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Assessment of the Remaining Strength Factor for Pipelines Subject to Local Metal Loss

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Abstract

This paper presents a procedure for determining the remaining strength factor (RSF) for pipelines that have components subject to local metal loss. The demands from API 579-1/ASME FFS-1 regarding the characterisation of the flaws' gravity by using the minimum value of RSF are respected by applying the procedure proposed by the authors. The case studies presented in the paper lead to the conclusion that, for an operative and sufficient level of confidence evaluation of pipelines with this type of flaws, the RSF value calculated by considering the profile and real dimension of the detected flaws can be utilized, and that the decision of applying the laborious method for determining the minimum value of RSF, recommened by API 579-1/ ASME FFS-1, is not always justified.

Key words: *pipeline, local metal loss, Remaining Strength Factor – RSF*

Introduction

Local metal loss type flaws, that consist in the general or local thinning of the pipeline metallic wall, by metal loss, due to corosion or erosion processes (Local Thin Area – LTA, Pittings – PIT, Grooves – GRO, Gauges – GAU), are the most important cause of the pipelines' failure during exploitation [1-3]; for example, approximately 85% of the failures recorded in that last 10 year on the pipelines of the national system of transport of natural gases are caused by this type of flaws.

If, at the periodic evaluation of a pipeline, local metal loss type flaws are detected, it is imposed to evaluate the remaining strength and the remaining life of the pipeline. The first step of the assessment consists of investigating the pipelines' area and completing a recording/measurement card for each of the detected flaws, that has to contains the following categories of information [4, 5]:

a) the characteristic dimensions of the pipeline area: the outside diameter, nominal thickness (design thickness) of the pipeline's wall t_n and the efective thickness t (real, measured) of the wall outside the flaw area;

b) the flaw dimensions: the axial/longitudinal extent s_p, also named the flaw's length and the circumferential/transversal extent c_p, also named the flaw's width;

c) the measurement plan of the wall thickness in the flaw area, that, as can be seen in Figure 1, mentions the number and positions of the axial (numbered A_k, with k = 1 ... n_{pa}) and transversal (numbered C_j, with j = 1 ... n_{pc}) inspection plans, and the number ($N = n_{pca}n_{pa} \geq 15$) and positions of the nodes, where the thickness measurement are taken;

d) the results of measuring the thickness wall t_i, i = 1 ... N, in all the N nodes of the plane inspection network.

The results from the measurement/recording card of a flaw are utilized for:

a) determining the critical thickness profiles – CTP, on the axial direction (by projecting the minimum values of t_i , established in each circumferential plan $C_{j,}$ on one of the A_k plans), as is shown in Figure 1;

b) the processing of statistic results of the wall thickness measurements in the flaw area and determing the mean, the standard deviation, the variance, and the coeficient of variation of the wall thickness values t_i, i = 1 ... N, using the equations:

$$t_{am} = \frac{\sum_{i=1}^{N} t_i}{N} \; ; \; t_{sd} = \sqrt{\frac{\sum_{i=1}^{N} (t_i - t_{am})^2}{N-1}} \; ; \; COV = \frac{t_{sd}}{t_{am}} \; ; \tag{1}$$

if $COV \leq 0.1$, then the flaw is considered to be a local thin area, with a constant wall thickness t_{am} (or, if a conservative assessment is need, the value $t_{mm} \cong t_{am}$, t_{mm} = min[t_i, i = 1 ... N]), and if $COV > 0.1$, the assessment will consider the real configuration of CTP.

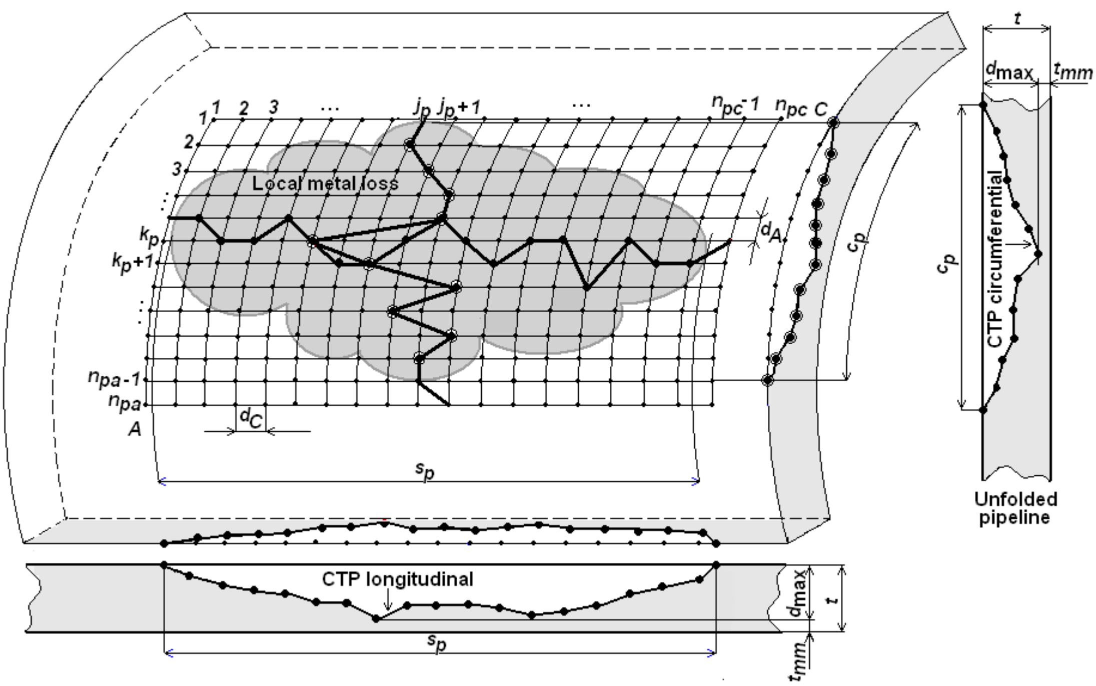

Fig.1. The measurement plan and construction of critical thickness profile in an area with local metal loss

Determining the Remaining Strength Factor for Pipelines with Flaws

The procedures recommended by [4, 5] predict that the assessment of a pipeline with local metal loss will concentrate in the first step on the longitundal extent of CTP in the flaw area and will lead to the determination of the remaining strength factor for a pipeline with flaw.

If the detected flaw is characterised by a value $COV > 0.1$, RSF has to be determined with equation [4]:

$$RSF = \min\left[\frac{1-\frac{A_{d,i}}{A_{0,i}}}{1-\frac{1}{M_{t,i}}\frac{A_{d,i}}{A_{0,i}}}; i = 1...n_d\right], \tag{2}$$

where the areas $A_{d,i}$ şi $A_{0,i}$ are defined for a sequence of divisions of the CTP ($i = 1...n_d$), selected by considering the indications from Figure 2, and $M_{t,i}$ is the (Folias) factor for weakening of the pipeline due tu to the presence of a flaw with lenght corresponding to subdivision $i = 1...n_d$ of CTP, that can be established with the following equation:

$$M_{t,i} = \sum_{j=0}^{10} C_j \lambda_i^j = \sum_{j=0}^{10} F_j s_{p,i}^j, \ i = 1...n_d \tag{3}$$

where $s_{p,i}$ is the length of subdivision $i = 1...n_d$, C_j, $j = 1...10$ are constant, having the values mentioned in Table 1, and λ_i and F_j are defined by the following equations:

$$\lambda_i = \frac{1,285 s_{p,i}}{\sqrt{D_e t}} = \beta_p s_{p,i}, \ i = 1...n_d; \ F_j = C_j \beta_p^j, j = 1...10. \tag{4}$$

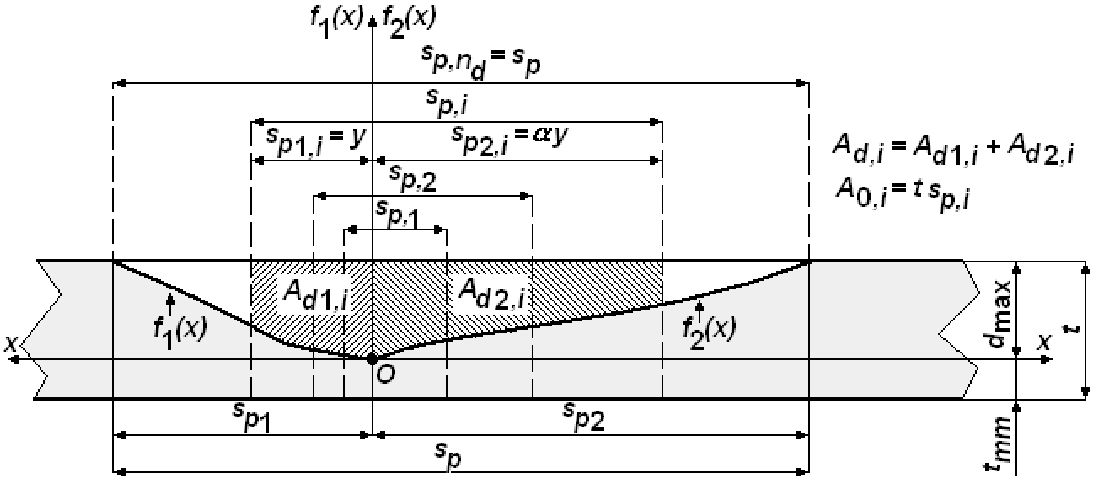

Fig. 2. CTP division for determining RSF for a pipeline with flaw

Table 1. The values of the constants from the analytical expression of the Folias Factor

C_0	C_1	C_2	C_3	C_4	C_5
1.0010	$-1.4195\cdot10^{-2}$	$2.9090\cdot10^{-1}$	$-9.6420\cdot10^{-2}$	$2.0890\cdot10^{-2}$	$3.0540\cdot10^{-3}$

C_6	C_7	C_8	C_9	C_{10}
$2.9570\cdot10^{-4}$	$1.8460\cdot10^{-5}$	$7.1553\cdot10^{-7}$	$1.5631\cdot10^{-8}$	$1.4656\cdot10^{-10}$

If the detected flaw is a local thin area ($COV \leq 0.1$), the equation for RSF has the simple form:

$$RSF_{LTA} = \frac{1-\frac{d_{\max}}{t}}{1-\frac{1}{M_{t,n_d}}\frac{d_{\max}}{t}}, \tag{5}$$

where $d_{\max} = t - t_{am}$ (or, for a conservative assessment, $d_{\max} = t - t_{mm}$).

For determining *RSF* by using equation (2), the authors proposed the following procedure, easy to implement in a technical computer software.

a) drawing on CTP the systems of coordinate axes, as indicated in Figure 2, with the origin O in the transversal plane in which the thickness t_{mm} (and the maximum flaw depth $d_{\max}$) were recorded and dividing the lenght of the defect, s_p, into 2 segments of lenghts s_{p1} and s_{p2}, respectively $(s_p = s_{p1} + s_{p2})$

b) determining the expression for two statistical regression polynomials, that analitically describe the CTP portions found on both sides of the origin O: $f_1(x) = \sum_{i=1}^{m} A_i x^i$ and $f_2(x) = \sum_{i=1}^{m} B_i x^i$; evidently, these function simultaneously satisfy the conditions: $f_1(0) = f_2(0) = 0$ and $f_1(s_{p1}) = f_2(s_{p2}) = d_{\max}$;

c) determining the sequence of subdivisions of CTP ($i = 1...n_d$), each subdivisions (of lenght $s_{p,i}$) being made up of two portions $s_{p1,\,i} = y$ and $s_{p2,\,i} = \frac{s_{p2}}{s_{p1}} y = \alpha\, y$; evidently, this way of choosing the divisions corresponds to the conditions $n_d \to \infty$; $s_{p,i} = (1+\alpha)y$, with $y \in (0\,;\, s_{p1}]$

d) computing the areas $A_{0,i} = t(1+\alpha)y$ and $A_{d,i} = A_{d1,i} + A_{d2,i}$:

$$A_{d1,i} = d_{\max} y - \int_0^y f_1(x)dx = \sum_{i=1}^{m} \frac{A_i}{i+1} y^{i+1} \; ; A_{d2,i} = d_{\max} \alpha y - \int_0^{\alpha y} f_2(x)dx = \sum_{i=1}^{m} \frac{B_i \alpha^{i+1}}{i+1} y^{i+1} \; ; \tag{6}$$

e) writing *RSF* as:

$$RSF = \min\left[RSF(y) = \frac{1 - Q(y)}{1 - \dfrac{Q(y)}{M_t(y)}} ; y \in (1; s_{p1}] \right], \tag{7}$$

$$Q(y) = d_{\max} - \sum_{i=1}^{m} D_i y^i \; ; \; M_t(y) = \sum_{j=0}^{10} F_j y^j \, , \tag{8}$$

where $D_0 = \frac{d_{\max}}{t}$; $D_i = \frac{A_i + B_i \alpha^{i+1}}{(i+1)(1+\alpha)t}$, $i = 1...m$; and $F_j = C_j \beta_p^j$, with $\beta_p = \frac{1{,}285(1+\alpha)}{\sqrt{D_e t}}$;

f) searching for the local extrema of the function $RSF(y)$, in the interval $y \in (0\,;\, s_{p1}]$, between the roots of the equation $RSF(y) = 0$, which is equivalent to:

$$M_t^{/}(y)Q(y)[Q(y)-1] - M_t(y)Q^{/}(y)[M_t(y)-1] = 0 \, , \tag{9}$$

where $M_t^{/}(y)$ and $Q^{/}(y)$ are the derivatives with respect to the variable y of the functions $M_t(y)$ and $Q(y)$;

With the root y_m of equation (9), which corresponds to a minimum of $RSF(y)$ and is found in the interval $(0\,;\, s_{p1})$, the value of the remaining strenght factor $RSF = RSF(y_m)$ is determined.

RSF is a measure of the maximum level of hoop stress that can be generated in the pipeline's wall without the danger of failure in the local metal loss area; in other words, if, when desiging the pipeline, a minimum acceptable level for its resistance was imposed, this level can be defined with an acceptable valued, denoted RSF_a; usually, for pipelines, the used value for RSF_a is 0.9. In conclusion, if the area with local metal loss of a pipeline is characterised by a value $RSF \geq RSF_a$, we can decide to maintain the pipeline, working at the operating pressure level; if $RSF < RSF_a$, there are two options: a) intervening with maintenance work to fix the existing flaw and for reestablish the load capacity of the pipeline; b) keep the pipeline with the flaw operational, but reduce the operational pressure at a p_{od} level:

$$p_{od} = \frac{RSF}{RSF_a} p_c, \tag{10}$$

where p_c is the design pressure of the pipeline (without flaws).

The Results of Several Case Studies Regarding the Determination of RSF

The procedure for determining the *RSF* for pipelines subject to local metal loss was implemented in a MathCAD computational program and was tested for several case studies regarding the evaluation of the remaining strength of areas with local metal loss flaws found on a pipe with D_e = 508 mm and $t_n = t$ = 8.8; all the local metal loss flaws had length s_p = 105 mm, width c_p = 50 mm and maximum depth $d_{\max}$ = 5.5 mm ($t_{mm} = t - d_{\max}$ = 3.3 mm; s_{p1} = 35 mm and s_{p2} = 70 mm; α = 2; β_p = 0.0577), the CTP configuration in the areas where these flaws have been found is described analytically in Table 2 and graphically in Figure 3. The results obtained by applying the procedure for determining the RSF for the areas with flaws are presented in Figure 4 and Table 3.

Table 2. The coefficients of the polynomial functions that describe CTP for the flaws from the case studies

Flaw		**D1**	**D2**	**D3**	**D4***	
f_1(x) coefficients	A_1	$3.63567 \cdot 10^{-2}$	$1.57143 \cdot 10^{-1}$	$3.66686 \cdot 10^{-1}$	$3.63567 \cdot 10^{-2}$	
	A_2	$2.08766 \cdot 10^{-2}$	-	$-6.54685 \cdot 10^{-3}$	$2.08766 \cdot 10^{-2}$	
	A_3	$-8.42340 \cdot 10^{-4}$	-	$-6.43500 \cdot 10^{-5}$	$-8.42340 \cdot 10^{-4}$	
	A_4	$9.83982 \cdot 10^{-6}$	-	$2.29596 \cdot 10^{-6}$	$9.83982 \cdot 10^{-6}$	
$f_2(x)$ coefficients	B_0	-	-	-	-	14.48446
	B_1	$5.11413 \cdot 10^{-2}$	$7.85714 \cdot 10^{-2}$	$3.05014 \cdot 10^{-1}$	$8.25999 \cdot 10^{-2}$	$-9.5483 \cdot 10^{-1}$
	B_2	$1.86513 \cdot 10^{-4}$	-	$-6.12729 \cdot 10^{-3}$	$1.74695 \cdot 10^{-2}$	$2.16010 \cdot 10^{-2}$
	B_3	$2.90577 \cdot 10^{-6}$	-	$4.13901 \cdot 10^{-5}$	$-9.97680 \cdot 10^{-4}$	$-1.4000 \cdot 10^{-4}$
	B_4	-	-	-	$1.26350 \cdot 10^{-5}$	-

* for the D4 flaw, the function $f_2(x)$ has two analytical expressions $f_{21}(x)$ and $f_{22}(x)$, on the domains mentioned in Figure 3.

The results obtained by doing these case studies brought to attention the following aspects regarding the determination of the *RSF* for pipelines with local metal loss flaws:

a) The characterization of the remaining strength of pipelines with flaws using the $RSF_{LTA,}$ value, computed considering $d_{\max} = t - t_{\text{mm}}$ is very conservative and not recommended in cases when the wall thickness in the flaw area leads to values of $COV > 0.1$ (this shows that the flaws can not be considered to be LTA).

b) for pipelines with local metal loss flaws having $COV > 0.1$, RSF_{LTA}, computed considering $d_{\max} = t_{am}$ doesn't always have the possible minimum value, through which the real reduction of the load capacity determined by the existence of flaws can be appreciated;

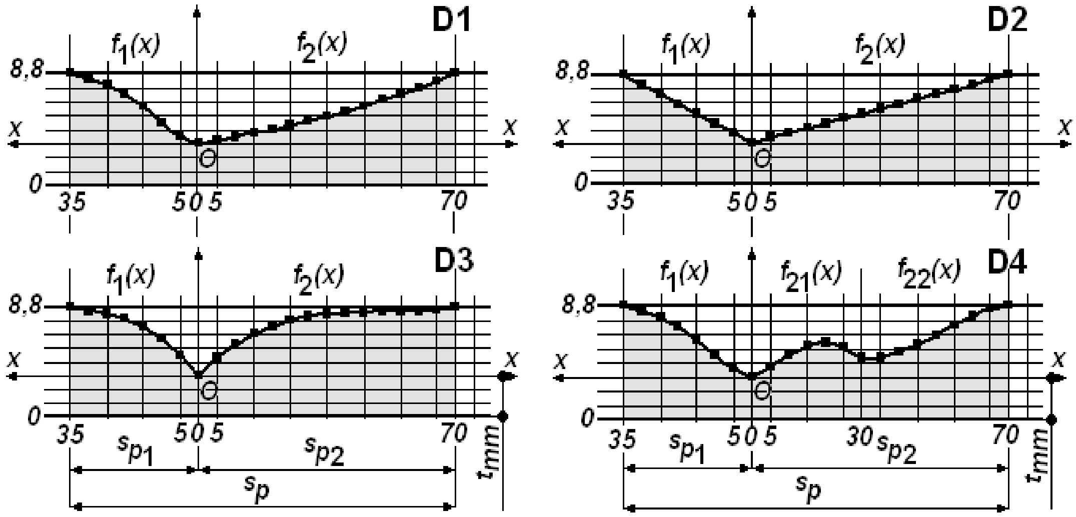

Fig. 3. The CTP configuration for the flaws considered in the case studies

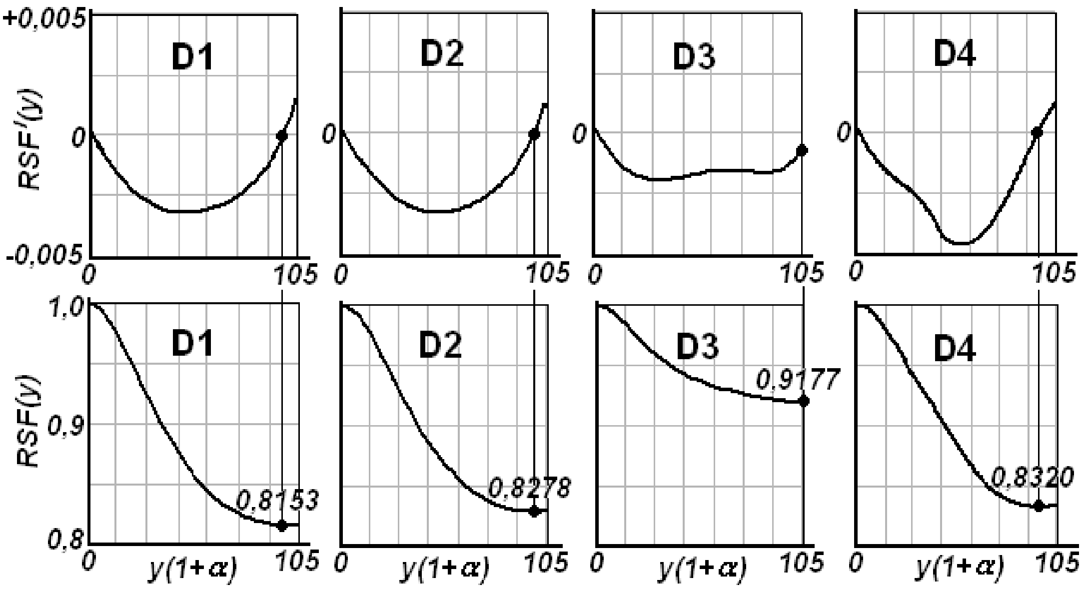

Fig. 4. The synthesis of the results obtained for the considered case studies

Table 3. The summary of the results obtained for the considered case studies

Flaw		D1	D2	D3	D4
Flaw characteristics	t_{am}, mm	6.2635	6.3173	6.9585	6.2590
	t_{sd}, mm	1.4222	1.4011	1.2351	1.4205
	COV	0.2271	0.2218	0.1775	0.2269
Remaining strength factor	$RSF(s_{p1})$	0.8163	0.8285	0.9177	0.8332
	RSF_{LTA} *	0.8443	0.8482	**0.8925**	0.8440
	RSF	**0.8153**	**0.8278**	0.9177	**0.8320**

* computed considering $d_{\max} = t_{\text{am}}$; for $d_{\max} = t - t_{\text{mm}} = 5.5$ in all cases we obtained $RSF_{LTA} = 0.5685$

c) the *RSF* values computed using equation (1), by applying the previously described subdivision procedure, describe with a high level of confidence the remaining strength of pipelines with local metal loss flaws; it can be considered that applying equation (1), which involves a laborious work procedure, is not always justified, because the obtained *RSF* values are very close to $RSF(s_{p1})$, that can be obtained much more easily.

Starting from this acknowledgement, the authors propose the following way of approaching the problem of determining the *RSF* for pipelines with local metal loss flaws:

a) $RSF(s_{p1})$ and RSF_{LTA} are determined (considering $d_{\max} = t_{am}$) and the value:

$$RSF_m = \min[RSF(s_{p1})\ ;\ RSF_{LTA}]; \tag{11}$$

b) RSF_m is compared to RSF_a; if both values are close, one determines *RSF* with equation (2), using the procedure proposed in the present paper, otherwise one makes a pertinent decision concerning the pipeline with flaws (maintaining it in exploitation or applying maintenance works in the flaw area) by comparing the values RSF_m and RSF_a.

The validity of the work procedure previously proposed, justified by the results obtained by performing the previously presented case studies, has also to be verified for the case of the pipelines with a group of local metal loss flaws. For this type of cases, [4, 5] does the following recommendations:

a) each group of local metal loss flaws is analyzed and then it is decided if the flaws interact; in this case it can be applied the procedure presented in [4];

b) if the flaws of the group don't interact, they can be considered to be individual/independent flaws and the procedures for determining the *RSF* previously presented should be applied; if some flaws of the group do interact, the group of flaws will be considered an individual flaw, the CTP will be drawn on the longitudinal extent, and the *RSF* will be determined using equation (2).

Because the CTP of an individual flaw equivalent to a group of interacting flaws can, on the longitudinal extent, have the configuration presented in Figure 5, the previously mentioned procedures for determining the *RSF*, applicable for pipelines with flaws having the CTP configuration like the one presented in Figure 2, should be modified and adjusted correspondingly, so that they can also be used for pipelines with groups of interacting flaws; these modifications and adjustments will be the object of future research.

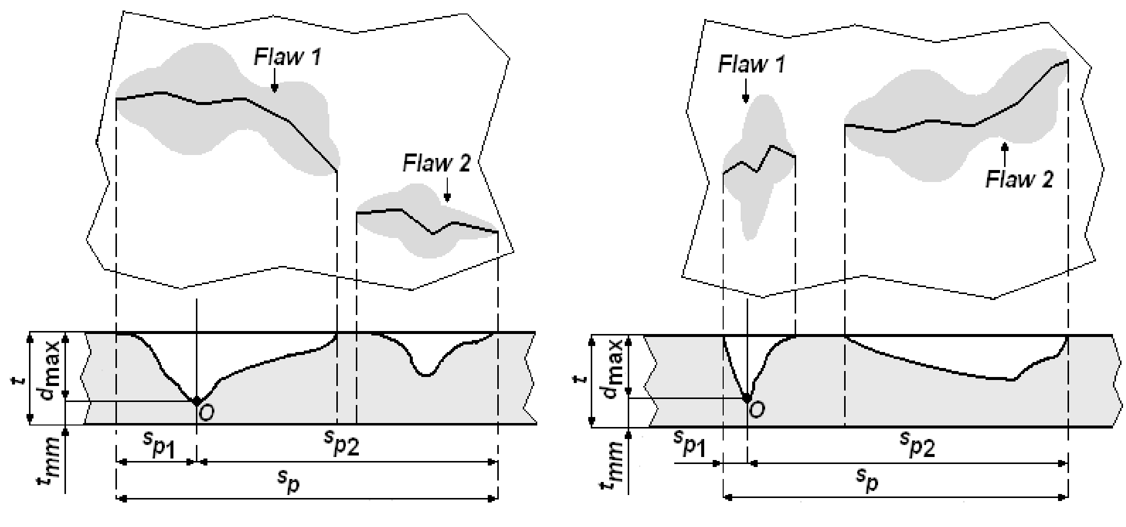

Fig. 5. The CTP configuration on the longitudinal extent for the individual flaw equivalent to a group of interacting flaws

Conclusions

The analysed procedure and the performed case studies lead to the following conclusions:

a) for determining the remaining strength factor *RSF* for pipelines with local metal loss, equation (2) recommended in [4] is applied; to this end, one must use the procedure proposed in the paper, implemented by the authors in a computationally specialized product (software), easy to use in the case of pipelines with individual flaws;

b) in many cases, as are the ones studied in the paper, the procedure for determining the *RSF* can be simplified, as the authors proposed, without any consequences regarding the precision of evaluating the remaining strength of pipelines with flaws;

c) in order for the procedures for determining the *RSF* recommended in the paper to have a general character, they should be adjusted for pipelines with groups of interacting flaws; the solution for this problem will be the object of future research.

Acknowledgements

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Evaluarea factorului rezistenței reziduale pentru conductele cu defecte locale de tip lipsă de material

Rezumat

În lucrare se prezintă o procedură de determinare a factorului rezistenței reziduale (RSF) pentru conductele tehnologice şi de transport care prezintă defecte suprerficiale locale de tip lipsă de material. Aplicarea procedurii propuse de autori asigură respectarea cerințelor formulate în API 579-1 /ASME FFS-1 privind caracterizarea gravității acestor defecte cu ajutorul valorii minime a RSF. Studiile de caz prezentate în lucrare conduc la concluzia că pentru o evaluare operativă şi cu un nivel de încredere suficient a conductelor cu astfel de defecte se poate utiliza valoarea RSF calculată considerând configurația şi dimensiunile reale ale defectelor depistate, nefiind întotdeauna justificată aplicarea metodei laborioase de determinare a valorii minime a RSF, recomandată de API 579-1 / ASME FFS-1.