RELATIONS BETWEEN MECHANICAL AND FRACTURE - MECHANICAL PROPERTIES OF LINEPIPE MATERIALS

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1. Introduction

Mechanical properties, namely the yield stress ($R_{p0,2}$ or $R_{t0,5}$) and ultimate tensile stress R_m, are very important for pipes since they determine the strength reliability of pressure pipelines, especially gas pipelines [1]. Because the operational hoop stress σ_φ in a pipeline is a percentage of the yield stress, high yield stress materials allow higher stresses, and hence higher pressures to be applied in a particular pipeline. An increased allowable hoop stress in a pipeline means that for a given pressure of transported medium a bigger diameter of the linepipe can be used.

During a few last decades new gas pipeline materials were developed, starting from steel CSN 411378 with the yield stress $R_{t0,5} \approx 300$ MPa, through L360MB, L415MB, L450MB to L485MB with the yield stress $R_{t0,5}$ exceeding 485 MPa. The latter steel is so far the top steel in the assortment of the steels manufactured at the Arcelor Mittal Ostrava, a.s., Czech Republic for gas pipelines.

2. Mechanical Properties of Gas Linepipe Materials

As far as we confine ourselves to the yield stress and ultimate tensile stress of gas linepipe materials we can describe their variations during the three basic technological stages of pipe manufacture: (i) the rolled-out sheet, (ii) the roll-bent and spirally welded-up pipe, and (iii) the pipe subjected to final pressurization to the level approximately 0,95 $R_{p0,2}$ for about 45 seconds. The results of mechanical tensile tests for various materials are presented on Fig.1 and Fig.2.

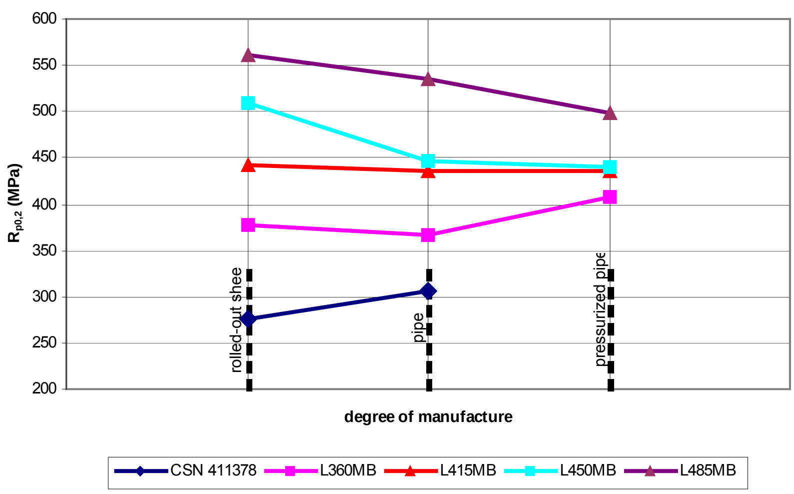

Fig.1 Variation of the yield stress $R_{p0,2}$ during manufacture of pipes from various materials

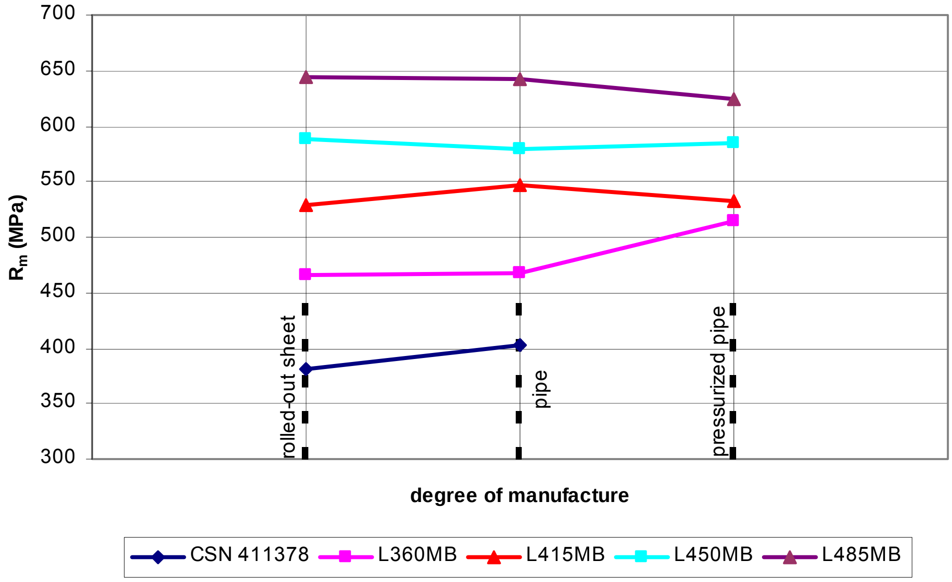

Fig.2 Variation of the ultimate strength R_m during manufacture of pipes from various materials

As can be seen from Fig.1 the roll-bending of the rolled-out sheet and welding-up of contacting edges leads to a small decrease of the $R_{p0,2}$ magnitude, except the lowest strength steel CSN 411378 where a certain increase of $R_{p0,2}$ was observed. The biggest decrease of the yield stress $R_{p0,2}$ was found for L450MB steel. The pressurization of the pipes improved the $R_{p0,2}$ quantity for L360MB steel but reduced it for the L485MB steel, whilst leaving it almost unchanged for the steels L415MB and L450MB. Unfortunately the data for CSN 411378 steel are missing. The ultimate tensile strength during roll-bending of the rolled-out sheet and welding-up the contacting edges did not exhibit expressive changes (see Fig.2). A small increase can be observed for steels CSN 411378 and L415MB and a very slight decrease for the highest strength steels, i.e. L485MB and L450MB. The pressurization of the pipes led to an expressive increase for the L360MB steel and a small decrease for L415MB and L485MB steels, whilst that for L450MB remained practically unchanged.

Coming back to Fig.1, the final magnitudes of the yield stress $R_{p0,2}$ keep an increasing sequence for higher strength grades of the steels, although the difference of the $R_{p0,2}$ values for steels L415MB and L450MB is very small. On the other hand, it is necessary to say that the $R_{t0,5}$ quantities, which are decisive for grading the steels, strictly comply with the condition that the actual $R_{t0,5}$ magnitude is equal or greater than the number specified in the steel designation.

3. Fracture Properties of Gas Linepipe Materials

Fracture-mechanical properties of materials can be characterized with a sufficient generality by their fracture toughness, determined by magnitudes of the J integral: J_{in}, $J_{0,2}$ and/or J_m, where J_{in} is the so called initiation magnitude for a stable subcritical crack growth, $J_{0,2}$ is the magnitude of the J integral corresponding to the real crack extension upon monotonic stable loading $\Delta a = 0.2$ mm and J_m is the magnitude of the J integral which corresponds to the attainment of the maximum force on the „force – force point displacement" curve. For illustration, such a curve is plotted on Fig.3 for one of the compact tension specimens taken from pressurized pipe made from steel L450MB.

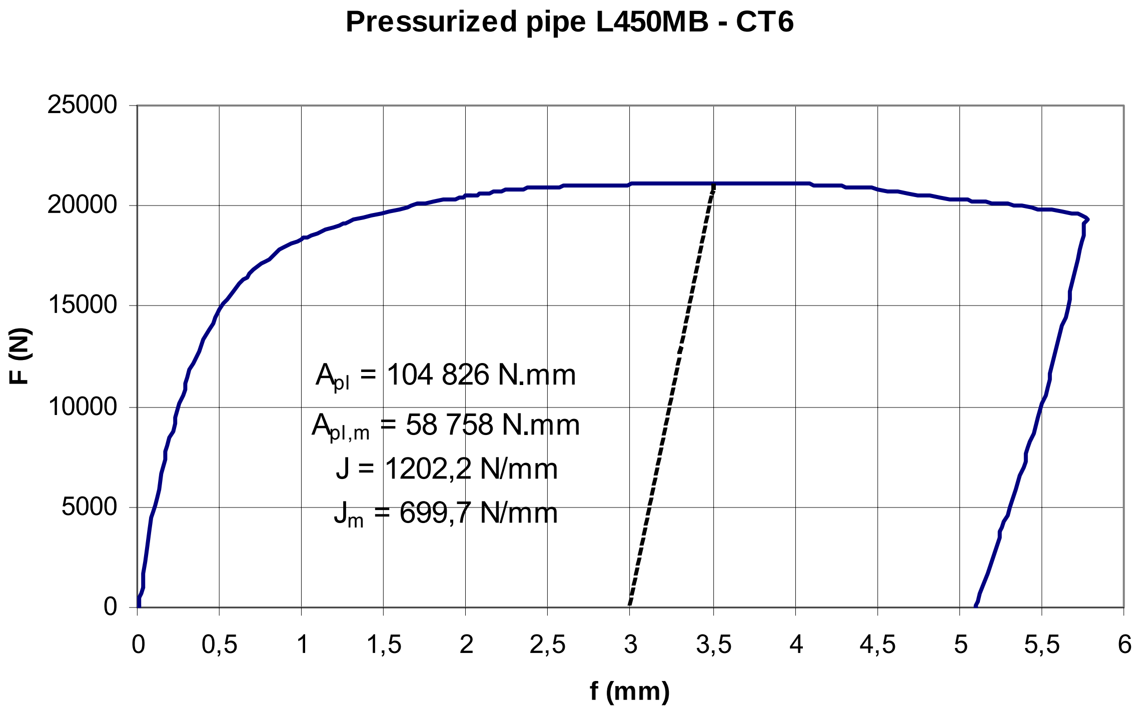

Fig.3 The „force – force point displacement" curve for the specimen CT6 (pressurized pipe, axial crack direction)

With a reference to Fig.3 the J integral can be calculated by the formula:

$$J = \frac{K^2}{E} + \frac{A_{pl}}{t.(w-a)} f_{(a/w)} \qquad (1)$$

When the magnitude of the J integral J_m is concerned, the quantity A_{pl} in the equation (1) is substituted by $A_{pl,m}$, where A_{pl} is the area under the full F-f curve, whilst $A_{pl,m}$ is only the area bounded by the part of the F-f curve limited by the maximum force and the dotted line parallel with the elastic part of the F-f curve. If the load point displacement f is sufficiently high a stable crack extension Δa occurs. If the J integral is plotted against the crack extension Δa, a so called R curve can be obtained. This is done by drawing a parabola

$$J = c_1 \left(\Delta a\right)^{c_2} \qquad (2)$$

where c_1 and c_2 are constants, through experimental points (Δa , J) using the least-squares method. As an example, the R curve for the pressurized pipe from L450MB steel is presented on Fig.4.

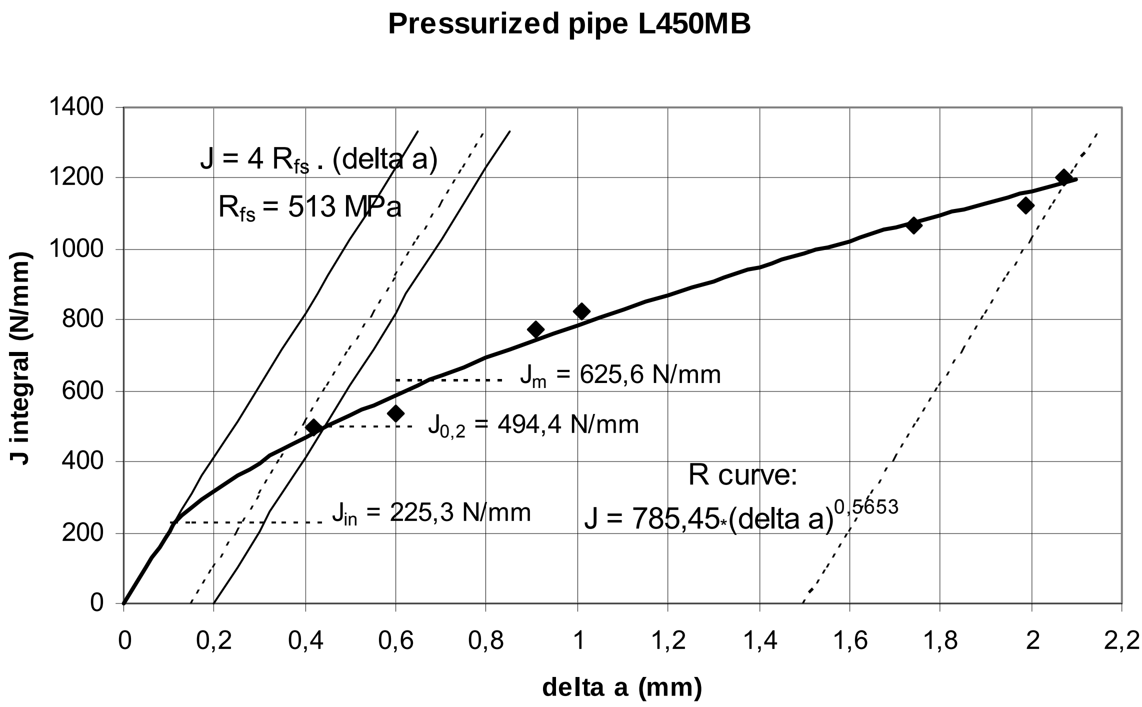

Fig.4 R curve for a pressurized pipe
(crack in the axial direction)

Besides the R – curve there is also plotted the so called „blunting line“, which expresses an apparent crack extension due to blunting of the crack tip. The slope of this straight line is taken here as 4 R_{fs} , where R_{fs} is the flow stress, taken as an average of the yield stress and the U.T.S. Normally it is recommended to take the slope of the blunting line as 2 R_{fs} , but, on the other hand, it is well known [2] that the equation of the blunting line proceeds from the relation $J = M \cdot \delta \cdot R_{fs}$, where the factor M depends on the $R_{p0,2}/E$ ratio and the Ramberg-Osgood hardening exponent n and, as a rule, it varies between one and three. If we consider the mean value M=2, then we obtain the slope 4 R_{fs}. The intersection of the blunting line with the R curve determines the initiation magnitude of the J integral J_{in} for a stable subcritical crack growth. Parallely with the blunting line there are also plotted by dotted lines two offset lines: 0.15mm and 1.5mm which bound the valid values of experimental (Δa , J) points. Except of these there is also plotted a parallel line with the blunting line in the distance

0.2mm. The intersection of the R - curve with this line determines the J integral $J_{0,2}$. Magnitudes of the J integrals , frequently considered as fracture toughness of material, namely J_{in} , $J_{0,2}$ and J_m , are indicated by horizontal dotted lines.
Similar R – curves can be constructed for other gas linepipe materials as ČSN 411378, L360MB, L415MB and L485MB - the top gas linepipe material from the assortment of the Arcelor Mittal Ostrava, a.s. The summary results of fracture toughness parameters of pressurized pipes made from these materials are presented on Fig.5.

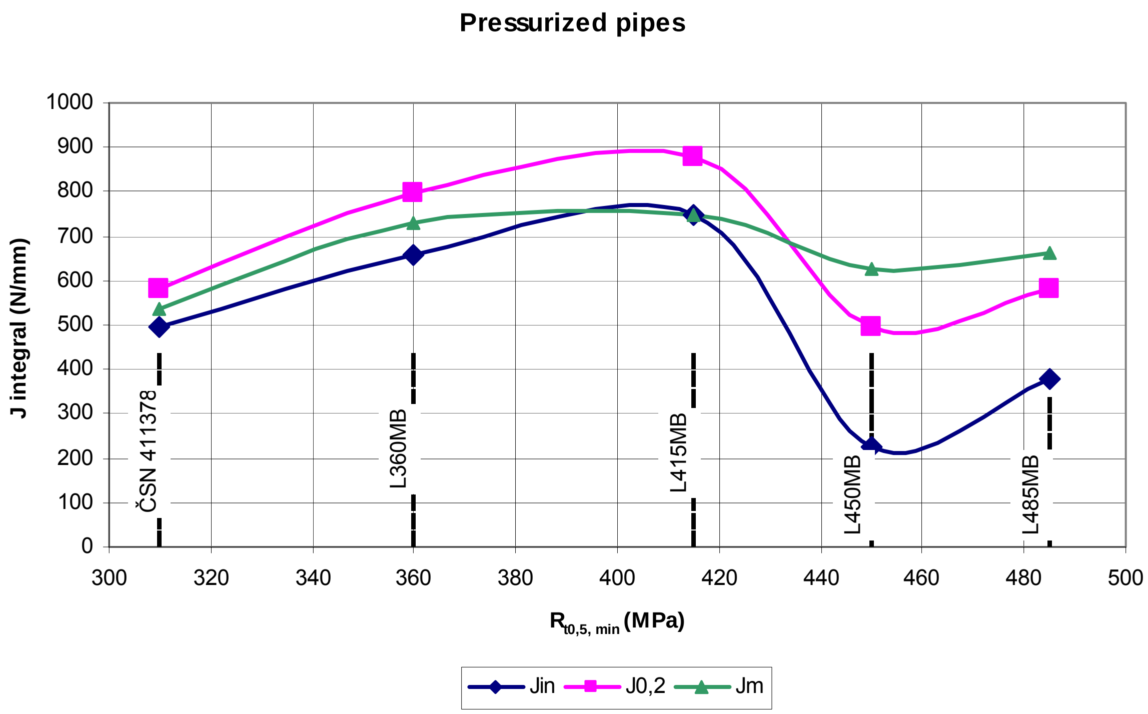

Fig.5 Dependence of the fracture toughness characteristics on the yield stress for pressurized pipes

As it follows from this figure, the fracture toughness parameters exhibit an increasing trend up to the yield strength ~ $R_{t0,5}$ = 415 MPa. For greater yield strengths than 415 MPa the fracture toughness characteristics decrease reaching minimum values for the yield strength approximately $R_{t0,5}$ = 450 MPa . The biggest values of the fracture toughness parameters are those exhibited by the $J_{0,2}$ parameter up to about $R_{t0,5}$ = 430 MPa. For greater yield strengths it is then the J_m parameter which exhibits the biggest magnitudes. The lowest magnitudes of the fracture toughness parameters are those exhibited by the J_{in} parameter, this being valid practically for the whole range of the yield strengths investigated. This is very important from the viewpoint of choosing a suitable fracture toughness parameter for prediction of fracture conditions. It can be stated that from the viewpoint of fracture resistance the most suitable material for manufacture of gas linepipes is steel L415MB because it exhibits both good static strength characteristics and high magnitudes of the fracture toughness.

4. Relation between mechanical and fracture – mechanical properties of gas linepipe steels

If we look at materials from which pipes for gas pipelines are manufactured then we can make the following sequence of the materials according to their increasing static strength properties:

ČSN 411378 → L360MB → L415MB → L450MB → L485MB

The corresponding magnitudes of the yield stress $R_{t0,5}$ form the following sequence:

310 MPa → 360 MPa → 415 MPa → 450 MPa → 485 MPa

The highest stress in a pipe wall is the hoop stress σ_φ which is given by the relation:

$$\sigma_\varphi = \frac{p\,D}{2t} = \lambda\,R_{t0,5} \qquad (3)$$

where λ is the so callled design factor. For transmission gas pipelines it is $\lambda = 0{,}72$. As for the diameter to wall thickness ratio D/t we have made an investigation into this ratio for 13 pipelines of various dimensions and materials. The results are presented on Fig.6.

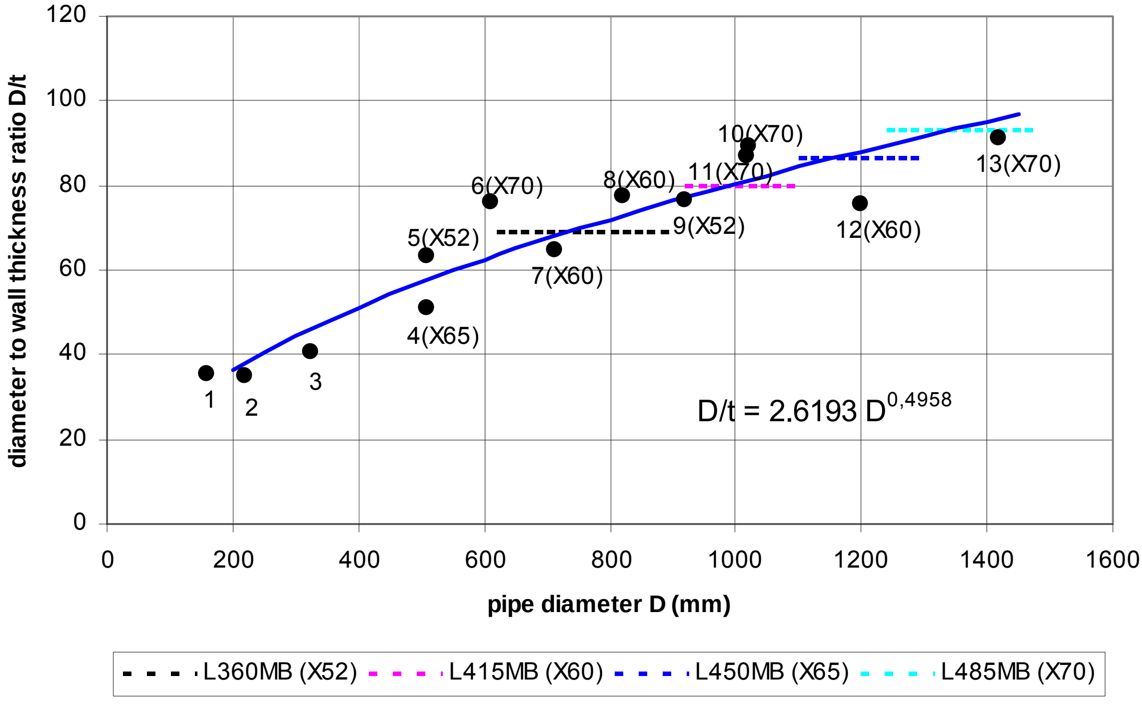

Fig.6 Variation of the diameter to wall thickness ratio with the pipe diameter

Each pipeline is marked by a number and its material is shown in brackets. The smallest diameter pipelines, marked 1, 2, 3, were made from low-carbon steels and these are not specified on the figure. Specification of other materials is in terms of the API (American Petroleum Institute) specification. This means that X52 corresponds to L360MB, X60 to L415MB, X65 to L450MB and X70 to L485MB. A parabola was drawn through experimental points using the least – squares method and its equation obtained the form

$$\frac{D}{t} = 2.6192\, D^{0.4958} \qquad (4)$$

Equ.(4) can approximately be written as

$$\frac{D}{t} = 2.6\sqrt{D} \qquad (5)$$

Magnitudes of the diameter to wall thickness ratio D/t for steels L360MB, L415MB, L450MB and L485MB, as determined from relation (3) for gas pressure p = 7.5 MPa and design factor $\lambda = 0.72$, are represented at the Fig.6 by colour horizontal dashed lines.

From relations (3) and (5) it follows

$$D = \left(\frac{\lambda}{1.3\,p}\right)^2 R_{t0,5}{}^2 \qquad (6)$$

which shows that for a particular pressure *p* and design factor λ the diameter of the gas linepipe depends on the second power of the yield stress $R_{t0,5}$. For example if we consider gas pressure p = 7.5 MPa and design factor λ= 0.72 then we can arrive at the results presented in Tab.1.

material	**D (mm)**	**t (mm)**	**σ_φ (MPa)**	**$R_{t0,5}$ (MPa)**	**$\lambda = \sigma_\varphi / R_{t0,5}$**
L360MB	700	10.2	257.4	360	0.72
L415MB	930	11.7	298.1	415	0.72
L450MB	1 100	12.8	322.3	450	0.72
L485MB	1 280	13.8	347.8	485	0.72

Tab.1 Dimensions and stresses regarding various materials of gas pipelines

The wall thickness *t* for each material was calculated according to equation (5). The magnitudes of dimensional quantities of gas pipelines from various materials correspond to the above mentioned pressure (7.5 MPa) and design factor (0.72). Decreasing the diameter D and increasing the wall thickness means lowering the design factor λ and improving thus the safety of a pipeline. From Table 1 it is seen that the development of steels for gas pipelines goes up to higher magnitudes of the yield stress, because higher yield stress enables to apply higher operational pressures of the gas or to allow bigger diameters of pipes for a particular pressure.

Now we can put a question: What requirements follow from this trend for the fracture toughness of the gas linepipe steels? It is clear that fracture toughness determines critical fracture parameters (fracture pressure, crack size) so that there should be an endeaver to make the fracture toughness sufficiently high to prevent fracture of the pipeline. The relations shown above ensure a reliable operation of a gas pipeline as far as there is no crack in the pipe wall. When a crack appears in the wall and its dimensions enable its fatigue growth then it is very likely that a critical crack depth is reached after some time of operation and the ligament bellow the part-through crack breaks. In this moment the through crack can either become stationary or it can move in compliance with the leak-before-break criterion (LBB) [3]. This criterion says that crack moves unstably as far as the fracture toughness of pipeline material is less than the fracture parameter, e.g. the stress intensity factor K_I or the J integral J. It means that

crack does not propagate when $$K_I \le K_c \quad or \quad J \le J_c \tag{7a}$$

crack propagates unstably when $$K_I > K_c \quad or \quad J > J_c \tag{7b}$$

The stress intensity factor for a through crack in a pipe can simply be calculated by the formula

$$K_I = M_T \, \sigma_\varphi \sqrt{\pi \, c} \tag{8}$$

where c is the effective half-length c_{eff} of the through crack according to Fig.7 and

$M_T = \sqrt{1 + 1.255\,\lambda^2 - 0.0135\,\lambda^4}$ is the so called Folias correction factor with

$\lambda = \dfrac{c}{\sqrt{R\,t}}$, where R is the pipe mean radius

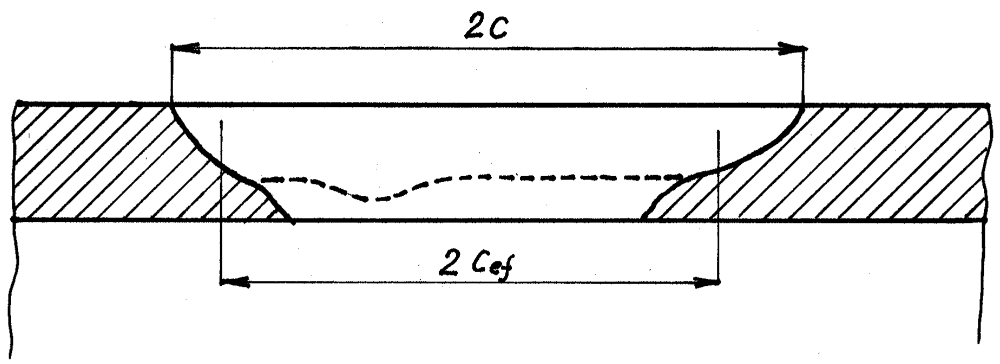

Fig.7 Schematic representation of the through crack in a pipe wall

The J integral of the through crack can be calculated by the engineering GS formula [4]:

$$J = \frac{K^2}{E'}\left[1 + \frac{2\alpha n}{(n+1)}\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right] \qquad (9)$$

where α, n, σ_0 are the Ramberg – Osgood constants and K is the stress intensity factor given by equ.(8).

When the LBB criterion is not fulfilled , i.e. the condition (7b) is valid, the crack can either move for a long distance (until it reaches a different material of higher fracture toughness or it enters a pipe with a greater wall thickness) or it can stop in a short distance, e.g. in the length of a single pipe [5]. The first alternative takes place when the fracture toughness K_c is less than its minimum level K_c^* for arresting a propagating crack. When the fracture toughness K_c is greater than this minimum value the other alternative takes place, i.e. the crack stops in a short distance. The greater the fracture toughness the shorter the distance of the crack arrest. The situation is schematically shown on Fig.8.

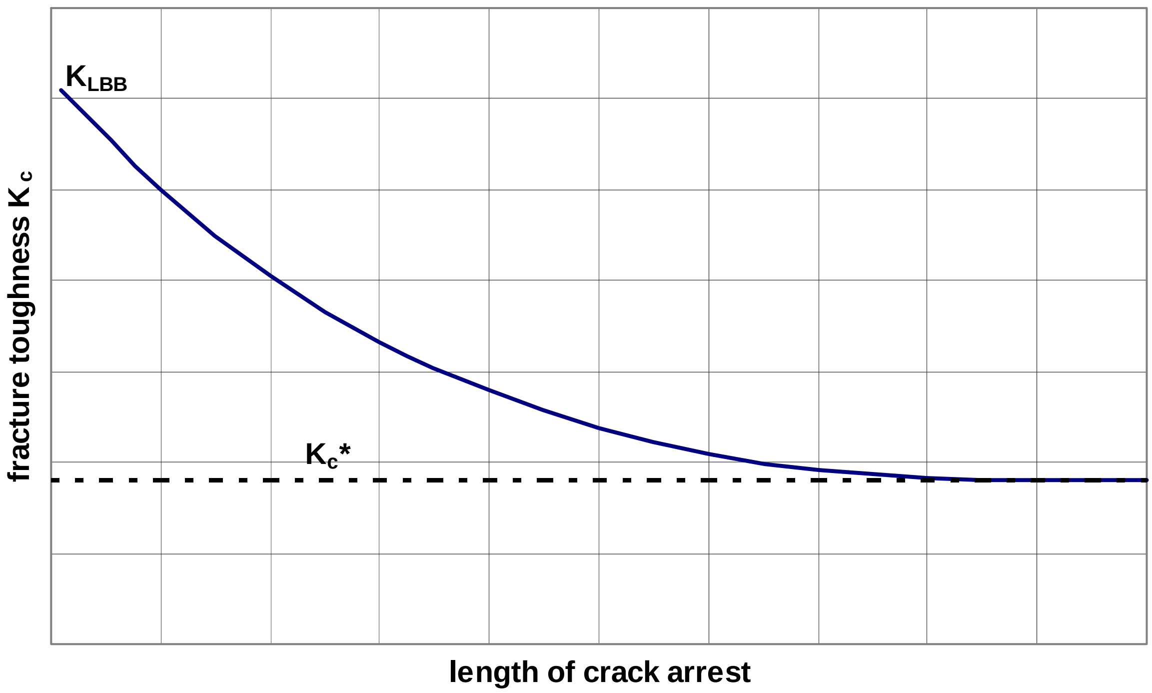

Fig.8 Variation of the fracture toughness with the length of crack arrest

This figure clearly shows that starting with the fracture toughness at the level K_{LBB} (meeting the LBB criterion) for the length equal to the critical crack length $2c_{crit}$ (for a given pressure p) the fracture toughness K_c gradually decreases with an increased length of crack arrest. For $K_c < K_c^*$ there is no crack arrest at all. From this point of view the limit fracture toughness K_c^* for arresting propagating crack becomes a very important characteristic [6]. As a matter of interest we shall derive an approximate formula for determination of the limit fracture toughness K_c^* . We shall start with an empirical relation of AISI (American Iron and Steel Institute) for the minimum impact work on 2/3 thickness Charpy specimens which is necessary to arrest running ductile (shear) fracture [7]:

$$KV_{2/3} = 2.377\,x10^{-4}\,\sigma_{\varphi}^{\,1.5}\sqrt{D} \qquad (10)$$

From relation (10) the notch toughness KCV [J/cm^2] can be determined as

$$KCV = \frac{KV_{2/3}}{0.8x0.667} = 1.875xKV_{2/3} \qquad (11)$$

While notch toughness test is dynamic in nature and K_c tests are static the fact that loading rate and notch sharpness effects on the upper shelf of the transition curve are not very significant entitles us, to some extent, to use the empirically established relationship of Rolfe, Novak and Barsom [8] between the fracture toughness K_c and the notch toughness KCV for V-notch Charpy specimens

$$\left(\frac{K_c}{R_e}\right)^2 = 0.517\frac{KCV}{R_e} - 0.00635 \qquad (12)$$

This relationship is adjusted to units K_c [MPa√m], R_e [MPa], and KCV [J/cm^2] commonly used.

By substituting KCV in equ.(12) with KCV given by (11), identifying K_c with K_c^* and considering relations (3) and (6) it can be arrived at the following expression

$$K_c^{\,*} = R_e\sqrt{2.304x10^{-4}\lambda^{1.5}\left(DxR_e\right)^{0.5} - 6.35x10^{-3}} \qquad (13)$$

It is seen that the limit fracture toughness for arresting a propagating crack K_c^* increases with pipe diameter D, yield stress R_e and design factor λ . For illustration, the variation of fracture toughness K_c with the length of arresting a crack is shown on Fig.9 for two pipelines: (i) D = 700 mm from steel L360MB, and (ii) D = 1 280 mm from steel L485MB. It is considered that the gas pressure is p = 7.5 MPa and the initial crack length at the instant of crack instability is 2c = 200 mm. The fracture toughness K_{LBB} is something over 300 MPa√m for both pipelines.

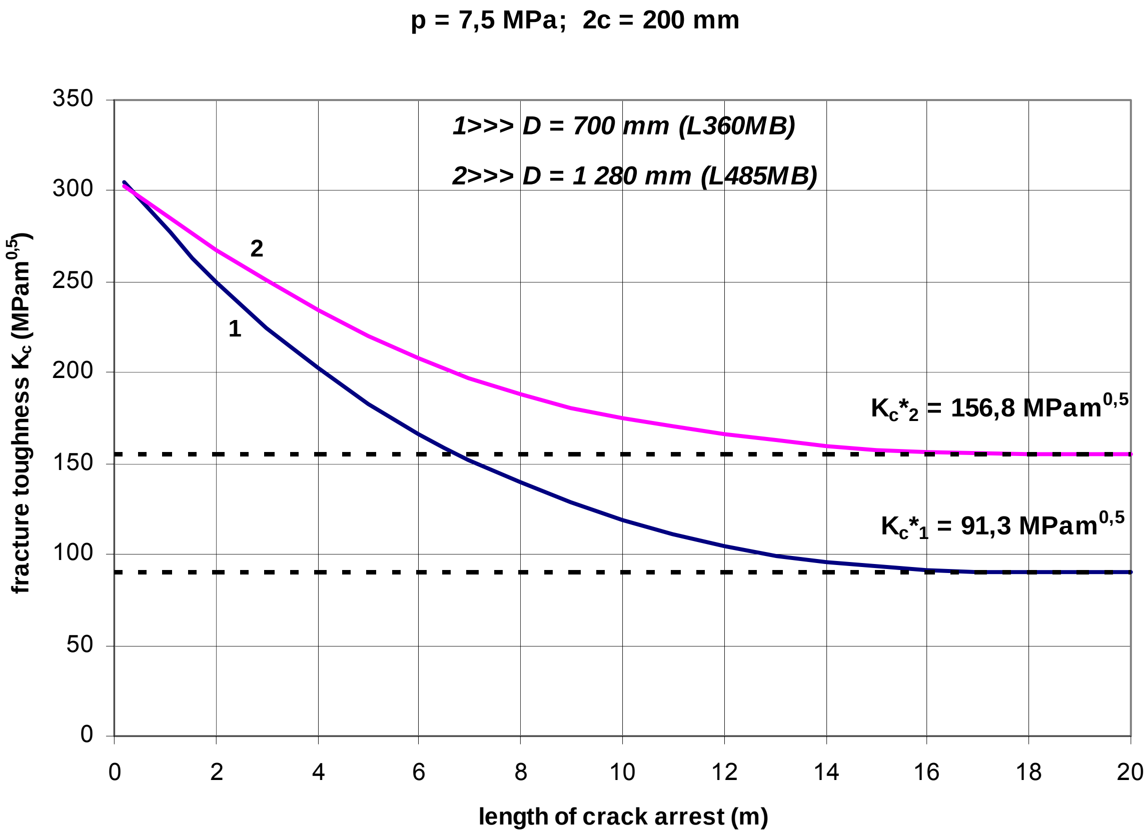

Fig.9 Variation of the fracture toughness for arresting a crack on the length of arrest for two different gas pipelines

The diagrams on the figure show that the decrease of the fracture toughness is greater for the smaller diameter of the linepipe and the fracture toughness itself reaches a smaller limit value K_c^* (91.3 MPa√m) than for the bigger diameter linepipe (156.8 MPa√m).
A very important dependence can be obtained if $(D \times R_e)^{0.5}$ in the relationship (13) is substituted by $\frac{\lambda}{1.3p} R_e^{1.5}$ which comes from equ.(6). Then we can obtain the following expression

$$K_c^* = R_e \sqrt{1.407x10^{-4} \frac{\lambda}{1.3p} R_e^{1.5} - 6.35x10^{-3}} \qquad (14)$$

This relationship gives us a dependence between the limit fracture toughness K_c^* for arresting a crack and the yield stress R_e (or $R_{t0,5}$) for a given gas pressure p and design factor λ . This dependence is presented on Fig.10 for the gas pressure p = 7.5 MPa and the design factor λ = 0.72.

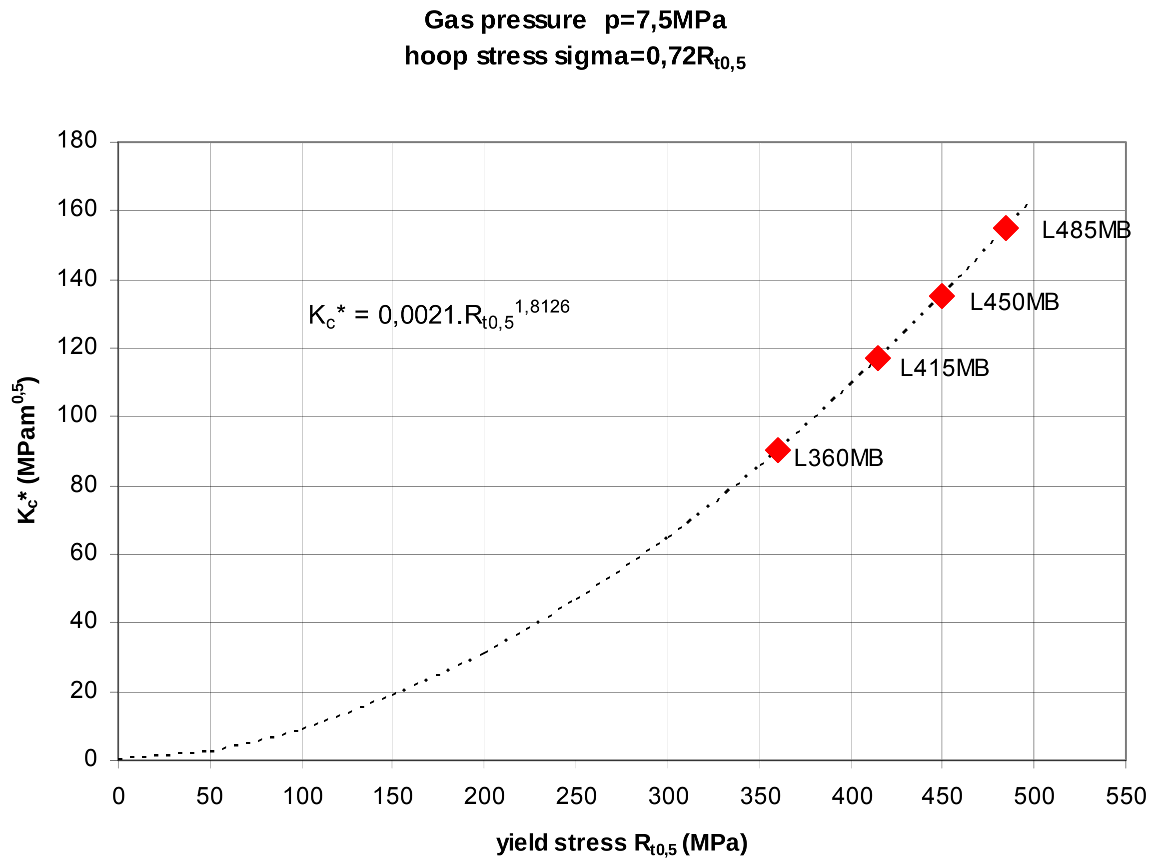

Fig.10 The required limit fracture toughness for arresting a propagating crack K_c^* in relation to the yield stress $R_{t0,5}$ of the pipe material used

The figure clearly demonstrates that for a safe operation of a gas pipeline (preventing an unstable crack propagation for a long distance in case the LBB criterion is not observed) it is necessary for the limit fracture toughness K_c^* to be increased as the yield stress of pipe material is increased. The K_c^* - $R_{t0,5}$ dependence corresponds to almost the second power of the yield stress.

Recalling the Fig.5 we can see that in practice this is not exactly a case. The fracture toughness for statically stronger steels (L450MB and L485MB) is found to be smaller than that for steels of a lower yield stress (L415MB, L360MB). It follows from here that for pipelines made from high yield stress steels there is a higher risk of unstable crack propagation when the LBB criterion is not met. The operators of gas pipelines should keep this in mind and should therefore ensure regular NDT inspections of the pipelines.

5. Conclusions

An investigation into mechanical and fracture – mechanical properties of gas linepipe steels covering the range from CSN 411378 to L485MB made it possible to draw the following conclusions:

a) Static strength properties of pipes made from these steels varied during the process of their manufacture, the variation of the yield stress being more expressive than that of the U.T.S. The final product of pipe manufacture – pressurized pipes – satisfied the requirements of the standards. It can roughly be said that pressurization of pipes – realized for reducing residual stresses in the pipes – led to some improvement of the yield strength and partly of the U.T.S. for low yield stress pipes, whilst for high yield stress pipes the pressurization led to some worsening of these properties.

b) For ensuring a reasonable exploitation reliability of gas pipelines containing crack – like defects in the pipe wall the fracture toughness of the pipe material should be increased as the yield stress is increased. To prevent unstable ductile crack propagation in the pipeline for a long distance the increase in the fracture toughness should approximately be quadratic with the yield stress. In reality this does not hold for high yield stress materials (starting approximately with the yield stress $R_{t0,5}$ = 430 MPa) so that for these high yield stress materials there is a higher risk of unstable crack propagation when the leak-before-break criterion is not met. This calls for regular NDT inspection of gas pipelines, especially those which are made from statically stronger steels.

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