HYDROGEN EFFECT ON FATIGUE LIFE OF A PIPE STEEL

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Abstract Transport by pipe is the means more used, at the present time, to convey energies of their point of extraction until their field sites final. To limit any risk of explosion or of escape and thus to limit the geological problems of pollution and the human risks, it is necessary to be able to know the mechanical properties of the steels used in the manufacture of these pipes. With the reduction in oil stocks, it is necessary to find a new energy. Hydrogen is this new energy vector, it thus will also be necessary to be able to transport it. This study makes it possible to emphasize the assignment of the lifespan of hydrogen on a pipeline steel normally used in the transport of gas. The fatigue tests in 3 points bending are carried out on samples not standards because of dimensions of the tube of origin.

I. Introduction

Fracture causes in pipes

The causes of the failures of the gas pipelines are various natures. They can appear either by a fracture, or by a leak (it depends of the nature of the fluid transported). The majority of these failures are caused by pitting corrosion or cracking by stress corrosion, but there are also problems related to the defects of welding. Movements of ground (landslip, earthquake ...) can also be the cause of damage on the buried pipelines. The owners of pipelines study these problems for a long time and have a good knowledge of the methods allowing to manage them.

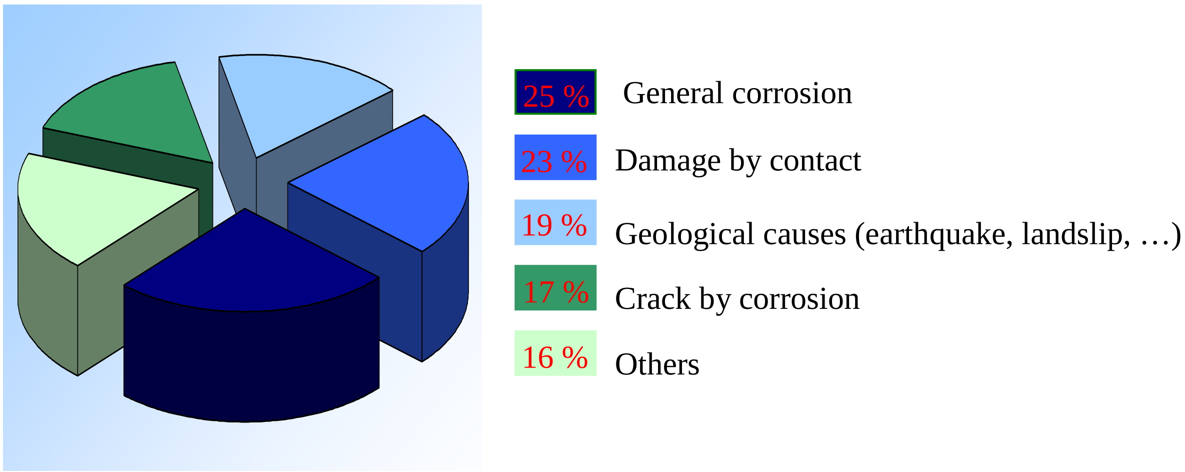


Fig. 1: Causes of the fracture of pipelines in the course of exploitation recorded by the members of the ACPRÉ of 1985 to 1995 [1].

But it should not all the same neglect the external mechanical aggressions (cf Figure 1). Indeed, it happens that the pipelines are damaged or perforated accidentally at the time of work of excavation by machines of building. The problems of crack initiation in fatigue and the ruptures emanating of stress concentrations are at the origin of more than 90% of the ruptures in service. The presence of a geometrical discontinuity such as a notch will cause the weakening of the fracture resistance of the pipeline. Since it will reduce the section of the pipe, while making it more sensitive to the operating pressure and the efforts caused by the movements of the grounds, then an effect of local amplification of the stress will make increase this defect exponentially.

The figure 1 shows also that the fracture due to corrosion accounts for 42% of the cases. This is why our study will characterize the impact of a notch subjected to corrosion over the lifespan of a steel constituting these pipelines.

Steel used

The steel used is a steel intended for the manufacture of pipeline, employed in the Ukrainian network. The standard chemical composition of this steel is shown in the table 1.

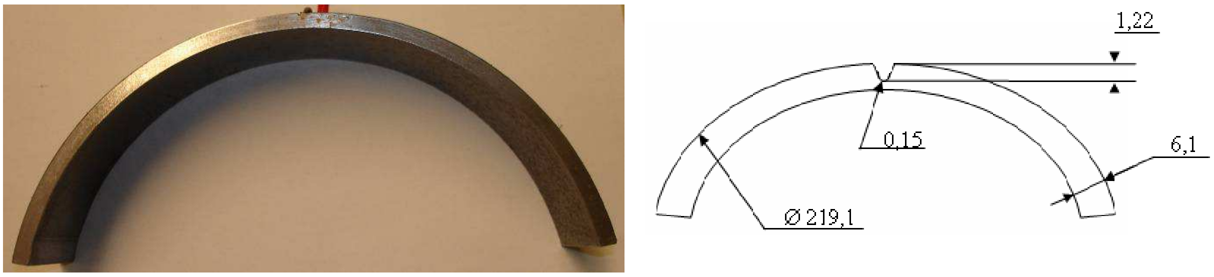
Table 1. Chemical composition of the steel (mass proportion in %) [2].

C	Mn	Si	Cr	Ni	Mo	S	Cu	Ti	Nb	Al
0,22	1,22	0,24	0,16	0,14	0,06	0,036	0,19	0,04	<0,05	0,032

Fatigue test

Sample used

The sample modelled hereafter in the picture 1 and 2, result from a gas pipe used in the Ukrainian network. It has an external diameter of 219,1 mm for a 6,1 mm thickness. As the pipe has a strong curve and a low thickness, it is not possible to produce traction or standardized bend-test samples. This is why we chose to carry out test on curved samples. These samples are cut in arcs of 160° for a width of 60 mm (the zone comprising the welding being avoided). The notch is used to reproduce the possibility that these pipes have to be scraped by machines (as excavator, digger, scraper,…). The notch in V at 45° is carried out on 20% thickness of the curved sample, it has a depth of 1,22mm. The ray of notch bottom is 0,15mm.



Picture 1 and 2: Sample used

Electrolytic solution

The electrolytic solution is used to have a strong concentration in hydrogen ion in the closeness of the mechanical notch. This synthetic solution NS4 (Natural Soil 4) represents the ground surrounding the pipelines where the phenomenon of stress corrosion was observed throughout the world. It is a standard composition.

Table 2: Chemical compound of the NS4 solution [3].

Chemical compound	Formula	Concentration (mg/L)
Potassium chloride	KCl	122
Sodium hydrogenocarbonate	NaHCO3	483
Hydrated calcium chloride	CaCl2,2H2O	181
Hydrated magnesium sulfate	MgSO4,7H2O	131

This solution was prepared from these chemical compounds and distilled with deionised water, the solution volume is about 17 litters. A pump is used to have always a homogeneous solution during the fatigue test. This solution has a natural pH between 8 and 8,5. The measurement done during the first test gave a value of 8,56. To decrease the pH until 6,7 during the fatigue test, we have used a bubbling of CO_2 gas and another of N_2 gas to stabilize the solution and to take off oxygen inside. During all the test the level of the pH is controlled and regulated between 6,6 and 6,7. The bubbling of gas set out again in the following way: 80% of N_2 gas and 20% of CO_2 gas.

Equipment

- *Fatigue machine:*

The 3 points bending device is constituted by a hydraulic machine INSTRON 1341 allowing to apply a load or a displacement, a load cell to control the load (from 0 to 10kN), and a control panel to manage the type of cycle (sinus, trapezoid, or rectangular), the frequency, the nominal load... On this machine we have positioned the assembly below:

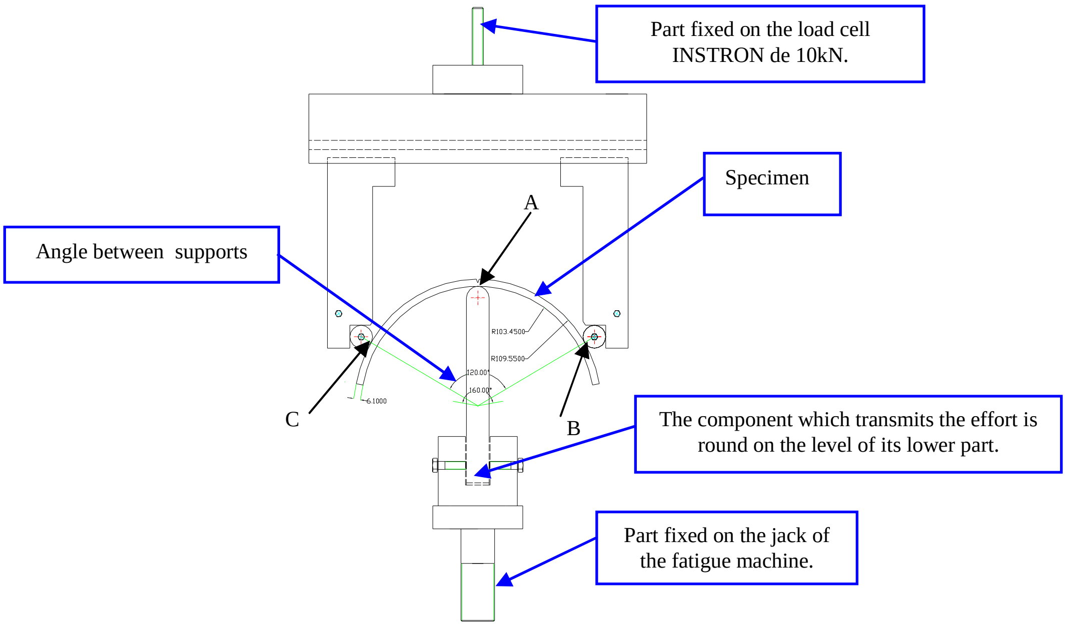


Fig. 2: Assembly of the 3 points bending

All parts of this assembly are in stainless steel: 316L, to limit corrosion problem. The corrosion of the assembly could deteriorate the quality of the NS4 solution and thus reduce its efficiency. The three cylinders used in this assembly are in PVC to insulate the assembly electrically and so reduce the leakage currents.

- *Hydrogen cell:*

The hydrogen cell is a box which surrounds the assembly of 3 points bending, and which thus makes it possible to contain the NS4 solution. It was carried out using PVC plates which were welded between them to ensure a good sealing. This cell is not closed because the volume of the solution contained is rather large. And the bubbling of N_2 gas is sufficient to guarantee the no presence of oxygen inside. To control electrolysis, we used a Potentiostat. Full remote monitoring of the system is performed by a PC computer. The EC-Lab software permits to process all the parameters and the data (as : work potential, test duration, signal type, limits, …). This electrolysis is carried out with three electrodes:

- The working electrode (in blue on the figure 4): is the sample because we want to make a reduction of this sample (hydrogen atom are adsorbed on the surface of the sample and with the time they can diffuse towards the interior of the sample).
- The counter electrode (in yellow on the figure 4): is made with a stainless steel (platinum). It is used to measure the evolution of current during the fatigue test.

- The reference electrode (in red on the figure 4): is saturated calomel electrode. It is used to control the tension applied.

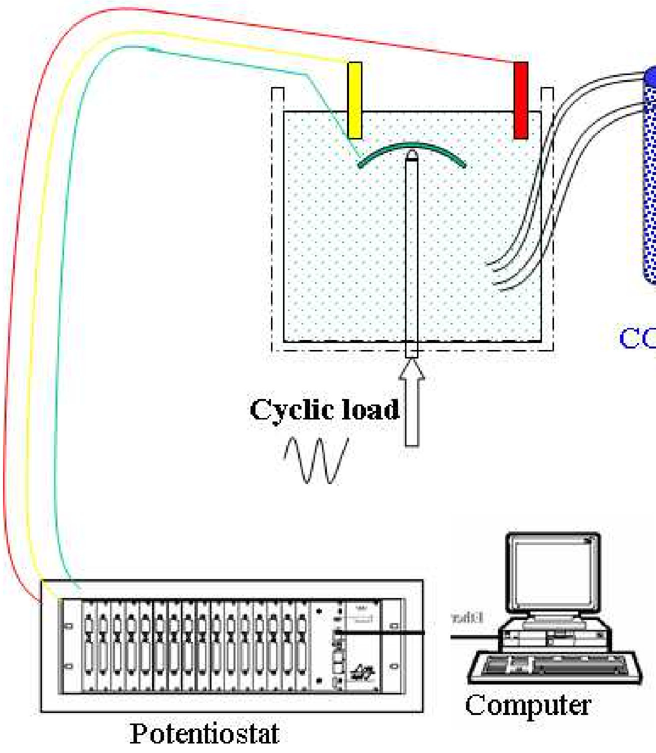
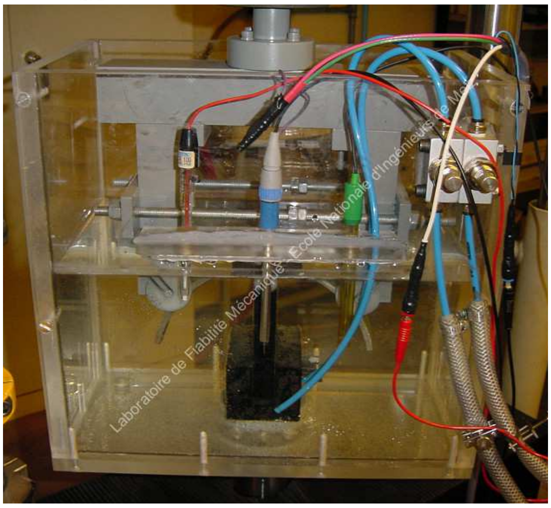


Fig. 3: Assembly of the hydrogen cell



Picture 3: Hydrogen cell

The free potential of this steel is -0,8 V_{sce}, this data has been got by plotting the polarisation curve of this steel. We have chosen to set the work potential at -1V_{sce}, at this potential we will certainly carry out a reduction of the sample near the notch (adsorption of hydrogen atom on the sample) [4].

Results

Parameters of the tests in presence of air

We have chosen to take a loading cycle with a shape sinusoidal. The frequency is fixed at 7Hz, and with a ratio of load of 0,5, because the pressure in these pipes, as the figure 4 shows it, is contained between 40 and 70 bars ($R = \frac{P_{\min}}{P_{\max}}$ (1), soit $R = \frac{40}{70} = 0{,}57$). On average, the passage of the minimum pressure to the maximum pressure is done in one day.

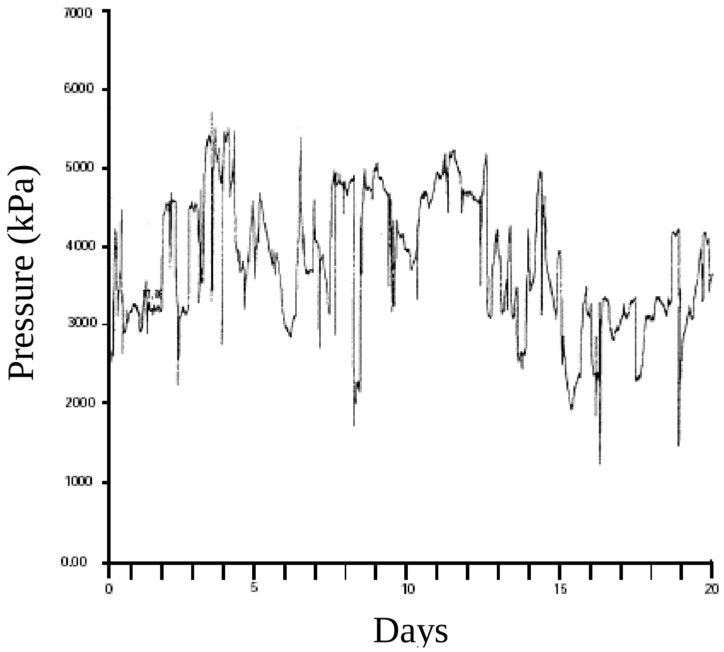


Fig. 4. Profile of pressure during 20 days for a pipeline with liquid products [1].

The loading amplitudes were selected manners to have lifespan contained between 50000 and 300000 cycles. To know roughly these loads, we used, the diagram of Haigh and the relation of Basquin:

$$\sigma_a = C * N_R{}^b \tag{2}$$

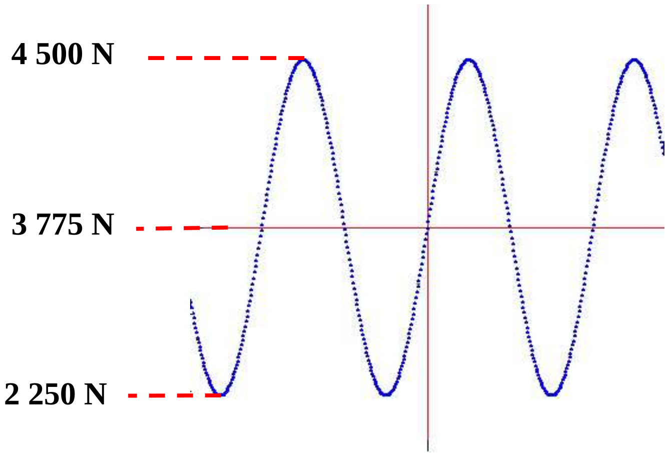


Fig. 5. Shape of the cycle used during the fatigue test

We carried out 12 tests with 6 different amplitudes of loading, so there are 2 points by different tests.

Parameters of the tests in presence of hydrogen

In order to compare these two tests in different atmospheres, we tried to keep the maximum of same parameters. So we have carried out these tests with the same ration of load and the same loading amplitude. We have just changed the frequency, because with a weaker frequency, we are sure to have a good diffusion of the hydrogen atoms toward the notch of the sample. The frequency is fixed at 0,5Hz. The work potential of the electrolyse is kept constant during the test at -1V$_{sce}$.

Comparison between the two results

We can see on the figure 6, the comparison between the fatigue tests carried out in presence of air and hydrogen. These curves bring to the fore the harmful effect of hydrogen on a steel. Indeed, the lifespan in presence of hydrogen is decreased by 70%.

Comparison between the 2 Wöhler curves :

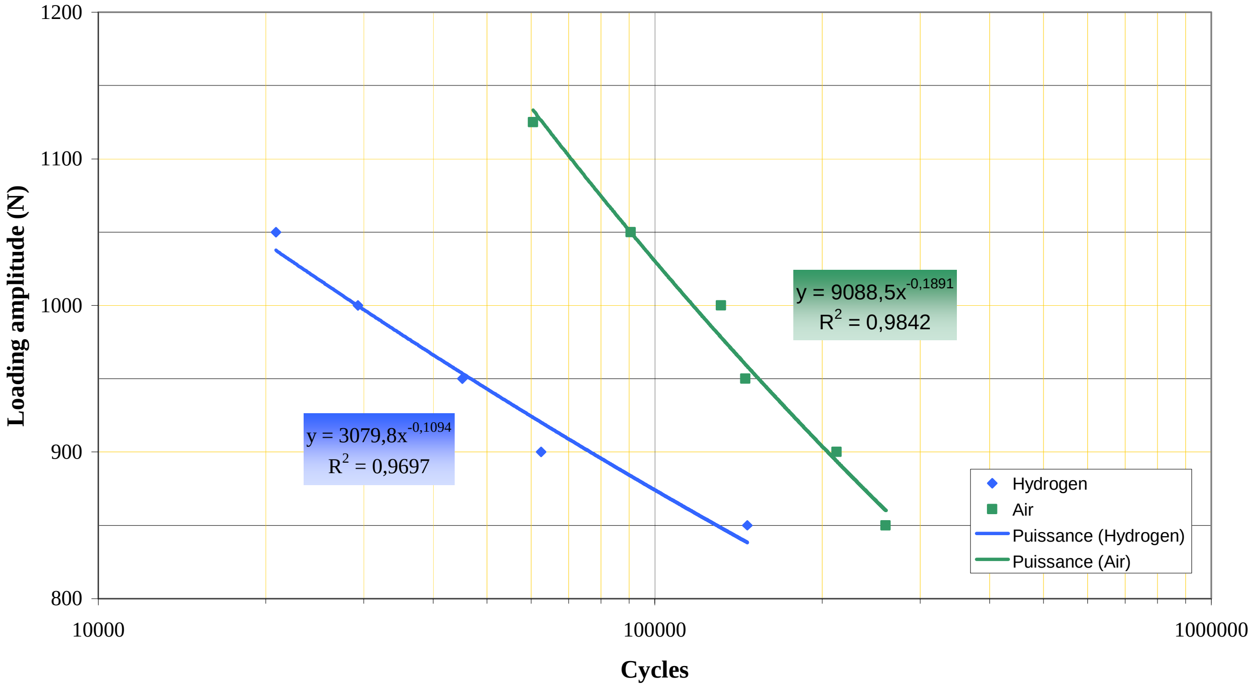
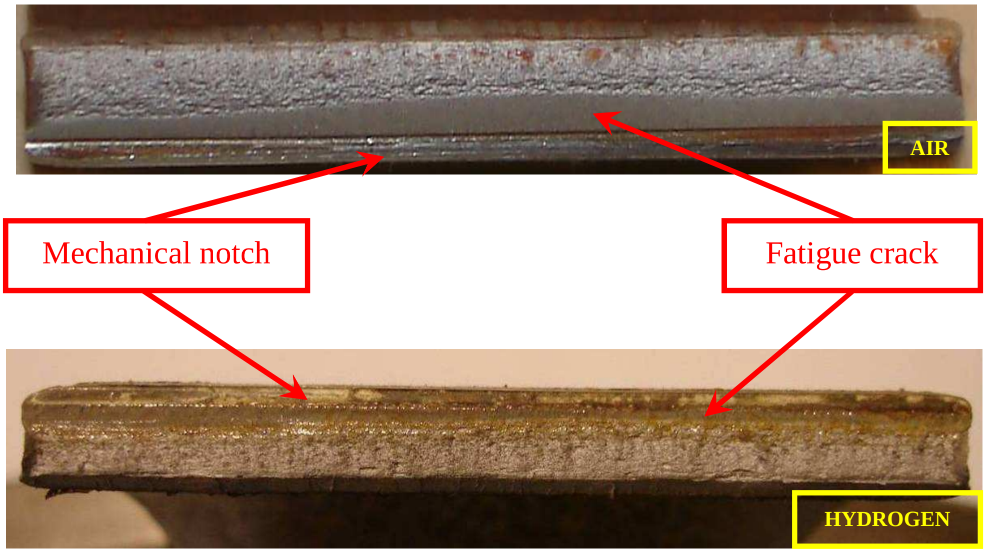


Fig. 6. Wöhler curves in presence of air and hydrogen.

The coefficient of the Basquin relation “b” obtained for the test in presence of air is -0,19. It is a value close to the values found in the literature for this steel (-0,2). What enables us to validate these curves. In presence of hydrogen, the Basquin coefficient is decreased by 42%.

The pictures 4 and 5 show the different fracture appearance that we have had after these fatigue tests. It is possible to distinguish two distinct zones. The first corresponds to the fatigue crack it has a smooth and silky surface. The second, as for it, has a facies with grains which is characteristic of a brutal fracture. The first zone corresponding to the fatigue crack for the test in presence of hydrogen is definitely weaker than the fatigue crack in presence of air. We can observe a reduction of 70% over the length of the crack propagation.



Pictures 4 and 5: Fracture appearance after the fatigue test

Conclusion

This study permits us to give prominence the dangerousness of hydrogen on these steels intended for the manufacture of pipelines, when the latter were subjected to a scratch on approximately 20% their thickness. A complementary study is undertaken to determine the effect of hydrogen on the crack initiation. The initiation crack is in this case detected by a device of acoustics emissions. The presence of hydrogen is always due to an electrolysis of a solution NS4.

References

1. Rapport de l’enquête MH-2-95, “Fissuration par corrosion sous tension des oléoducs et des gazoducs canadiens”, Office National d’Energie, (1996)
2. C. Monin, “Etude de l’impact de l’hydrogène sur un défaut de soudage de canalisation par l’approche déterministe”, Ecole Nationale d’Ingénieur de Metz, (2001)
3. A. Benmoussat and M. Hadje, “Corrosion behaviour of low carbon line pipe steel in soil environment”, JCSE, volume 17, (2005)
4. J.L. Crolet and G. Béranger, “Corrosion en milieu aqueux des métaux et alliages”, Techniques de l’Ingénieur, M150-4