Influence of hydrogen on deformation aging   
of low alloy steel during operation

Olha Zvirko[0000-0002-6973-6804], Dmytro Demianchuk,   
Oleksandr Tsyrulnyk[0000-0001-9038-966X], Denys Bartoshevskyi

Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine, 5, Naukova St., Lviv 79060, Ukraine

olha.zvirko@gmail.com

**Abstract.** Deformation aging of steels results generally in embrittlement. An assumption of the possibility of occurrence of deformation ageing of steels at the microscale due to internal stresses induced by hydrogen under long-term operation was made. It was substantiated experimentally using the low-alloy pipe steel subjected to different treatment with and without preliminary electrolytical hydrogen charging and low-temperature tempering. The basic mechanical properties of the steel, impact strength, fracture toughness, and resistance to stress corrosion cracking were assessed. It was revealed that low-temperature tempering did not affect the mechanical behavior of the steel. However, the steel subjected to the procedure of combining preliminary hydrogen charging with subsequent low-temperature tempering was characterized by a significant decrease in fracture toughness and resistance to stress corrosion cracking. Hydrogen had an impact on the embrittlement of the steel through the strain aging at local sites being preferable for hydrogen diffusion.

**Keywords:** Steel, Deformation aging, Hydrogen, Embrittlement, Residual stress.

1. Introduction

Deformation aging of steels consists in the fixation of carbon and nitrogen atoms on dislocations, known as the formation of Cottrell clouds. This complicates the plastic deformation of the metal, which causes its embrittlement [1–3]. The standard DSTU 9166:2021 regulates the procedure of deformation aging of steels in laboratory. Deformation aging involves two main steps: first, the plastic deformation of the metal, which activates sources of dislocation generation, and second, moderate and relatively short-term heating of the deformed metal to facilitate the diffusion of interstitial atoms such as carbon and nitrogen to dislocations to form atmospheres around them.

It is well-known that electrolytic hydrogen charging of steels lead to internal stresses [4, 5]. It was assumed that the internal stresses induced by hydrogen charging could reach such a high level as to cause microplastic deformation at certain local microstructural sites, accompanied by the generation of dislocations. These localized areas within the metal serve as traps for hydrogen and contributes to the accumulation of high pressure molecular hydrogen in them. Therefore, the hydrogenation of steels can serve as a source of dislocation generation even without the previous plastic deformation at the macroscale. This is one of the necessary conditions for implementing the deformation aging. However, the requirement for subsequent heating of the metal after hydrogen charging remains the same. In the presented paper, this assumption was confirmed experimentally using the low-alloyed pipeline steel 17H1S.

1. Experimental, Results and Analysis

A series of specimens were tested: in as-delivered state; after low-temperature tempering for 1 hour at 250 ºС (LTT250); after in-laboratory preliminary electrochemical hydrogen (PEH) charging followed by low-temperature tempering for 1 hour at 250 ºС (PEH + LTT250). PEH charging of specimens was carried at a current density 50 mА/сm2 for 100 hours in an aqueous H2SO4 solution (pH2.0) with adding 2 g/l thiourea. All specimens were cut out from the pipe longitudinally oriented relative to the pipe axis. Basic mechanical characteristics, as well as resistance to stress corrosion cracking (SCC), were determined by tension tests of cylindrical specimens with a diameter and a gauge length of 5 mm and 25 mm, respectively. The strain rate was 3×10-3 s-1 and 3×10-7 s-1 in air and NS4 test solution, respectively. Charpy impact toughness (KCV) and fracture toughness by the J-integral method (standard ASTM E 813) were also determined. Table 1 summarizes the mechanical properties of the 17H1S steel in different treated states.

The low-temperature tempering (LTT250) had no significant effect on the mechanical behaviour of the investigated steel. Combining PEH with low-temperature tempering for 1 hour at 250 ºС according to the (PEH + LTT250) regime, while not affecting the strength, plasticity, and impact toughness of the steel, slightly reduced its fracture toughness (by approximately 10%) and noticeably decreased its SCC resistance (the reduction in area RA reduced from 69% to 53%).

**Table 1.** Mechanical properties and SCC resistance of the studied pipeline steel 17H1S in different states.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Steel state | Ultimate strength  σUTS [MPa] | Yield strength σYS [MPa] | Reduction in area  RA [%] | Impact toughness  KCV [J/сm2] | Fracture toughness  *J*0.2 [N/mm] |
| As-delivered state | 531 | 428 | 71 | 129 | 322 |
| LTT250 | 535 | 433 | 72 | 125 | 330 |
| PEH + LTT250 | 533 | 435 | 74 | 131 | 286 |

It was revealed that the mechanical characteristics at a macro-scale, such as plasticity and impact toughness, are not sensitive to hydrogen-induced strain aging. Furthermore, fracture toughness, which is characteristic of a meso-scale, determined by J-integral method, is more sensitive to hydrogen. However, the most efficient method among all the methods used was resistance to SCC, which is considered a micro-scale characteristic. The microfractographic analysis revealed the signs of embrittlement for SCC testing. The embrittlement features correspond to the well-known regularity of the dominance of the intergranular pathways for hydrogen diffusion in low-alloy steels.

References

1. Vodopivec, F.: Strain ageing of structural steels. Metalurgija 43(3), 143–148 (2004).
2. Tsyrul’nyk, О.Т., Kret, N.V., Voloshyn, V.A., Zvirko, O.I.: A procedure of laboratory degradation of structural steels. Materials Science 53 (5), 674–683 (2018).
3. Yang, Y., Zhang, B., Wang, Y., Jiang, Z., Li, K.: Mechanical behaviors and constitutive model of structural steel influenced by strain aging. Journal of Constructional Steel Research 192, 107211 (2022).
4. Tiegel, M. C., Martin, M. L., Lehmberg, A. K., Deutges, M., Borchers, C., Kirchheim, R.: Crack and blister initiation and growth in purified iron due to hydrogen loading. Acta Materialia 115, 24–34 (2016).
5. Mogilny, G. S., Shyvaniuk, V. N., Teus, S. M., Ivaskevich, L. M., Gavriljuk, V. G.: On a mechanism for enhanced hydrogen flux along grain boundaries in metals. Acta Materialia 194, 516–521 (2020).