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Assessment of in-service degradation of gas pipeline steel taking into account susceptibility to stress corrosion cracking

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Abstract

Stress Corrosion Cracking (SCC) is often identified as one of the predominant failure causes of high-pressure gas transmission pipelines. Long-term operation of pipelines causes degradation of mechanical properties of pipeline steel, including a significant decrease in brittle fracture resistance and resistance to SCC. For oil and gas pipeline steels, there are regulatory requirements for impact toughness, disregarding steel condition, namely as-received or serviced. However, SCC resistance of pipeline steels, being very important for structural integrity, is not regulated. In the present work a new method to evaluate in-service degradation of pipeline steels, taking into account increasing susceptibility of operated metal to SCC, was developed. To ensure a safe operation of gas pipelines, it is suggested that the minimum allowable value of SCC resistance characteristics, in particular, the threshold of J-integral based stress intensity factor for SCC J_{scc}, should be defined and regulated. It is quite difficult to input these characteristics into regulatory requirements, therefore the developed method is based on modification of regulated limit values of impact toughness for as-received and serviced metal conditions separately, taking into account increasing susceptibility of serviced steel to SCC. The method was applied to evaluate in-service degradation of API 5L X52 ferrite-pearlite pipeline steels. The developed method considers different SCC susceptibility of as-received and serviced pipeline steels and shows there are limitations in regulating the same limit value of impact toughness for as-received and serviced pipeline steels.

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Keywords: gas pipeline; degradation; fracture; safe operation

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1. Introduction

Ukraine, being one of the most important transit countries to the countries of European Union, has the extended network of gas transmission pipelines. However, pipeline aging and degradation of pipeline steels under operation can cause many problems. Thus, embrittlement, deterioration of mechanical and corrosion properties is often the results of in-service degradation, as it was demonstrated in numerous issues by Meshkov et al. (2015), Nykyforchyn et al. (2016, 2017), Zvirko et al. (2017, 2018), Bolzon et al. (2018), Maruschak et al. (2018). This leads to a loss of the initial mechanical properties, primarily, resistance to brittle fracture, which were put in engineering calculations at pipeline design stage.

At the same time Stress Corrosion Cracking (SCC) is identified as one of the predominant failures in pipeline steels in wet environments, which causes a rupture of high-pressure gas transmission pipes. Thus, analyzing the causes of emergency failures of Ukraine's gas transit pipelines occurred in 2003 – 2007 years, it was revealed that the main reasons of these ruptures were SCC, namely formation of crack-like defects of 0.6 – 3.0 m in length and 6 – 12 mm in depth due to damage of the insulation of pipes, increase corrosion activity of soil environments and violation of cathodic protection regime (Krasovskii et al. (2012)). Furthermore, in such cases just SCC resistance defines a serviceability of non-operated metal. Therefore, it is important to compare degradation of brittle fracture resistance, for example, impact toughness, of steel under service, from one hand, and SCC resistance, from another hand. Such comparison is interesting since impact toughness belongs to characteristics practically always put in regulative documents (DSTU EN ISO 3183:2017 / API 5L, DSTU B A.3.1-32:2015 and others).

Deterioration of critical steel structures under operation calls for effective methods for condition evaluation. In the present research a new method for evaluation of in-service degradation of pipeline steels taking into account increasing susceptibility of operated metal to SCC was developed.

2. Objects, materials and methods

The research objects were low-carbon low-alloyed ferrite-pearlite pipeline steels: 17H1S (Ukrainian code, 0.17C-Mn-Si, API 5L X52 strength grade) and API 5L X52. Pipeline steels in the as-received state and after long-term (up to 53 years) operation were investigated. Sections of pipes being investigated were cut from gas transit pipelines after different time of operation (up to 53 years).

Impact toughness KCV of the pipeline steels was determined using Charpy specimens of a standard thickness of 10 mm with a V-shaped notch. Specimens were cut in the longitudinal direction of pipes.

The susceptibility to SCC of the pipeline steels was investigated. The specimens were cut from the real pipes in the longitudinal direction. The SCC tests were carried out using compact pre-cracked specimens. SCC resistance was determined by *J*-integral method by loading of the 0.5CT compact specimens, 10 mm thick. Series of 5–7 specimens for every metal state were tested in accordance to the procedure (ASTM E 813) at different level of increment of pre-fatigue crack. Two steps were followed: pre-cracking and slow strain rate tensile loading. In first step, each specimen was subjected to constant amplitude fatigue testing with stress ratio R = 0.1 in order to initiate fatigue crack; in second one a displacement controlled, constant deformation rate of 10 μm/hour was applied to the specimen. The NS4 solution containing (g/L) 0.122 KCl; 0.483 $NaHCO_3$; 0.181 $CaCl_2{\cdot}2H_2O$; 0.131 $MgSO_4{\cdot}7H_2O$, simulating the soil environment was used as the test medium. SCC measurements were performed at room temperature, in the open circuit condition. Susceptibility to SCC was evaluated by the threshold of J-integral based stress intensity factor J_{scc} obtained for pre-cracked specimens of the studied pipeline steels (corresponding to pre-crack initiation according to ESIS P4-92 D).

3. Susceptibility of operated pipeline steels to SCC

Since materials with low resistance to brittle fracture are usually highly sensitive to the effect of aggressive media, it should be taking into account possible increasing sensitivity of long-term operated pipeline steels to SCC. Both the initiation of SCC and the ability of SCC to increase in depth can be facilitated in operated pipeline steels due to degradation. Recent studies on SCC (Gabetta et al. (2008), Zvirko et al. (2016)) showed that susceptibility of pipeline steels to SCC increased after long-term operation or in-laboratory accelerated degradation. Thus, resistance of the 30 years operated API X52 pipeline steel to SCC evaluated by testing the pre-cracked specimens in the model environment, simulating aqueous condensate on the internal pipe surface, under the open circuit conditions was significantly lower than that of the as-received steel (Fig. 1); cathodic polarization by current density of 0.1 A/m^2 additionally decreased the threshold J_{scc} values of steels, as it was demonstrated by Gabetta et al. (2008).

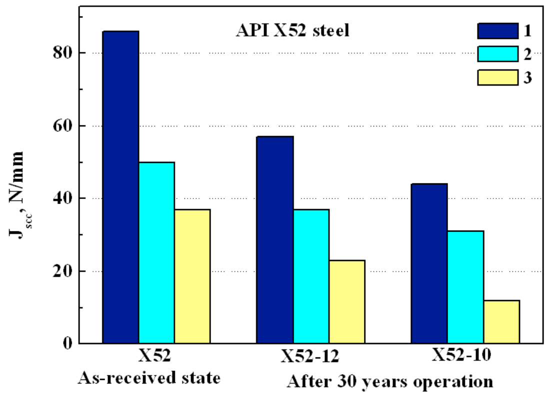

Fig. 1. Crack growth resistance of the API X52 pipeline steel in the as-received (X52) and post-operated (X52-12 and X52-10) states in air (1), in corrosion environment at corrosion potential (2) and in corrosion environment during cathodic polarisation (3).

According to the research results carried out by Zvirko et al. (2016) on smooth specimens using the slow strain rate tension method, no susceptibility of the 17H1S pipeline steel in the as-received state to SCC in NS4 test solution was revealed, and the API X60 pipeline steel with higher strength was characterized by very low sensitivity to SCC. Thus, the presence of the corrosive environment slightly facilitated fracture of the API X60 steel specimens in comparison with the test in air: reduction in area and elongation insignificantly decrease. However, the degraded pipeline steels became more sensitive to SCC than in the as-received state. The pipeline steel with lower strength (17H1S) exhibited the lower resistance to SCC then the pipeline steel with higher strength (API X60).

4. A new method for evaluation of in-service degradation of pipeline steels taking into account susceptibility to SCC

For oil and gas pipeline steels, there are regulatory requirements for impact toughness (DSTU EN ISO 3183:2017 / API 5L, DSTU B A.3.1-32:2015); it should be at least ~ 50 J/cm^2 at ambient temperature, disregarding steel condition, namely as-received or serviced. However, SCC resistance of pipeline steels, being very important for structural integrity, is not regulated.

In the present work a new method to evaluate in-service degradation of pipeline steels, taking into account increasing susceptibility of operated metal to SCC, was developed. To ensure a safe operation of gas pipelines, it was suggested that the minimum allowable value of SCC resistance characteristics, in particular, the threshold of J-integral based stress intensity factor for SCC J_{scc}, should be defined and regulated. It is quite difficult to input these characteristics into regulatory requirements, therefore the developed method is based on modification of regulated limit values of impact toughness for as-received and serviced metal conditions separately, taking into account increasing susceptibility of serviced steel to SCC. The method was applied to evaluate in-service degradation of API 5L X52 ferrite-pearlite pipeline steels (Fig. 2).

Data of impact toughness and threshold of J-integral based stress intensity factor of the 17H1S (API 5L X52 strength grade) and API 5L X52 pipeline steels in as-received state and after operation (up to 53 years) are analysed and presented in Fig. 2. The boundary lines were considered as conservative dependencies of impact toughness KCV $= f(\tau)$ and threshold of J-integral based stress intensity factor $J_{scc} = f(\tau)$ of pipeline steels on operation time τ. The threshold of J-integral J_{scc} of steels was determined in NS4 test solution, which simulates soil environment. As seen in Fig. 2, impact toughness of steels in the as-received state (~ 100 – 300 J/cm^2), is at least twice higher than the minimum allowable value (50 J/cm^2). At the same time, impact toughness of serviced steel decreases and may reach values below this level. According to these data, such reduction of resistance to brittle fracture occurs after 20 – 25 years of operation.

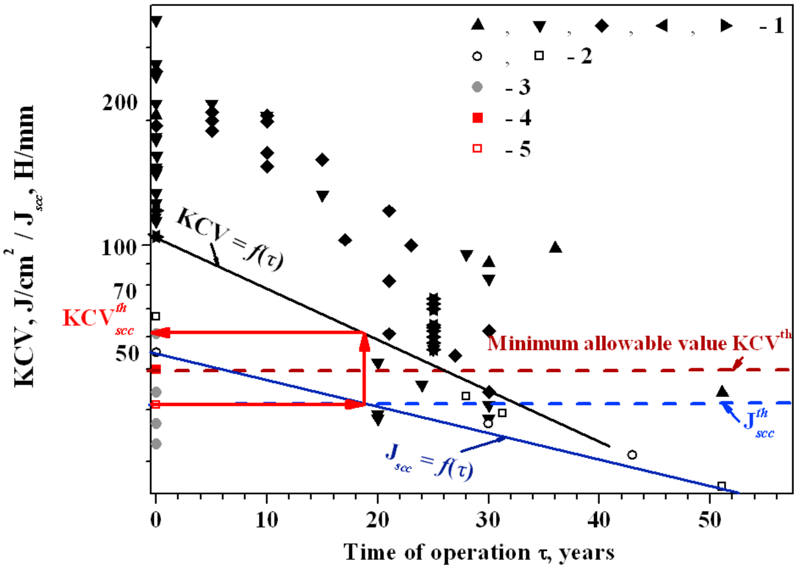

Fig. 2. Determining the minimum allowable level of impact toughness KCV^{th}_{scc} for operated pipeline steel with the threshold of J-integral J^{th}_{scc} (5): KCV (1, 3, 4) and J_{scc} (2, 5) for API X52 pipeline steels in the as-received state and after different operation time τ, as well as after heat treatment (3, 4, 5).

In order to obtain steel with microstructure with impact toughness comparable with minimum allowable level KCV^{th}, the 17H1S steel in the as-received state (API 5L X52 strength grade) was subjected to heat treatment with different tempering temperature. The steel was subjected to hardening (heating at a temperature of 910 °C and quenched in water), then to tempering for 2 hours at temperatures in the range from 200 to 500 °C. After heat treatment impact toughness of steel was evaluated. Experimental results are presented in Fig. 3. The graph illustrates that about 445°C tempering gives the microstructure with impact toughness comparable with minimum allowable level KCV^{th}. The threshold of J-integral based stress intensity factor, measured for this steel in NS4 solution (41 N/mm), was considered as the minimum allowable level J^{th}_{scc} for the as-received pipeline steel with minimum allowable level of impact toughness. Based on data presented in Fig. 2, it can be assumed that serviced steel can achieve this value of J-integral after about 19 years.

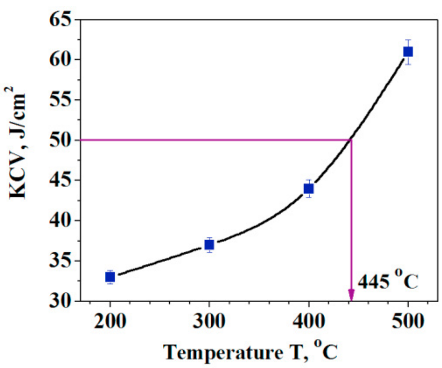

Fig. 3. Dependence of impact toughness KCV of the 17H1S steel in the as-received state on tempering temperature after hardening.

Based on these data and dependences on time (KCV = $f(\tau)$ and $J_{scc} = f(\tau)$), the minimum allowable level of impact toughness KCV_{scc}^{th} (about 65 J/cm^2) for serviced pipeline steel, having minimum allowable level of J-integral J_{scc}^{th} was determined. Therefore, this level of impact toughness KCV_{scc}^{th} should be considered as minimum allowable for evaluation of in-service degradation of ferrite-pearlite serviced pipeline steels by SCC resistance.

In contrast to known methods based on limit values of regulated mechanical characteristics, it takes into account possible differences in characteristics of SCC resistance of steels depending on their condition – as-received one or operated one with damaging, despite the same resistance to brittle fracture.

The developed method considers different SCC susceptibility of as-received and serviced pipeline steels and shows there are limitations in regulating the same limit value of impact toughness for as-received and serviced pipeline steels.

4. Summary

A new methodical method considered increasing susceptibility of operated pipeline steel to SCC to evaluate in-service degradation of pipeline steels was developed. It is based on modification of regulated limit values of impact toughness for as-received and serviced metal conditions separately. The method was applied to evaluate in-service degradation of API 5L X52 ferrite-pearlite pipeline steels. The developed method considers different SCC susceptibility of as-received and serviced pipeline steels and shows there are limitations in regulating the same limit value of impact toughness for as-received and serviced pipeline steels.

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