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Assessing the Impact of Lamination-Like Flaws on the Operating Safety of Natural Gas Transmission Pipelines

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Abstract

This work highlights, by analyzing the causes of some technical accidents, the danger represented by the presence of lamination-like flaws in the steel pipes natural gas transmission pipelines are made of and presents a method of numerical simulation of the process that causes the extension of these flaws and that can lead to the explosive failure of these pipelines, many times accompanied by burning. The work also accentuates the fact that the severity of lamination – like flaws of the pipes the natural gas transmission pipelines are made of is directly correlated to the mechanical strength and toughness properties of the steel the pipes are made of and to the particularities of the operating conditions of pipelines, mainly to the frequency and the amplitude of the pressure variations of the conveyed gas.

Key words: *natural gas transmission pipeline, lamination-like flaws, Fitness-For-Service (FFS) assessment*

The Threat / Danger Represented by the Lamination – Like Flaws of Pipes

The lamination-like flaws can be defined as planar crack-like defects, of some decohesion areas or some structural formations of significant brittleness, generated during the manufacturing process of the rolled strips the (longitudinally or helically) welded pipes for pipelines are made of [1]. These flaws are characterized, as it can be seen in figure 1, as follows:

- limited extension, determined by the existence within the bar strips subjected to rolling (cast ingots, slabs) of some local defects (contaminant segregations, solid inclusions, gas cavities, shrinkage holes etc.);
- preferential orientation on the rolling direction and positioning between the strips of the structures attained by hot plastic deformation;
- extension by fusion (coalescence), due to the forming of some small bond cracks between adjacent defects, situated between the rows of the rolling structure placed at different levels in the pipe wall.

The presence of these flaws in the pipes the pipelines are made of determines the sensitive growth of the operating failure risk of these and the occurance of some technical accidents with major consequences; in figure 2 there are presented suggestive images regarding the severity of the accidents produced in an operating pipeline due to lamination – like flaws of the pipes the pipeline is made of.

The factors that can determine the growth of the severity of lamination-like flaws of pipes and also the failure risk of pipelines made of such pipes are [2,3]:

- inducing in the rolled strips with such flaws, due to the use of unadequate lamination conditions, of some unequilibrium microstructures (for instance of Widmanstatten type), of significant brittleness and high tendency of crack initiation and / or extension (propagation) by the action of monothonic or cyclic mechanical loads;
- distortion of the configuration and the creation of some bond cracks between adjacent defects, situated between the rows of the rolling structure placed at different levels in the rolled strips, due to the bending of the strips (U/O or helical) while constructing (longitudinally or helically) welded pipes;
- the use of some pipeline operating conditions characterized by frequent loads when overpressurized or by cyclic pressure variations of high amplitude of the conveyed gas.

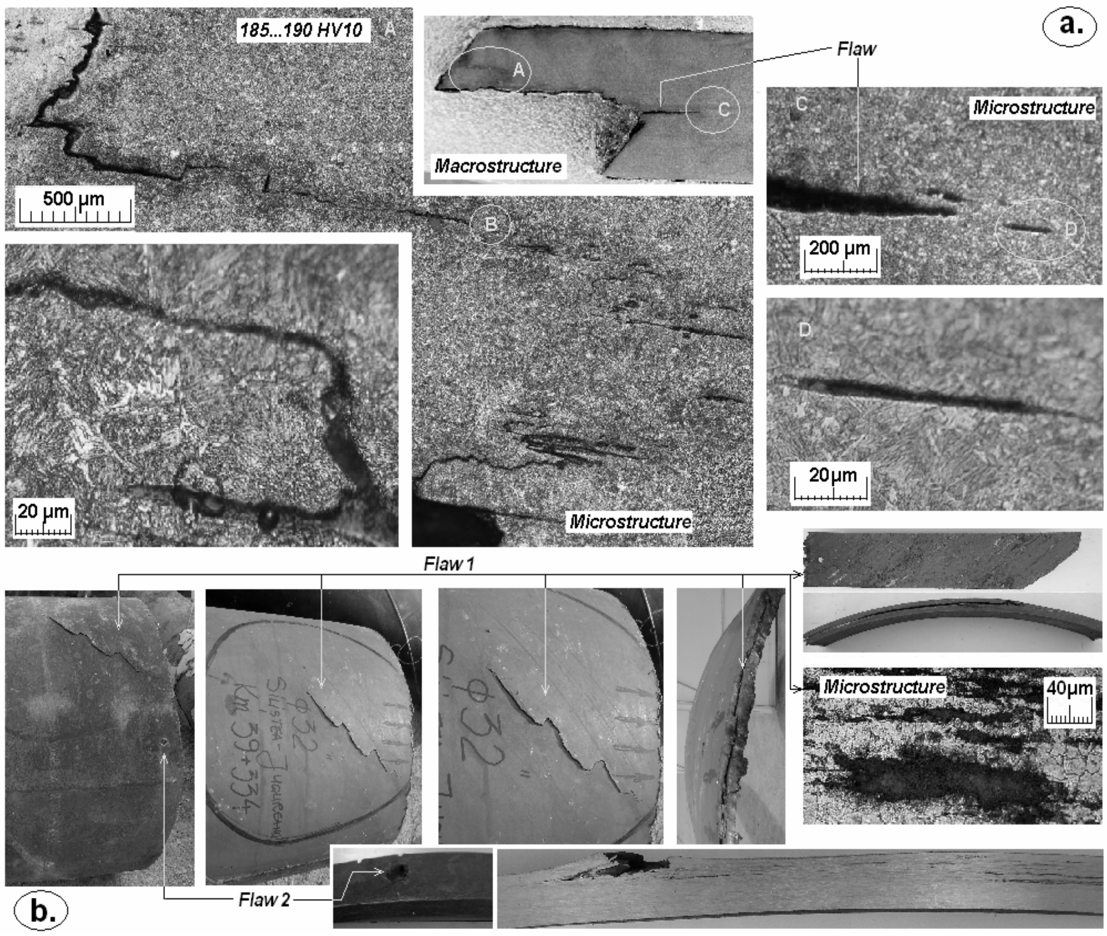

Fig. 1. Lamination-like flaws present in the pipes of pipelines that failed during operation

The Failure Mechanism of Pipelines with Lamination-Like Flaws

The main scenario regarding the in-service failure of a pipeline composed of a pipe whose quality is affected by the presence of some lamination-like flaws can be formulated as it follows [2,3]: the lamination-like flaws of the strip the pipe of unadequate quality was made of, bedded within this strip and extended over long distances in the rolling direction, generates the effects of stress concentration typical for cracks and extend slowly, under the action of a significant number of pressure variations of the conveyed gas, until some critical dimensions are reached when their unstable high rate propagation is produced, over distances which increase as the toughness of the strip structures used for pipes decreases.

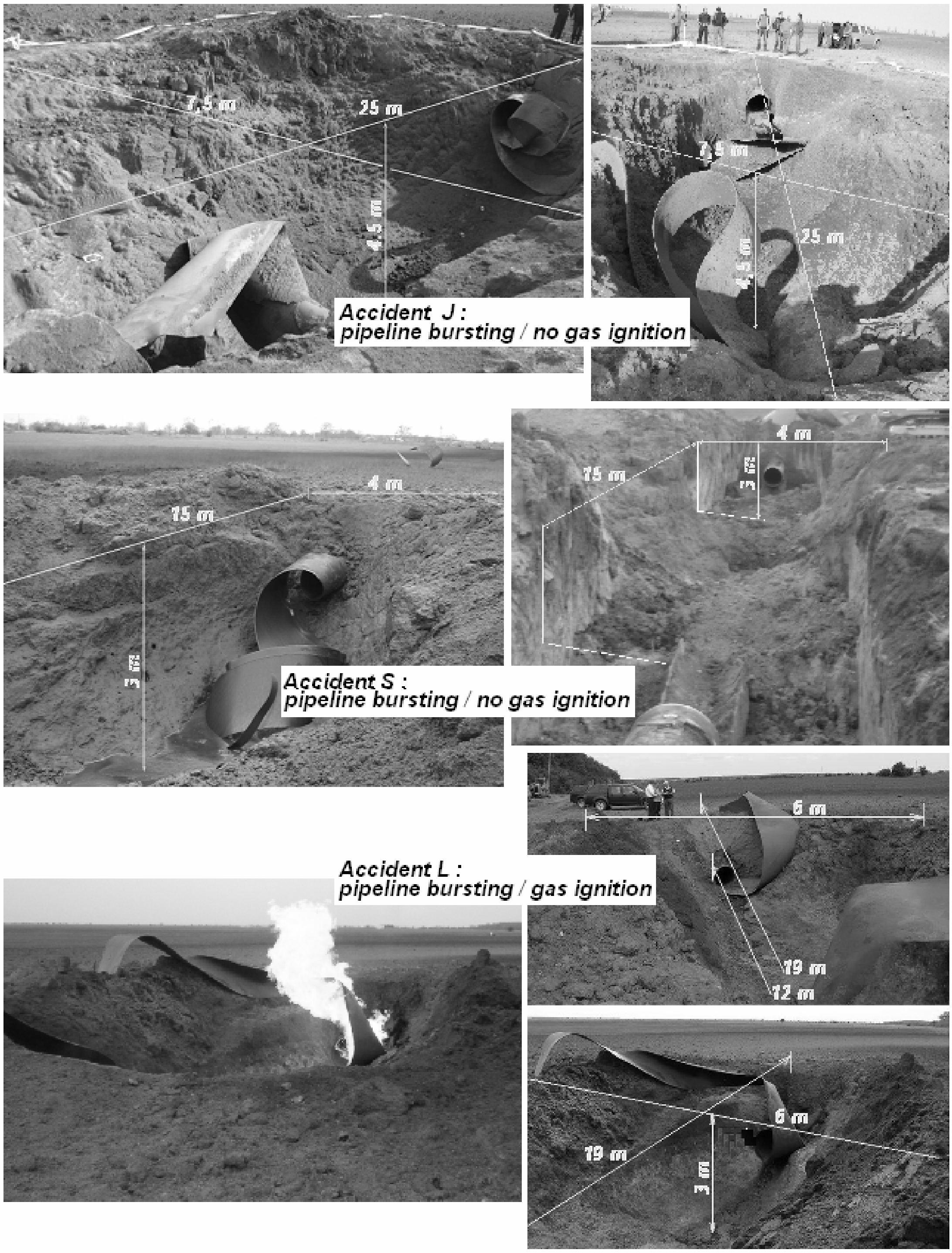

Fig. 2. Technical accidents produced due to lamination-like flaws of the pipes the natural gas transmission pipelines are made of

The numerical simulation by the finite element method – MEF, performed by using the diagram in figure 3 (adjusted for studying the cases corresponding to the occurance of the accidents presented in figure 2), attested the possibility of the (previously presented) scenario to materialize, meaningly the occurance of failure caused by the presence of lamination-like flaws in the pipes the natural gas transmission pipelines are made of and highlighted the effects of stress concentration generated by the presence of these defects, effects that accentuate with the increase in width L_d and / or in the inclination angle β [2,3]. The standard [4] suggests the assessment of the integrity of the mechanical structures, such as pipes with lamination - like flaws, considering that these flaws are equivalent to some radial cracks in the pipe wall, having the depth $2a$ determined by projecting them on a normal plane to the directions of the main stresses generated within the pipe wall by the pressure of the conveyed gas and that these cracks extend only by opening (mod 1), recommendations that justify the use of the diagram presented in figure 4 and that confer to the analyzed issue a character of uncertainty (because a radial crack with the depth $2a$ may correspond to more lamination – like flaws, with different values of the characteristic dimensions L_d and β – see fig. 3).

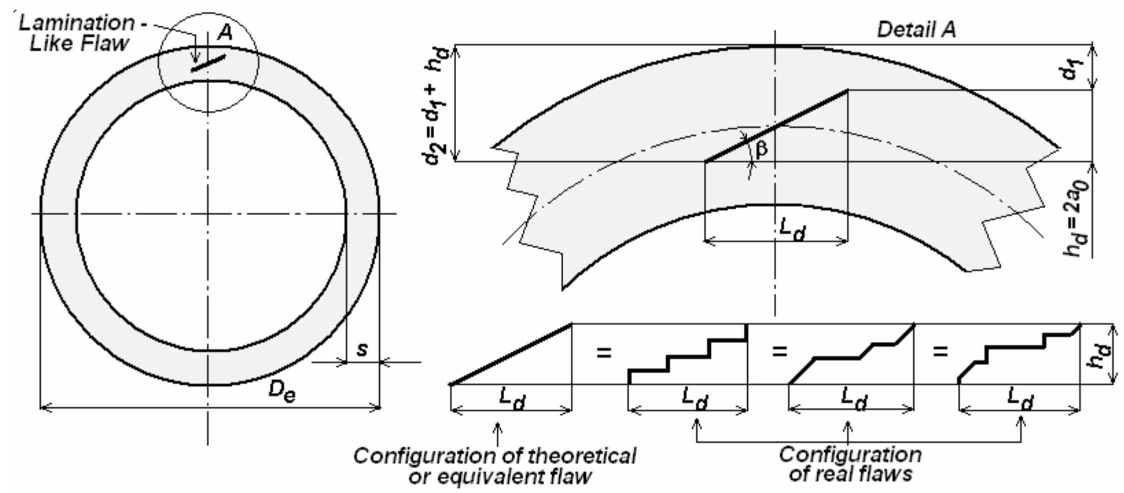

Fig. 3. Diagram used for the simulation with FEM of the effects of the presence of lamination – like flaws in the pipes natural gas transmission pipelines are made of

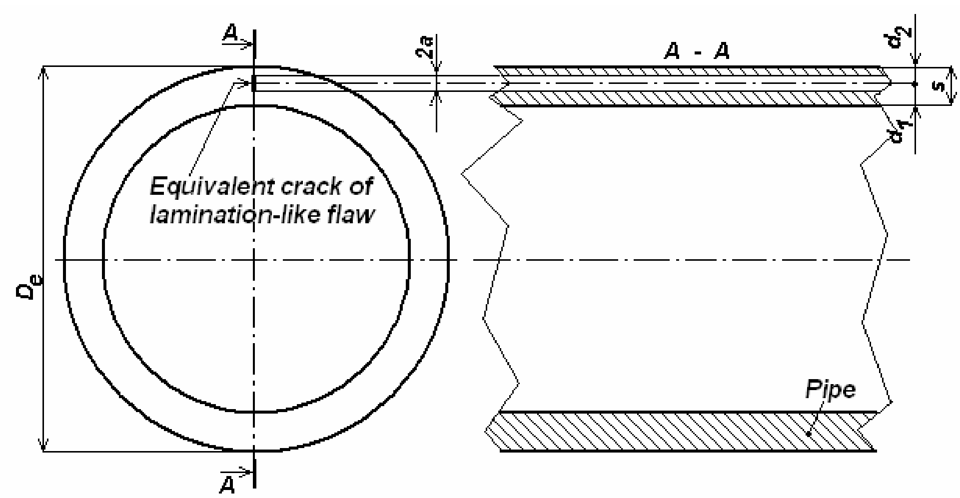

Fig. 4. Diagram for assessing the influence of lamination-like flaws upon the operating safety of natural gas transmission pipelines

Simulation of the Behaviour of Pipelines with Lamination – Like Flaws

Considering the previously discussed issues, the authors of this work conceived a numerical simulation algorithm of the process of radial crack extension (equivalent to the lamination – like flaw within the pipes the pipelines are made of) under the action of varying loads produced by the operating pressure variations on natural gas transmission pipelines, consisting of the following steps:

Step 1. The input data necessary to the calculations are determined:
a) The outside diameter of the pipeline D_e and the wall thickness s; by knowing these reference dimensions there can be calculated: the outer radius of the pipe $R_e = D_e/2$; the inner radius of the pipe $R_i = R_e - s$;
b) The initial half-depth of the crack a_{0f};
c) The mechanical strength and toughness properties of the material (steel) the pipes are made of: the yield strength $R_{t0,5}$ (the tensile stress required to produce a total elongation of 0.5%), the tensile strength R_m, the elongation $A_{2\text{in}}$, the reduction of area Z, the Charpy V-notch impact test absorbed energy KV, the fracture toughness $K_{mat} = K_{1C}$;
d) The mechanical load spectrum of the pipeline while assessing its structural integrity (the minimum $p_{\min,j}$ and maximum $p_{\max,j}$ operating pressures, the mean pressures $p_{m,j} = (p_{\min,j} + p_{\max,j})/2$ and the pressure variations $\Delta p_j = p_{\max,j} - p_{\min,j}$ both for all load cycles $j = 1... N_t$, and for possible additional mechanical loads);
e) The Partial Safety Factors – PSF corresponding to the degree of uncertainty regarding the determination of the mechanical loads of the pipeline, the determination of the stress and strain conditions in the defective area, the estimation of the crack dimensions and the determination of the mecanical strength and toughness properties of the material (steel) the pipes are made of; the standard [1] prescribes the use of three partial safety factors: PSF_s – the partial safety factor for the stress intensity; PSF_a – the partial safety factor for the crack dimensions; PSF_K – the partial safety factor for the fracture toughness of the material the pipe is made of.

Step 2. There is determined the „cycle by cycle" assessment procedure of the radial crack extension existing within the pipe wall and there is also determined the criterion for establishing the pipeline fatigue life / endurance (defined by the number of variation cycles of the operating pressure until the cracked pipeline fails or by the length in service of the pipeline till it fails in the cracked area). So, if the lamination-like flaw (having the width L_d and the inclination β – see fig. 3) corresponds to a design radial crack (see fig. 4) having the half-depth a_{0f}, it will be preceded like this:
a) it is considered that the initial radial crack in the pipe wall has the half-depth $a_0 = PSF_a a_{0f}$;
b) at the first variation cycle of the operating pressure the crack has the initial half-depth $a_{0,1} = a_0$ and extends during this cycle with Δa_1, at the second variation cycle of the operating pressure the crack has the initial half-depth $a_{0,1} = a_{0,1} + \Delta a_1$ and extends during this cycle with Δa_2,..., at the variation cycle j of the operating pressure the crack has the initial half-depth $a_{0,j} = a_{0,j1} + \Delta a_{j-1}$ and extends during this cycle with Δa_j, at the variation cycle $j+1$ of the operating pressure the crack has the initial half-depth $a_{0,j+1} = a_{0,j} + \Delta a_j$ and extends during this cycle with Δa_{j+1} and so on;
c) at the beginning of the variation cycle of the pressure n, for which the half-depth of the crack fulfills the condition $a_{0,n} = a_{0,n-1} + \Delta a_{n-1} \geq \min(a_{ef}; a_{pe})$, the pipeline fails, a_{ef} is the half-depth of the crack for which its unstable extension occurs (brittle failure takes place), and a_{pe} – the half-depth of the crack for which the pipeline loses its tightness (gas leakages occur).

Step 3. There are determined the crack extensions during each variation cycle of the operating pressure. Considering that the growth rate of cracks respects a Paris type law with two stage crack growth, the cyclic extensions of the crack (in mm) are calculated by the relation [1-3]:

$$\Delta a_j = \frac{\mathrm{d}a}{\mathrm{d}N_j} = A_1 \Delta K_{1,j}^{m1},\ \text{if } \Delta K_{1,j} \le \Delta K_{sp}$$

or (1)

$$\Delta a_j = \frac{\mathrm{d}a}{\mathrm{d}N_j} = A_2 \Delta K_{1,j}^{m2},\ \text{if } \Delta K_{1,j} > \Delta K_{sp};$$

the cyclic variation of the stress intensity factor $\Delta K_{1,j}$ can be calculated by using the relation recommended by the standard [1]:

$$\Delta K_{1,j} = G_{0,j} \Delta \sigma_{ref,j} \sqrt{\pi a_{0,j}}\ , \tag{2}$$

where G_{0j} is a coefficient that, for radial cracks placed in the median area of the pipe wall (where $d_1 = d_2 = s/2$ – see fig. 4), has the values given by the formula:

$$G_{0,j} = a_G + b_G \left(\frac{2a_{0,j}}{s} \right)^3 , \tag{3}$$

with $a_G = 1{,}033471$ and $b_G = 1{,}703840$, while $\Delta\sigma_{ref,i}$ can be calculated by the formula [1]:

$$\Delta \sigma_{ref,j} = \frac{\Delta P_{b,j} + 3\Delta P_{m,j}\alpha_j + \sqrt{(\Delta P_{b,j} + 3\Delta P_{m,j}\alpha_j)^2 + 9\Delta P_{m,j}^2 \left((1-\alpha_j)^2 + \frac{4d_j\alpha_j}{s} \right)}}{3\left((1-\alpha_j)^2 + \frac{4d_j\alpha_j}{s} \right)}, \tag{4}$$

where, $d_j = \frac{s}{2} - a_{0,j}$, $\alpha_j = \frac{2a_{0,j}}{s}$, and $\Delta P_{m,j}$ and $\Delta P_{b,j}$ are determined by the formulas:

$$\Delta P_{m,i} = PSF_s \Delta p_j \frac{R_i}{s};\ \Delta P_{b,j} = PSF_s \Delta p_j \frac{R_e^2}{R_e^2 - R_i^2} \left[\frac{s}{R_i} - \frac{3}{2}\left(\frac{s}{R_i} \right)^2 + \frac{9}{5}\left(\frac{s}{R_i} \right)^3 \right]. \tag{5}$$

Step 4. There is determined the operating life of the pipeline until failure (the fatigue life /endurance of the pipeline), expressed by the number of pressure cycles N_c until the following condtion is fulfilled:

$$a_{0,n} = a_{0,n-1} + \Delta a_{n-1} \ge \min(a_{ef};\ a_{pe}), \tag{6}$$

where a_{pe}, previously specified, is, in case of radial cracks placed in the median area of the pipe wall, $a_{pe} = s/2$, and a_{ef}, also previously specified, corresponds to the half-depth of the radial crack for which the following condition is fulfilled:

$$G_0(a_{ef})\, p_{\max,n} \frac{R_i}{s} \sqrt{\pi a_{ef}} \ge K_{mat}, \tag{7}$$

$p_{\max,n}$ is the maximum pressure of the variation cycle of the operating pressure n, where the radial crack reaches the depth $2a_{ef}$, K_{mat} – the fracture toughness of the steel the cracked pipes of the pipeline are made of, $K_{mat} = K_{1C}$.

The algorithm, transposed into an software in EXCEL, can be used in order to explain the way the technical accidents occur during the operation of natural gas transmission pipelines made of pipes with lamination – like flaws. For exemplification, there are further presented the results obtained while analyzing the accident L (see fig. 2), produced due to the failure of a steel pipe with lamination – like flaws and an unadequate metallographic structure, characterized by low toughness. The initial data used in the analysis were:
a) $D_e = 813$ mm and $s = 9{,}52$ mm ($R_e = 406{,}5$ mm and $R_i = = 397$ mm);
b) $a_{0f} = 1{,}8...2{,}4$ mm (considering that the lamination – like flaws existing in the analyzed pipe had $L_d = 20...50$ mm, assumption very well confirmed by the metallographic images of the samples taken from the pipe that failed [3], it resulted that the inclination angle which correspond to these defects has been $\beta = 3^o...10^o$);

c) The steel grade the pipe that failed was made of (X52 – API Spec. 5L) had $R_{t0,5}$ = 740 MPa, R_m = 918 MPa, $A_{2\text{in}}$ = 15 %, KV = 8...15 J and the fracture toughness $K_{mat} = K_{1C}$ = 31...63 MPa$\sqrt{\text{m}}$;
d) The mechanical load spectrum of the pipeline during the approximative 20 years of service (the minimum operating pressured $p_{\min,j}$ and the maximum operating pressures $p_{\max,j}$, the mean pressures $p_{m,j} = (p_{\min,j} + p_{\max,j})/2$ and the pressure variations $\Delta p_j = p_{\max,j} - p_{\min,j}$ for all load cycles $j = 1... N_t$,) is the one shown in figure 5 (made on the basis of the data regarding the pressures measured daily during the last 16 months before the accident L occured);
e) PSF_s = 2,6; PSF_a = 1,5 and PSF_K = 1,0 [1] (under these circumstances it resulted that the initial radial cracks in the pipe wall that failed had $a_0 = PSF_a a_{0f}$ = 2,7...3,6 mm, while the fracture toughness of the pipe steel was taken $K_{mat} = K_{1C}$ = 31...63 MPa$\sqrt{\text{m}}$);
f) The growth rate of the cracks under the action of varying loads was considered to be corresponding to a Paris law with two stage crack growth, with $A_1 = 2{,}144 \cdot 10^{-10}$, $A_2 = 1{,}224 \cdot 10^{-8}$, m_1 = 5,10, m_2 = 2,88 and ΔK_{sp} = 6 MPa$\sqrt{\text{m}}$.

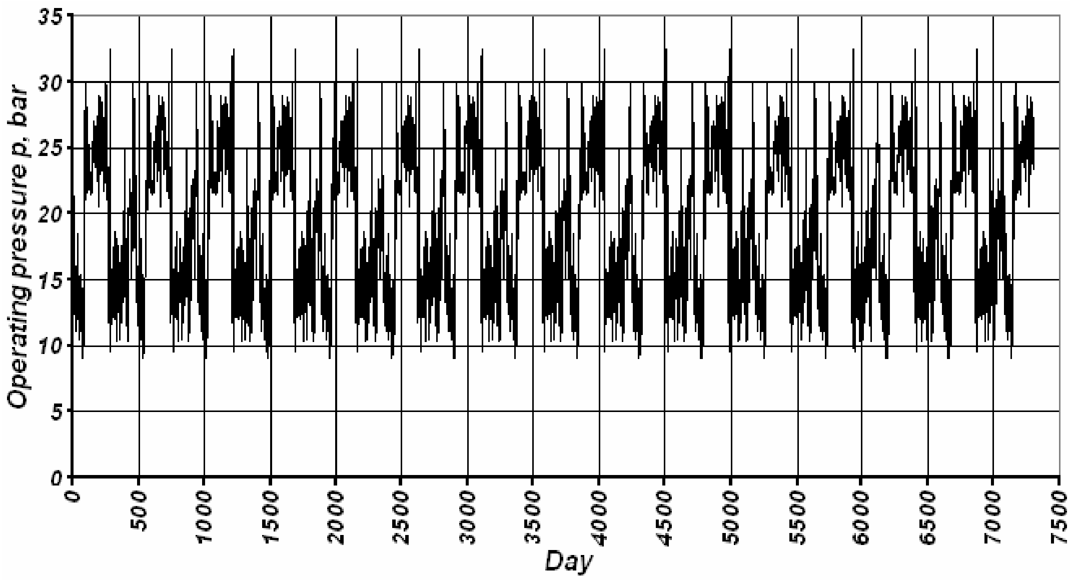

Fig. 5. The inner pressure load spectrum of the pipe that generated the accident L

The results obtained for this case study are synthesized in the diagrams presented in figure 6, which show how the growth of the crack depth took place under the pressure variation while operating the pipeline, how the maximum value of the stress intensity factor K_1 modified at the tip of the cracks and how K_1 and the fracture toughness of the pipe material K_{mat} correlated. It can be noticed that the numerical simulation showed that the lamination – like flaws could extend up to the critical size the pipeline failed at, in N_c = 6511...7341 cycles; because the length of the pressure cycle was of about one day, it results that the fatigue life / endurance obtained by calculations for the pipeline with lamination – like flaws, N_c = 6511...7341 days = 17,8...20,1 years, coincides with the service life of the pipeline up to the occurance of the accident L (about 20 years).

Considering the same initial data as before, but under the circumstances in which the pipe with lamination – like flaws had an appropriate structure, characterized by the usual levels of the mechanical strength and toughness properties for the X52 steel ($R_{t0,5}$ = 360... 380 MPa, R_m = 480...550 MPa, $A_{2\text{in}}$ = 25 %, KV = 55...60 J and the fracture toughness $K_{mat} = K_{1C}$ = 100...120 MPa$\sqrt{\text{m}}$) and by a law regarding the growth of fatigue cracks of Paris type with two stage crack growth, with $A_1 = 7{,}256 \cdot 10^{-13}$, $A_2 = 2{,}548 \cdot 10^{-8}$, m_1 = 5,855, m_2 = 2,548 and ΔK_{sp} = 33,5 MPa$\sqrt{\text{m}}$ [2], there were obtained by numerical simulation the results synthetically presented in figure 7.

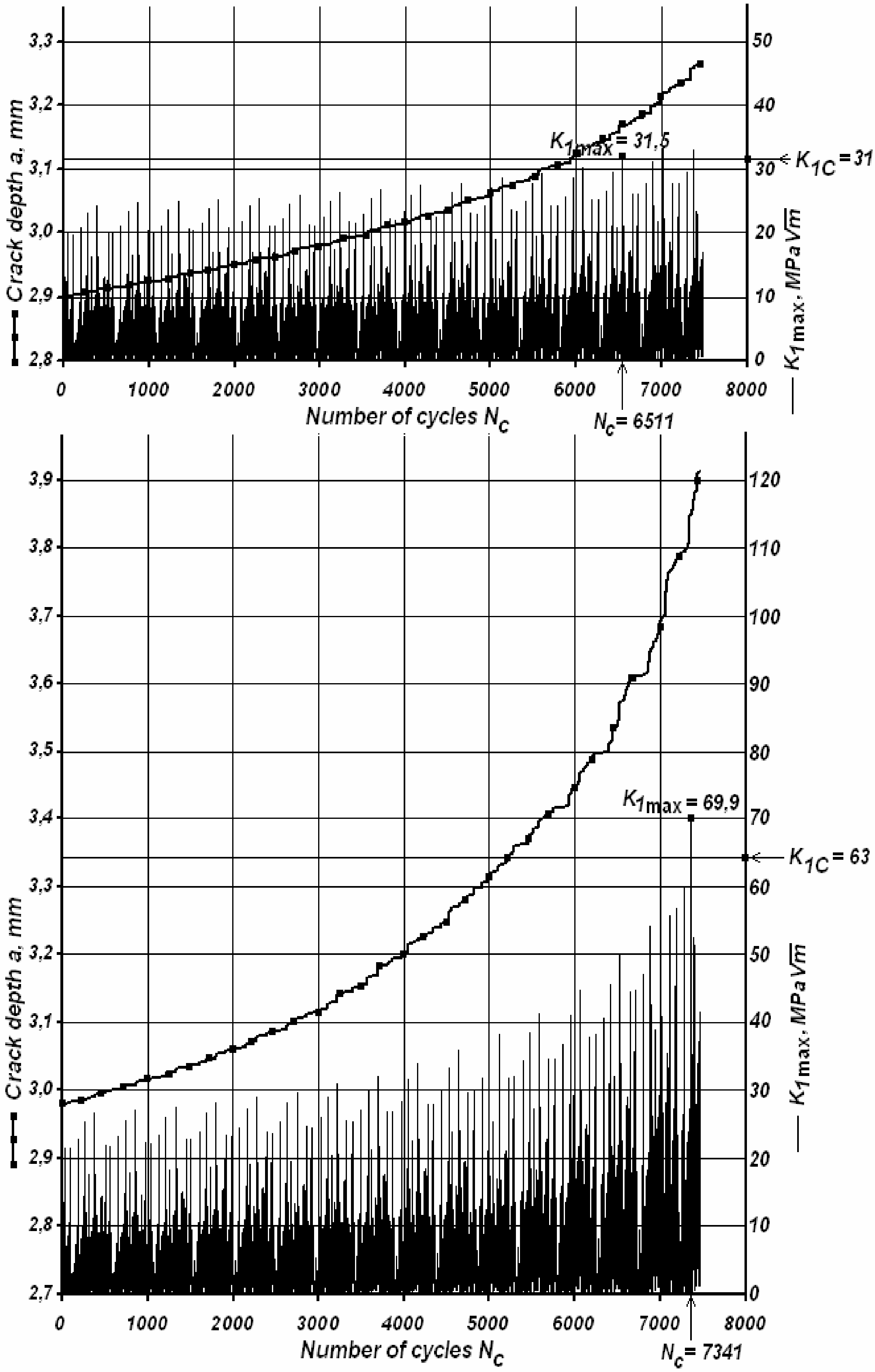

Fig. 6. The results obtained by numerical simulation if the accident L occurs

These results show that the presence of lamination – like flaws in a pipe with good levels of mechanical strength and toughness is less dangerous, the extension of these under the action of pressure variations occurring slower (comparing to the previous case, where the lamination – like flaws existed in a pipe with metallographic structure and inappropriate mechanical properties). The results in figure 7 suggest that the danger of failure due to lamination – like flaws is not removed, only the operating life till the failure of the pipeline that consists of the defective pipe is longer.

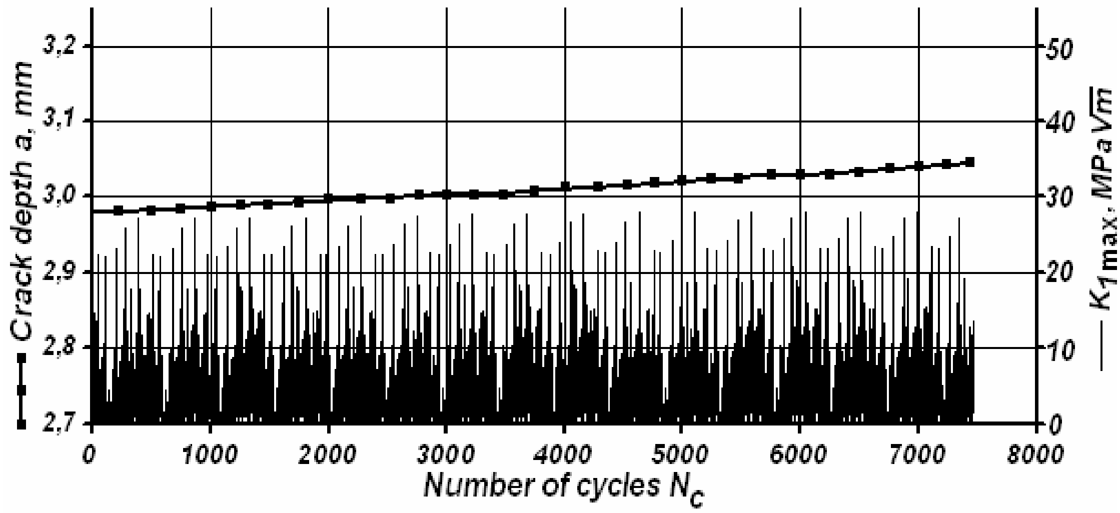

Fig. 7. The results obtained by numerical simulation for the case in which the pipe with lamination-like flaws that generated the accident L would have had a metallographic structure and appropriate mechanical properties

Multiple analyses performed in the same manner for different accident scenarioes presented in figure 2 showed that, usually, under the action of varying load determined by the pressure variations of the conveyed gas, the lamination – like flaws existing in the pipes reach critical sizes, leading to their unstable extension and the explosive failure of these pipes, before they lose their tightness; in other words, in case of pipelines made of pipes with lamination – like flaws there can not be usually fulfilled the premises of a „leak before break" behaviour, that could allow the possibility to detect gas leakages and to perform some maintenance works before the defective pipes experience the explosive failure.

Conclusions

The work, aiming to describe the threat / danger represented by the presence of lamination – like flaws in the pipes natural gas transmission pipelines are made of, led to the following conclusions:

- The lamination – like flaws are local planar crack – like defects, of some decohesion areas or some structural formations of significant brittleness, generated during the process of manufacturing the rolled strips the (longitudinally or helically) welded pipes for pipelines are made of, their presence could significantly affect the mechanical strength and the operating life of pipelines.
- The destructive effects of the presence of these flaws in the pipes of pipelines are severe if the steel pipes with such flaws are characterized by low toughness and if the pipelines are subjected to some overpressure varying loads, to major additional loads or to varying loads determined by cyclic variations, of high amplitude, of the pressure of conveyed gas.

➢ The algorithm and the software conceived by the authors of this work are useful tools for the numerical simulation of the in-service behaviour of pipelines made of pipes with lamination – like flaws. Using these in the analysis of some accidents that occur on such pipelines showed that, under the action of pressure variations of the conveyed gas: a) the lamination – like flaws extend slowly and hardly reach critical sizes when their unstable propagation takes place and the failure of pipelines occur, if the toughness of the steel the pipes are made of is high enough; b) the pipes with lamination – like flaws reach the explosive failure condition before they lose their tighntness, in other words if the premises of a „leak before break" behaviour can not be fulfilled, that could make it possible to detect gas leakages and to perform maintenance works before the pipeline fails.

➢ For diminishing the risk associated to the operating of the natural gas transmission pipelines it is necessary while constructing these pipelines to thoroughly verify the quality of the pipes used, paying special attention to the detection and the removal of pipes with lamination – like flaws and with inadmissible deviations from the pre-requisites regarding the structure and the mechanical strength and toughness properties.

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Evaluarea impactului defectelor de laminare asupra siguranței în funcționare a conductelor de transport al gazelor naturale

Rezumat

Lucrarea evidențiază, prin analiza cauzelor unor accidente tehnice, pericolul reprezentat de prezența defectelor de tip delaminare în țevile din oțel ale conductelor destinate transportului gazelor naturale şi prezintă o metodă de simulare numerică a procesului prin care aceste defecte se pot extinde şi pot determina cedarea explozivă, de multe ori însoțită de incendii, a acestor conducte. Lucrarea evidențiază, de asemenea, că gravitatea defectelor de tip delaminare ale țevilor pentru conductele destinate transportului gazelor naturale este în directă corelație cu caracteristicile de rezistentă mecanică şi tenacitate ale oțelului din care sunt realizate țevile şi cu particularitățile regimului de operare a conductelor, în principal cu frecvența şi amplitudinea fluctuațiilor de presiune ale gazelor transportate.