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Toward a non-destructive diagnostic analysis tool of exercises pipelines: models and experiences

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Abstract

Strategic networks of hydrocarbon pipelines, in long time service, are adversely affected by the action of aggressive chemicals transported with the fluids and dissolved in the environment. Material degradation phenomena are amplified in the presence of hydrogen and water, elements that increase the material brittleness and reduce the safety margins. The risk of failure during operation of these infrastructures can be reduced, if not prevented, by the continuous monitoring of the integrity of the pipe surfaces and by the tracking of the relevant bulk properties. A fast and potentially non-destructive diagnostic tool of material degradation, which may be exploited in this context, is based on the instrumented indentation tests that can be performed on metals at different scales. Preliminary validation studies of the significance of this methodology for the assessment of pipeline integrity have been carried out with the aid of interpretation models of the experiments. The main results of this ongoing activity are illustrated in this contribution.

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Keywords: diagnostic analysis; non-destructive testing; simulation models; pipelines.

1. Introduction

European energy needs are partly covered by hydrocarbons transported through a wide long distance network of pipelines. The main gas supplies originate from fields located in Saharan Countries and in the former Soviet Union (Pirani and Yafimava, 2016). Thus, the pipes are either exposed to a peculiar environment or exercised since a rather long time.

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Material aging and chemical interactions pose significant challenges on these strategic infrastructures, also in relation to environmental protection (Bolzon et al., 2011; Baryan and Olah, 2014). Meeting the expected safety standards implies significant maintenance investments, which may be adequately planned through effective structural health monitoring systems (Haesen et al., 2017).

The presence of flaws in the operated pipelines can be detected by visual inspection and ultrasonic measurement tools transported by pigging systems (Gupta and Sinbad, 2016). Localized defects trigger dangerous corrosion phenomena and should be therefore prevented. Their appearance is often preceded by diffuse material degradation, which can be evidenced by mechanical testing usually performed according to international Standards and carried out on samples machined from the pipe wall (Nykyforchyn et al., 2010; Fassina et al., 2012).

One of the most critical damaging phenomena that enhance the risk of premature failure, is represented by metal embrittlement. The possible evolution toward this critical condition has been attracting increasing attention in recent times also in view of the possible use, in the near future, of hydrogen for the storage and the transmission of the energy produced from renewable sources (Sherif et al., 2005).

Metal embrittlement is usually accompanied by the change of other mechanical properties, like yield limits and overall strength, which can be determined also by non-destructive testing techniques (Matsuo et al., 2014; Toribio et al., 2014). Former studies have for instance verified that the traditional uniaxial tensile tests and Rockwell (ISO 6508, 2005) indentation tests carried out at 2 kN maximum load provide equivalent results in terms of elastic limits and ultimate strength of several materials, when the geometry of the residual imprint is taken into account (Bolzon et al., 2012). This information source has been demonstrated to outperform the more traditional load-penetration curves in parameter identification problems (Meng et al., 2016).

Investigations based on traditional tensile tests and on indentation tests at 200 N maximum force have been conducted by Bolzon et al. (2017) and by Bolzon et al. (2018) on different types of pipeline steels, in the as received and degraded conditions. The experimental output was quite repetitive in the case of the uniaxial tests, performed on material samples of circular cross section with 4.9 mm diameter. More dispersed results were obtained from indentation, where the estimated radius of the sample surface in contact with the Rockwell tip is about 250 μm.

The correlation degree between these tests and the representativeness of the indentation results carried out at this scale can be inferred with the aid of a realistic simulation model of the material response, as illustrated in the present contribution.

2. Non-destructive diagnosis of pipeline steel

Instrumented indentation and/or enhanced hardness tests have been proposed as potentially non-destructive diagnostic tools of metal degradation in structural components (Bolzon et al., 2015). The fast and effective experiments rest on the pressure of a diamond (or hard metal) tip against the material to be investigated. A controlled load is applied to the instrument head, progressively increased up to some pre-fixed value and then brought back to zero. The penetration depth of the indenter tip, recorded against the applied force, is represented by the so-called indentation curves. Eventually, the geometry of the imprint left on the metal surface is also recovered at the removal of the instrument head. The relevant data are collected in digital form and processed with the aid of a simulation model of the experiment to recover the model parameters that minimize the discrepancy with the experimental output.

This approach has been validated by Bolzon et al. (2012) on different metal samples subjected to Rockwell indentation with up to 2 kN applied load. The numerical analyses are performed within a geometrically non-linear context to account for the large inelastic strains that develop in the material under the indenter tip and to enforce the progressive contact with the sample surface. The classical Hencky-Huber-von Mises elastic-plastic model with exponential hardening rule and properly calibrated constitutive parameters reproduces the response to indentation accurately.

Rockwell tests on pipeline steels in diverse conditions (as received, mechanically hardened, thermally treated and in-laboratory degraded) have been carried out by Bolzon et al. (2017) and Bolzon et al. (2018) at 200 N maximum force. The reduction by one order of magnitude of the load level compared to the assumption made by Bolzon et al. (2012) shall improve the manoeuvrability of the equipment to be eventually used for in situ diagnostic analysis. However, the portability benefit may be negated by a larger dispersion of the experimental output, more influenced by local variations of the material properties and/or by local irregularities. Still, the laboratory results indicate that sharply distinct families of curves concerning the as-received and degraded states are obtained in most analysed situation.

The verification of the possible correspondence between the evolution of the material characteristics and the output of indentation tests is performed by a numerical model, substantially equivalent to that validated by Bolzon et al. (2012). The fine mesh introduced for the present applications considers a semi-spherical volume of 1.5 mm radius discretized into 2175 4-node axis-symmetric finite elements. The side length of the square elements placed under the indenter tip is 5 µm, while the element size is progressively increased with the distance from the symmetry axis. The macroscopic mechanical properties inferred from the tensile tests performed on the same material sample define the constitutive parameters inserted in the model. The geometry of the tip, of conical shape with spherical rounding at the vertex, is defined by Standards (ISO 6508, 2005).

The graphs in Fig. 1 visualize the main output of the simulations concerning X70 steel. The as-received (continuous line) and aged (dashed lines) states are clearly distinguished both in terms of the indentation curves and for the profile of the residual imprints, which present a significant pile-up. The region mainly affected by indentation has a diameter of about 600 µm, consistent with the expectations. Notice that scales are different along the horizontal and vertical axes in Fig. 1(b).

The simulated indentation curves define the band, within which all experimental results are comprised; see Bolzon et al. (2018). A fairly good correspondence is also found, by comparing the numerical results with the mean experimental output recovered from the as-received and the degraded state.

No information about the actual geometry of the residual imprints is at present available but the relevant measurements may be performed in the near future.

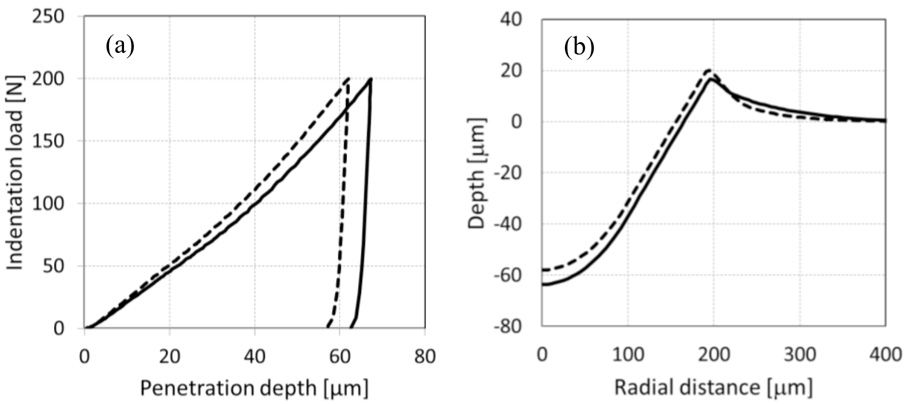

Fig. 1. Simulated response to Rockwell indentation test of X70 pipeline steel in the as-received (continuous line) and aged (dashed lines) conditions: (a) indentation curves; (b) profile of the residual imprint (detail).

3. Closing remarks

Effective energy transition grids and secure operation systems represent strategic goals for the consolidated growth of advanced economies, and imply significant investments to be partly dedicated to the retrofitting of the existing infrastructures. The priority of intervention actions on long term exercised pipelines can be planned on the basis of the measurements that can be collected from non-destructive indentation tests performed on-site. The substantial correspondence among the material properties that are reflected by the indentation curves and which can be recovered from traditional tensile tests has been verified for some pipe steel class. The reliability of the rich information connected with the geometry of the residual imprint shall be analysed in further studies.

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