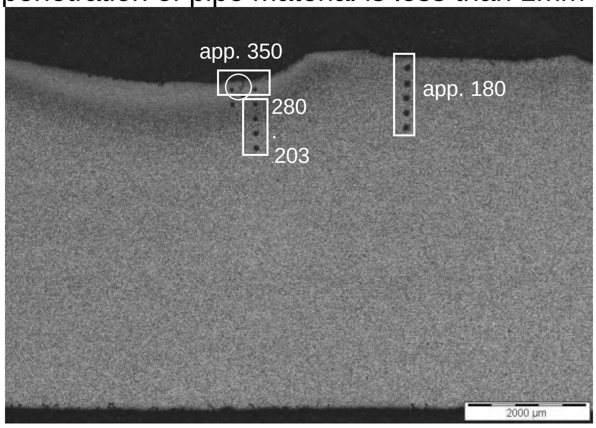


Fig. 6: Vickers hardness measurements

3.4 Laboratory investigations and full scale tests

Laboratory investigations with cold worked steel samples [16]

In order to simulate a pipeline steel surface that is hardened due to any mechanical impact a series of measurements was performed with cold worked steel samples, loaded with additional tensile stress and exposed to cathodic overprotection.

Steel rods (diameter 16mm) were prepared from pipeline steel (minimum requirements SMYS 485MPa, tensile strength 570MPa, elongation at break 18%). By careful cold working the diameter was reduced to 15, 13.5, 10.5 and 7mm respectively, resulting in increasing deformation and corresponding increasing tensile strength. From these rods the specimens were prepared with an equal diameter of 6mm. Fig. 17 shows stress-strain diagrams of the samples.

It is obvious that the tensile strength (UTS) is increased from 665MPa (diameter 16mm) up to 1124MPa (diameter 7mm) thus simulating characteristics of high strength pipeline steels (SMYS > 550MPa) and even hardening conditions, e.g. yielding HV400 [6]. For high deformation the relation between yield- and tensile strength is app. 1 and increasing tensile strength correlates with decreasing elongation at break. A circumferential 60° notch was machined into the 6mm diameter rod samples, which provokes multiaxial stress conditions at the edge if the sample is under external load. Table 1 shows for different sample diameters the values for tensile- and notch tensile strengths:

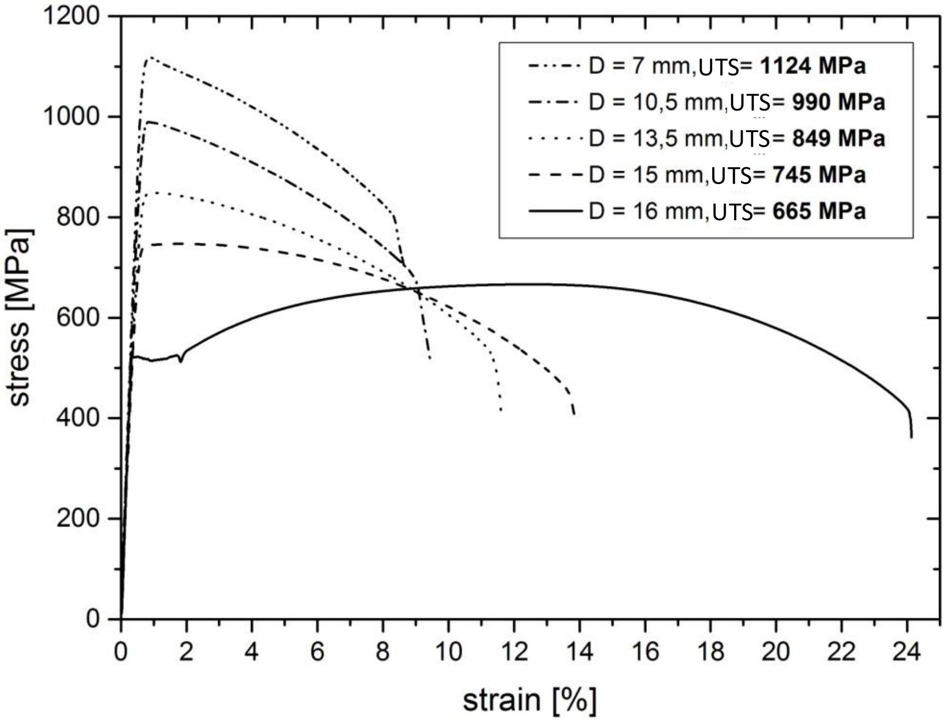


Fig.7: Stress-strain curves of differently deformed (cold worked) steel samples [16]

Table 1: Tensile strength and notch tensile strength of differently deformed steel samples

diameter (mm)	tensile strength (MPa)	notch tensile strength (MPa)
15	746	1285
13.5	849	1473
10.5	990	1580
7	1124	1757

Cathodic overprotection with a current density of $50A/m^2$ was applied to a $2.5cm^2$ surface area (the notch was located in the middle of this area) while the samples were under constant external stress; the electrolyte solution used was 0.2M Na_2SO_4; duration of tests was up to 1000h. The following results were obtained:

- Under constant external load up to 95% of the tensile strength no failure was observed for any sample, i.e. even high strength characteristics (tensile strength 1124MPa) did not provoke sensitivity against hydrogen induced stress corrosion cracking.
- Increasing the load above tensile strength results in reduced time to rupture, see fig. 8(the load is related to the notch tensile strength). Note: No rupture was found on notched samples loaded in air at 95% of notch tensile strength over 500h.
- At constant load (related to notch tensile strength) time to rupture decreases with increasing deformation, i.e. increasing tensile strength
- An evaluation of the real load leading to rupture, e.g. at 10h, results in a similar value for all samples, indicating that the stress at the notch, needed to initiate the rupture does not depend on the deformation/hardening.

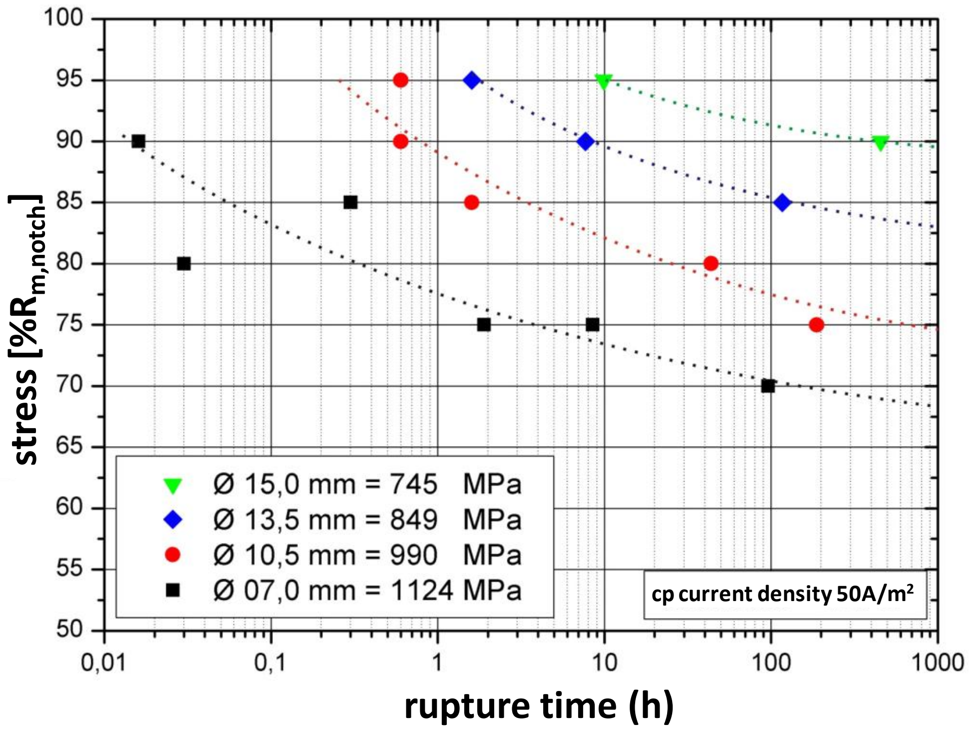


Fig.8: Time to rupture of cold worked steel samples under different external load (related to notch tensile strength, see table 1) [16]

Fig. 9 shows SEM pictures of the fractured metal surface and the hydrogen influence is obvious in the preinduced fracture zone. In this area the fractured surface shows a feathered and preferential transgranular fracture morphology. The remaining fracture occurs as ductile dimple fracture.

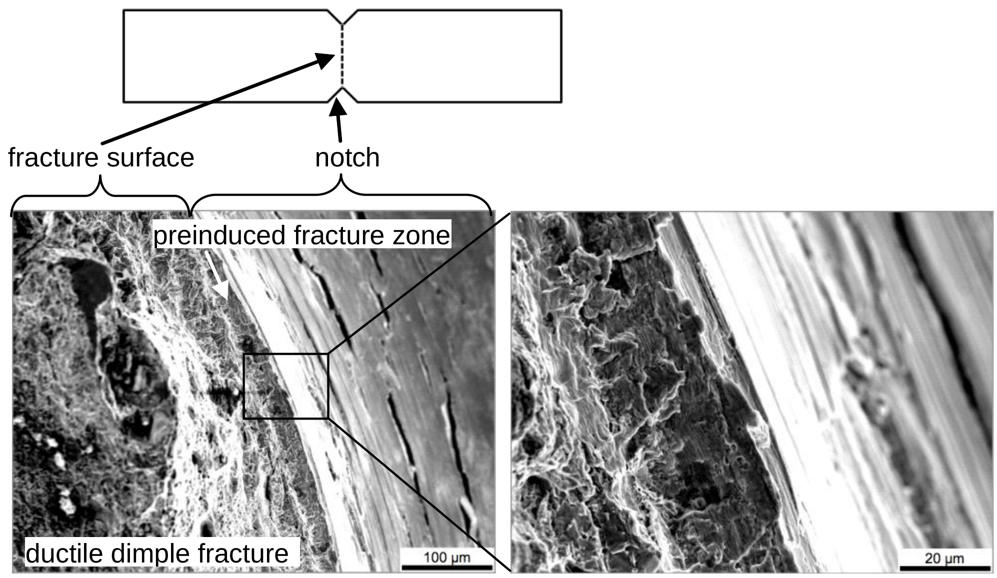


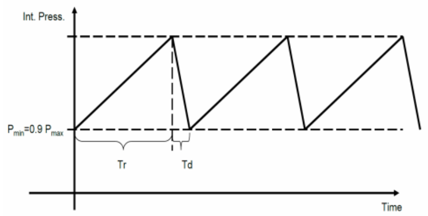
Fig.9: Hydrogen induced fracture on the notch of sustainability load test sample with stepwise crack growth and ductile dimple residual fracture

With regard to the assessment of the safety of pipeline it may be concluded from these investigations, that on high strength pipeline steels (SMYS > 550MPa) and even under conditions that result in a hardening of the steel (surface) a detrimental influence of cathodic overprotection is not obvious, provided the constant external load does not exceed the tensile strength of the material.

<u>Full scale tests [17]</u>

As a result from the literature review described in chapter 3.2 a full scale test was performed using pipes with artificial mechanical damages, simulating an impact of an excavator.

Test conditions were as follows:

<table>
<tr><td>Test pipe</td><td>Grade X70, diameter 1219.2mm, wall thickness 17.0mm, length 6m</td></tr>
<tr><td>Test pressure</td><td>P_{max}=101bar, P_{min}=91bar; correlating to 72% and 65% SMYS</td></tr>
<tr><td>Test cycles</td><td>4 cycles a day over 4 months yielding app. 3600 cycles in total; load pattern was: 

; strain rate: 10^{-8}/s</td></tr>
<tr><td>Pipe damages:

Fig. 10:
Typical gouge in a dent, produced by a simulated excavator; the picture shows the gouge after the test (coating partially removed due to MP-testing)</td><td>Gouge and combination of gouge in a dent - produced by a simulated excavator (35 ton)
15 damages in total
The following fig. 10 shows a typical gouge in a dent
</td></tr>
<tr><td>Electrolyte solution:</td><td>50 g/l Na_2SO_4 + 5 g/l $NaHCO_3$ with / without 0.5% NaCl;
Gas purging: 1 bar mixture CO_2/N_2 with CO_2 at 10%;
pH: 8 / 6.5
Conductivity: 44 / 52 mS/cm.</td></tr>
<tr><td>Cathodic protection</td><td>- Cathodic overprotection (quasi potential controlled) at J_{dc}≈36A/m^2 was applied to 7 damages
- Cathodic protection at (quasi potential controlled) at J_{dc}≈0.13A/m^2 was applied to 8 damages</td></tr>
</table>

Fig 11 shows an extract from the gouge in fig. 10 after 3591cycles

Fig. 11: Gouge from fig 8 after 3591 pressure cycles under cathodic overprotection

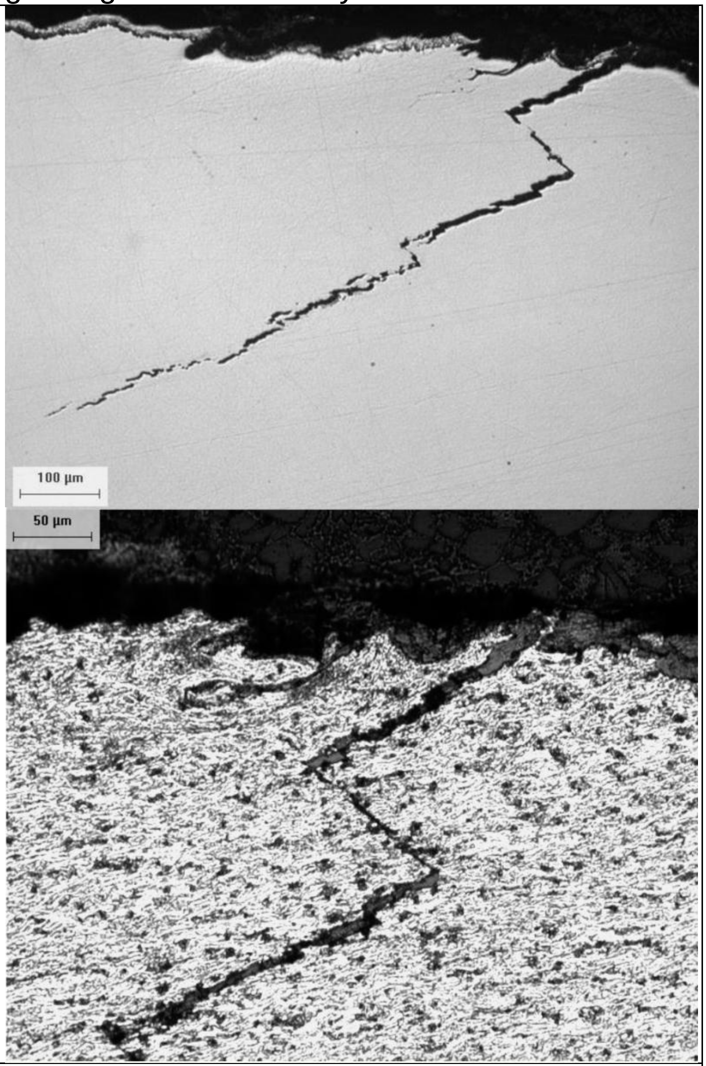


Fig. 12: Crack from the gouge (fig. 11) polished (top) and etched (bottom)

Figure 11 exhibits the end of the gouge of the damage from fig. 10, where cracks were observed. Figure 12 shows a crack after polishing (top) and after etching (bottom). In this case the crack is not branched, and the shape demonstrates that during growth there has been a change in the propagating direction by means of a 90° degree turn. The etched sample shows that cracks bounds are almost perfectly complementary, i.e. with no plastic deformation, so that if edges were touching, there would be neither gaps nor superposition. The crack reaches a depth of app. 0.5mm. It has been shown by hardness measurements (HV(100gr.)) that this depth is app. equal to the thickness of the altered steel layer; i.e. HV≈400 in the altered material, HV≈300 at depth≥0.4mm. From the analysis of all tests performed it is summarized that 6 damages (from 7 damages under cathodic overprotection) exhibited cracks similar to the one shown in fig. 12.

Investigations on damages that were tested under (normal) cathodic protection exhibited (only) two gouges with cracks. It needs to be stated that these cracks were less deep compared to the cracks that were found under cathodic overprotection. In fact their depth was restricted to the thickness of the excavator-tooth material that was deposited on the pipe-steel surface during the damaging procedure.

With regard to the assessment of the safety of pipeline it is concluded from these investigations, that the hardening of steel combined with a fluctuating external load (below SMYS of pipeline steel) and cathodic overprotection establishes a risk for hydrogen induced stress corrosion (it should be noted that the thickness of the hardened layer – as found in these investigations - is typically less than 1mm). There is also an indication that the propagation of cracks is slowed down when they reach the non altered/hardened material.

Note: Additional test are planned with a focus on applying an increasing number of pressure cycles.

4 Summary and conclusions

In case of cathodic (over)protection of buried pipelines and as a result of electrochemical reactions an increased concentration of adsorbed hydrogen on the steel surface has generally to be taken into account. Due to the absence of promotors the activity of adsorbed hydrogen and thus the concentration of absorbed hydrogen in the steel are low. There are some indications, however, from technical guidelines, literature and case histories, that a risk of hydrogen induced stress corrosion cracking exists in case of

- cathodic overprotection combined with
- high strength pipeline steels and/or
- a hardened steel surface, e.g. due to the impact of an excavator or trench cutting machine combined with
- pressure fluctuations

Tests that had been performed in different laboratories under various conditions are summarized as follows:

- An artificially hardened (controlled cold working up to tensile strength 1124MPa) pipeline steel (grade X70), exposed to constant external load (equal to tensile strength) and cathodic overprotection (J_{dc}=50A/m^2) is not sensitive to hydrogen induced stress corrosion cracking.
- A damaged/hardened pipeline steel (grade X70) surface (controlled damage by an artificial excavator), exposed to fluctuating external load (0.65 to 0.72 SMYS, app. 3600 cycles) and cathodic overprotection (J_{dc}=36A/m^2) appears to be sensitive to hydrogen induced stress corrosion cracking. Crack propagation rate appears to slow down when the crack depth reaches the transition from the hardened layer (thickness generally less than 1mm) to the non altered material.

With regard to the operation of the cathodic protection system on high pressure gas pipelines these results should be considered as follows:

- In order to minimize the risk for hydrogen induced stress corrosion cracking cathodic overprotection, e.g. $U_{IR\text{-}free}$<-1,2V, should be avoided on buried pipelines that are exposed to frequent (e.g. > 1/day) pressure fluctuations.
- The risk for hydrogen induced stress corrosion cracking appears to decrease with decreasing frequency and relative amplitude of pressure fluctuations.

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