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Micro and macro mechanical analysis of gas pipeline steels

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Abstract

The actual safety margins of gas pipelines depend on a number of factors that include the mechanical characteristics of the material. The evolution with time of the metal properties can be evaluated by mechanical tests performed at different scales, seeking for the best compromise between the simplicity of the experimental setup to be potentially employed in situ and the reliability of the results. Possible alternatives are comparatively assessed on pipeline steels of different compositions and in different states.

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1. Introduction

Pipelines of gas transportation networks are exposed to aggressive chemical media and to demanding working conditions. The actual safety margins of these infrastructures depend on a number of factors that include the gas pressure, the external actions, the environment characteristics and the material properties, which evolve with time. Aging increases the risk of fracture and the possibility of significant economic losses and severe environmental consequences (Gabetta et al., 2008; Fassina et al., 2012).

Failure prevention is usually performed by continuous monitoring activities implemented during pipeline operation. Visual inspections and ultrasonic measurements help detecting the formation and propagation of localized damages. In-bulk degradation is evidenced instead by the mechanical testing of material samples extracted from the pipe wall.

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The experiments are usually carried out according to standardized procedures, which are rather expensive and time consuming (Nykyforchyn et al., 2010). However, the diagnostic analysis of metal structures can rely on alternative, faster and cheaper non-destructive approaches. In particular, mechanical characterization methodologies based on indentation techniques can be considered in this context (Bolzon et al., 2015).

Indentation tests can be performed at different scales, seeking for the best compromise between the maneuverability of the equipment and the reliability of the experimental results. This approach permits to transfer the laboratory procedures to the field conditions, in order to develop effective structural diagnosis methods based on in-situ measurements.

Alternatives testing protocols have been comparatively assessed on pipeline steels of diverse grade and composition and in different states: as received, mechanically hardened, thermally treated and chemically degraded (Zvirko et al., 2016). This contribution summarizes the main results of this on-going research activity.

2. Materials and degradation processes

Low-alloyed 17H1S (Ukrainian code, equivalent to X52) and X60 pipeline steels have been considered for the present investigation. Material samples were extracted from real pipes. Microstructural characterization was performed by Zvirko et al. (2016), evidencing the different material texture visualized by the micrographs in Fig. 1.

Some samples were subjected to electrolytical hydrogen pre-charge in aqueous sulphuric acid solution (pH2) at 20 mA/cm² for 95 hours, followed by the thermo-mechanical treatment (aging) consisting of mechanical loading up to 2.8% axial strain and exposure to 250°C for 1 hour. The process simulates, on a laboratory scale, the effects of long-term exploitation. In particular, the preliminary electrolytic hydrogenation of the specimens before mechanical loading simulates the operational conditions in those situations where the moisture present in the transported gas condenses on the internal surface of the pipe and produces corrosion. Corrosion serves as a source of hydrogen (Tsyrunyk et al., 2008), which is absorbed by the metal and causes pipe wall hydrogenation. In such circumstances, the degradation of the metal is influenced by the mutual action of the stress state and of the hydrogen absorbed by the steel from the internal surface of the pipe. The role of hydrogen in the degradation process consists, in the first turn, in an acceleration of the damaging processes occurring in the metal.

The current density applied for the preliminary electrolytical hydrogen charging of the steel was not high enough to induce damaging during this process performed in laboratory conditions. However, further mechanical loading of the hydrogenated metal can lead to material degradation on the nano or microscale, similar to what occurs during long-term operation of pipeline steels (Nykyforchyn et al., 2010). Damages induced in X52 steel in service for more than 30 years are for instance visualized in Fig. 2.

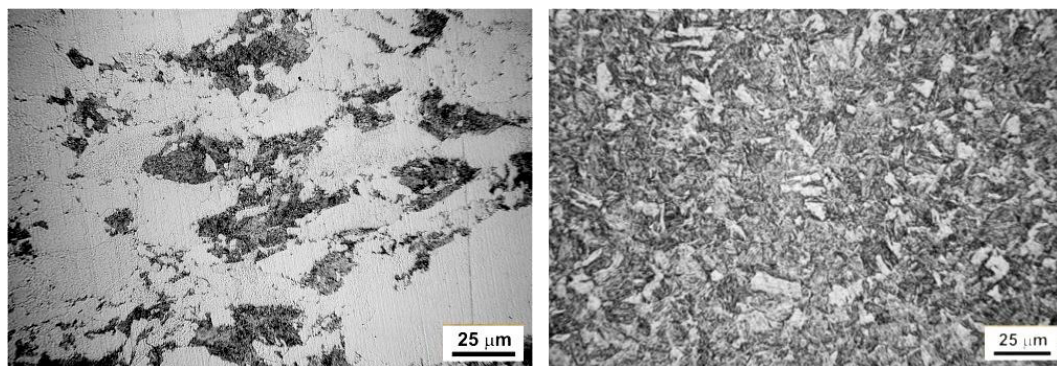


Fig. 1. 17H1S and X60 microstructure

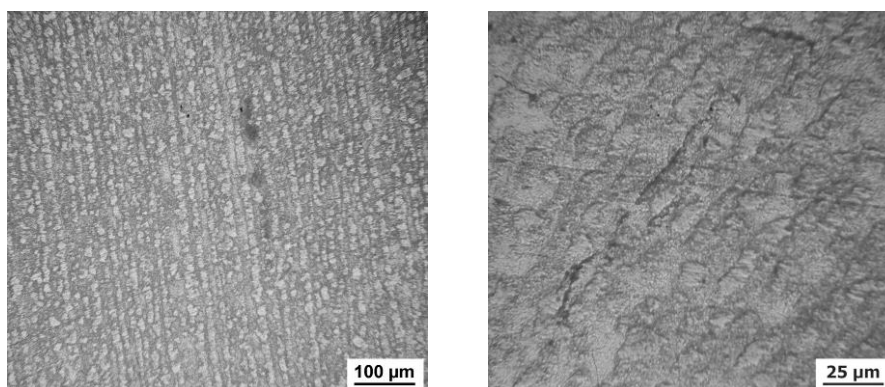


Fig. 2. Images of X52 pipeline steel after long-term (more than 30 years) operation on gas main, showing in-bulk damaging.

3. Mechanical testing

Uniaxial tensile tests have been performed on the material specimens shown in Fig. 3, cut from the pipe wall and machined to their final geometry before being subjected to laboratory treatments. As-received, artificially aged and degraded conditions were investigated.



Fig. 3. Tensile specimen.

The main results recovered from the tensile tests are summarized in Table 1. Both artificial aging and hydrogen degradation increase the initial yield limit and reduce both the transversal area and the maximum elongation, while the ultimate strength appears less affected by the termo-mechanical-chemical action. Variations are more pronounced for 17H1S steel.

The results presented in Table 1 are consistent with those reported by Liessem et al. (2004) for different pipes subjected to high temperature processes. However, the in-laboratory degradation method developed by Zvirko et al. (2016) fosters the development of in-bulk damage. This peculiarity distinguishes this process from the traditional aging method (Standard GOST 7268-82), which produces only strength increase and ductility reduction of the treated metal.

Table 1. Mechanical properties recovered from tensile tests.

| Steel type | Steel state | Ultimate strength σ_u [MPa] | Initial yield limit σ_y [MPa] | Ratio σ_y/σ_u [-] | Area reduction [%] | Elongation [%] |
|------------|-------------|---------------------------------------|---|----------------------------------|-----------------------|-------------------|
| 17H1S | As-received | 473 | 304 | 0.64 | 66.1 | 21.1 |
| | Aged | 486 | 375 | 0.77 | 63.2 | 16.1 |
| | Degraded | 467 | 426 | 0.91 | 46.4 | 10.9 |
| X60 | As-received | 565 | 489 | 0.87 | 77.6 | 21.9 |
| | Degraded | 610 | 551 | 0.90 | 71.3 | 16.4 |

The specimens to be subjected to tensile test require a laborious machining, which makes the approach rather expensive and time consuming. Instrumented indentation represents a faster and much cheaper mechanical characterization procedure with growing application for the diagnosis of metal structures (ISO 14577: 2002). This almost non-destructive technique may be performed also on operating components. Results equivalent to those of

traditional tensile tests are obtained (Bolzon et al., 2012; Bolzon et al., 2015) applying maximum forces comparable to those of hardness measurement (e.g., EN ISO 6508:2005).

The maneuverability of the testing device to be eventually operated in field conditions is evidently increased by reducing the maximum applied force. The representativeness of the results of indentation tests performed at different scales has been therefore evaluated, starting from applications at the micron scale, nowadays rather popular.

The material samples already subjected to the tensile tests were sectioned and lapped to produce flat surfaces suitable to indentation.

The output of the instrumented tests performed by pyramidal Berkovich tip at 500 mN maximum force have been presented by Bolzon and Zvirko (2016). No systematic trend induced by aging and hydrogen degradation could be evidenced for the investigated materials, likely due to small penetration depth (between 2 and 3 μm) of the indenter tip in the considered loading range.

Further tests have been carried out with a conical Rockwell tip at 200 N maximum load. The indentation curves relevant to X60 steel are visualized in Fig. 4. Some dispersion is observed, possibly related to the machining and former tensile testing of the specimens. However, the curve sets concerning the as received state (dashed) and relevant to the degraded material (continuous line) are sharply distinct. The penetration depth is reduced by the laboratory treatment, consistently with the increase of the initial yield limit and ultimate strength reported in Table 1.

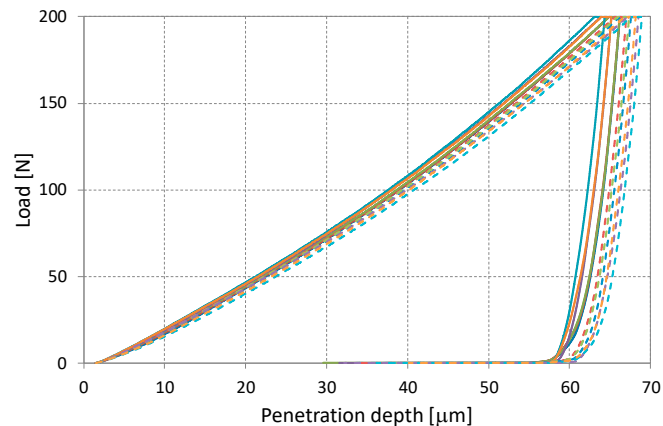


Fig. 4. Indentation curves relevant to X60 steel in the as-received (dashed) and degraded (continuous lines) state.

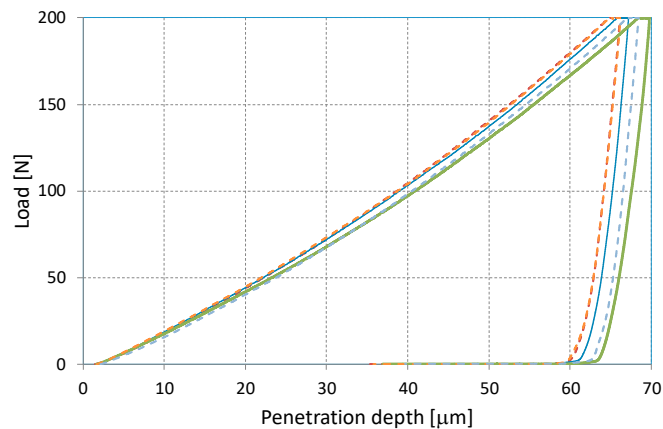


Fig. 5. Indentation curves relevant to 17H1S steel in the as-received (dashed), aged (thin continuous) and degraded (thick continuous lines) state.

The 17H1S steel samples were subjected to the same loading condition. The relevant indentation curves are visualized in Fig. 5. The results obtained in this case do not agree with the expectations.

Fig. 5 shows that the curves concerning 17H1S steel in initial state (dashed) and the mean curve representing the aging condition are overlapping. Furthermore, the graphs indicate that the penetration depth increases in the degraded condition, with values comparable to those exhibited by X60 steel despite the significantly lower mechanical characteristics exhibited by 17H1S. In particular, the ultimate strength of 17H1S steel is smaller than the initial yield limit of X60 in all considered conditions, see Table 1.

4. Discussion and closing remarks

The variation of the mechanical properties exhibited by 17H1S and X60 pipeline steels in the as-received and degraded (as illustrated in the above Section 2) states has been evaluated by different tests.

In the considered processes, metal portions extracted from the pipe wall have been machined to produce the small specimens shown in Fig. 2. Some of these samples have been subjected to chemo-thermo-mechanical treatments. All specimens have been lead to failure by uniaxial tensile tests. The resulting portions have been then sectioned, lapped and subjected to instrumented indentation to a maximum 200 N load.

The alternative experimental procedures implemented in the present study return consistent results for X60 steel. Comparison with the output of preliminary simulations of the indentation tests, carried out with a validated model of the experiment (Bolzon et al., 2012) using the mechanical characteristics reported in Table 1 as input parameters, shows that the agreement is fairly good also in quantitative terms. This outcome denotes that the steel portion affected by indentation is representative of the overall bulk response. In fact, the schematization of the Rockwell tip as a cone with 120° opening angle, indicates that the circular projected area of the surface in contact with the tested material has a diameter of about 230 μm for the maximum penetration depth (about 65 μm) reported in Fig. 4. Thus, the contact length is much larger than the characteristic dimensions of the microstructure shown in Fig. 1.

Similar penetration depths are shown by the graphs in Fig. 5, concerning 17H1S steel. Therefore, the indented volume should be also representative of the macroscopic response of this material. However, the results obtained in this case do not meet the expectations, not even for the as-received case. On the other hand, simulations suggest that the penetration depth of the indenter tip for the mechanical characteristics relevant to 17H1S steel, reported in Table 1, should be much larger than the measured ones. The present conjecture is that machining may have produced a significantly hardened metal layer near the surface of the material, which is no more representative of the overall bulk. Further investigations should give an answer this still open question.

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References

- Bolzon, G., Gabetta, G., Molinas, B., 2015. Integrity assessment of pipeline systems by an enhanced indentation technique. *ASCE Journal of Pipeline Systems Engineering and Practice* 6(1), 04014010, 1–7.
- Bolzon, G., Molinas, B., Talassi, M., 2012. Mechanical characterisation of metals by indentation tests: an experimental verification study for on-site applications. *Strain* 48(6), 517–527.
- Bolzon, G., Zvirko, O., 2017. An indentation based investigation on the characteristics of artificially aged pipeline steels. *Procedia Structural Integrity* 3C, 172–175.
- EN ISO 6508:2005. Metallic materials – Rockwell hardness test.
- Fassina, P., Bolzoni, F., Fumagalli, G., Lazzari, L., Vergani, L., Sciuccati, A., 2012. Influence of hydrogen and low temperature on behavior of two pipeline steels, *Engineering Fracture Mechanics* 81, 43–55.
- Gabetta, G., Nykyforchyn, H., Lunarska, E., Zonta, P.P., Tsyrlunyk, O.T., Nikiforov, K., Hredil, M.I., Petryna, D.Yu., Vuherer, T., 2008. In-service degradation of gas trunk pipeline X52 steel. *Materials Science* 48(1), 104–119.
- GOST 7268-82 Steel. Method for determination of ability to mechanical ageing by impact bend test.
- ISO 14577, 2002. Metallic materials – Instrumented indentation test for hardness and materials parameters.

- Liessem, A., Graef, M.K., Knauf, G., Marewski, U., 2004. Influence of thermal treatment on the mechanical properties of UOE linepipe. 4th International Conference on Pipeline Technology, Ostend, Belgium.
- Nykyforchyn, H., Lunarska, E., Tsyulnyk, O.T., Nikiforov, K., Gennaro, M.E., Gabetta, G., 2010. Environmentally assisted in-bulk steel degradation of long term service gas trunkline. *Engineering Failure Analysis* 17(3), 624–632.
- Tsyulnyk, O.T., Slobodyan, Z.V., Zvirko, O.I., Hredil, M.I., Nykyforchyn, H.M., 2008. Influence of operation of Kh52 steel on corrosion processes in a model solution of gas condensate. *Materials Science* 44(5), 619–629.
- Zvirko, O.I., Savula, S.F., Tsependa, V.M., Gabetta, G., Nykyforchyn, H.M., 2016. Stress corrosion cracking of gas pipeline steels of different strength. *Procedia Structural Integrity* 2, 509–516.