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Strength and Toughness Properties of Steel Pipes in the Superannuated Pipelines of the National Natural Gas Transmission System

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Abstract

The paper shows, analyzes and comments the results obtained by applying an experimental programme that aimed for the determination of the strength and toughness properties of pipes and welded joints of some superannuated pipelines of the national natural gas transmission system. The specimens used for this experimental programme were processed from the samples drawed from two superannuated pipelines: one sample from the pipeline Ungheni – Găneşti, operated since 1928 and one sample from the pipeline Ceanu Mare – Cluj, operated since 1948. The experimental results are analyzed and commented in terms of the current requirements regarding the strength and toughness of steel pipes for natural gas transmission pipelines.

Key words: *superannuated pipeline, chemical composition, strength and toughness properties.*

Introduction

The current infrastructure of the National Natural Gas Transmission System – NTS includes: a) 12813 km transmission pipelines and supply branch lines (with diameters between 50 mm and 1000 mm and operating pressure rates between 6 bar and 35 bar) and 553 km transit pipelines (with the diameter of 1000 mm and 1200 mm and the operating pressure of 54 bar); the total length of pipelines and branch lines belonging to NTS is L_{ct} = 13366 km; b) 5 gas compressor stations, with an installed capacity of 32MW; c) 51 vane control stations and/or technological knots; d) 966 cathodic protection stations; e) 772 gas odorization units.

The state of pipelines belonging to the NTS (depending to a great extent on their length of service) can be synthetically characterized by means of the *conventional length of exposure* L_{ce}, representing the sum of products between the length $L_{ct,i}$ and the length of service τ_i (up to now) for all pipelines and branch lines belonging to the NTS (obviously the sum of lengths $L_{ct,i}$ of the $i = 1...n$ pipelines and branch lines is L_{ct}). Currently the NTS is characterized by a conventional length of exposure $L_{ce} \cong 400000$ km·year, which means that the average length of service of the NTS pipelines is of nearly 30 years and, consequently, in order to keep the NTS working and to operate it safely there are necessary some procedures, judiciously elaborated, scientifically substantiated and exactly applied, for the assessment of the technical state of pipelines belonging to this system and for decision making regarding the increase of the length of service or the performing of maintenance, rehabilitation or modernization works. S.N.T.G.N. „TRANSGAZ"S.A., the technical operator of NTS, is the one responsible for the carrying out of these procedures, for the safe and qualitative operation of this system, for the economic efficiency and for the environmental protection [1]. The necessity of carrying out this task is also imposed by [2], where among the objectives that have to be reached by unfolding the activities in the field of natural gas there are also foreseen the following: a) the assurance of the natural gas supply continuity and safety for customers; b) the development of the field of natural gas, focussing at the same time on economic efficiency and environmental protection.

The normative documents (legislative documents, standards, technical prescriptions etc.) regarding the regulation of the quality of natural gas transmission pipelines (NGTP) and of their components (pipes, bends, fittings, valves, welded joints etc.) is published, revised, modified and improved almost every year, and the normal length of service of these pipelines is of decades; for instance, [3] stipulates for the main pipelines designed for oil, gas and industrial liquid transport, having the classification code 1.9.1 (where NGTP are also included), a normal length of service of 20...30 years. Under these circumstances, the evaluation of the extent to which the NGTP built and operated for many years correspond to the technical requirements in the current normative documents is the first step in determining the ability of these pipelines to operate safely further on [4-8]. This paper shows the results of this approach, consisting in the application of this kind of experimental programmes for determining the chemical composition , the microstructure and the mechanical properties of fragments sampled from some superannuated NGTP: a) a fragment (marked PF-UCG) sampled from the Cerghid area of the NGTP Ungheni – Cerghid – Găneşti (having the outer diameter D_e = 273,1 mm (10¾ in) and the design pressure p_c = 25 bar), operated since 1929; b) a fragment (marked PF-CMC) sampled from the Tunel area of the NGTP Ceanu Mare – Cluj (having the outer diameter D_e = 323,9 mm (12¾ in) and the design pressure p_c = 25 bar), operated since 1948; the photos of the two samples can be seen in Figure 1.

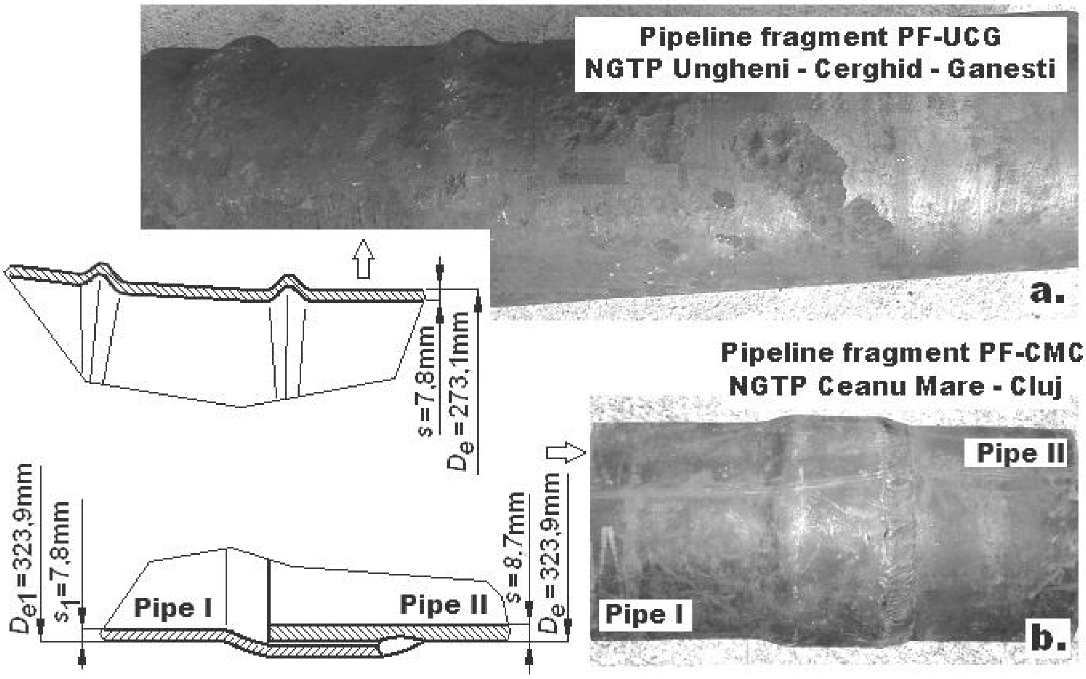

Fig. 1. Fragments of NGTP subjected to analysis:
a. PF-UCG, sampled from the NGTP Ungheni – Cerghid – Găneşti;
b. PF-CMC, sampled from the NGTP Ceanu Mare – Cluj

Content of the Experimental Programmes Performed

From the two fragments drawed from the NGTP there were taken specimens and samples for performing the experimental programmes; the locations the specimens and samples subjected to loadings and examinations were taken from are specified in Figure 2. The experimental programmes were performed according to the following steps: a) because the steel pipes for the NGTP have the quality defined mainly by the strength characteristics (conventional yield strength or proof strength total extension $R_{t0,5}$, upper yield strength R_{eH}, tensile strength R_m) and by the ductility (the elongation or percentage total extension at fracture A, the ratio $d_t = R_{t0,5}$(or R_{eH})/R_m), during the first stage of the experimental programmes there were determined these characteristics by means of the tensile test; knowing the tensile characteristics it was determined the mark (grade) of the steels the pipes for the NGTP have been made of, applying to this end the provisions stipulated in API Spec 5L / ISO 3183 and EN 10208-2; b) during the second stage of the experimental programmes it was determined the chemical composition and the metallographic structure of the NGTP pipes, it was estimated the manufacturing technology for these pipes and there were made estimations regarding the extent to which the pipes comply (from the point of view of composition and structure) with the provisions of the previously mentioned normative documents; c) during the third stage of the experimental programmes there was performed the notched-bar impact test and the results obtained for estimating the extent to which the NGTP pipes correspond to the specifications regarding the toughness stipulated in the previoulsy mentioned documents; d) during the last stage there were performed tests and examinations in order to define the quality of some details existing on the NGTP fragments; for PF-UCG there were performed metallographic examinations and hardness determinations on the samples from the wavings existings in the curved area, together with examinations of the pipe samples with local metal loss caused by corrosion, and for the PF-CMC there was performed a research of the fillet weld joint (the joint between two PF-CMC pipes), by means of: metallographic structure examinations and hardness determination, the nick-break test in order to reveal possible defects of the welded seam and the root and face bend tests in order to estimate the ductility of the welded joint.

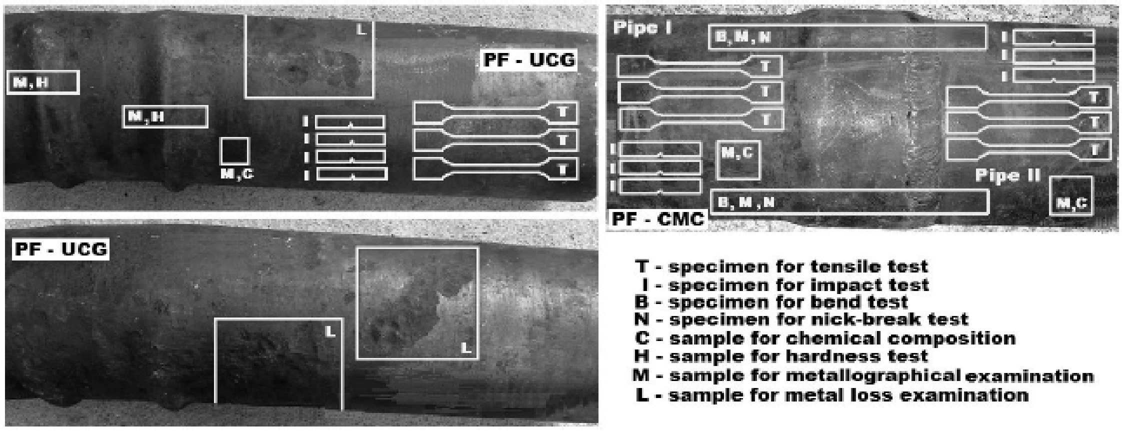

Fig. 2. Types of specimens and samples used within experimental programmes and the locations they were drawed from the PF-UCG and the PF-CMC

Results of the Experimental Programme Performed for the PF-UCG

The tensile test performed on specimens sampled from the PF-UCG led to the results shown in Table 1, the flow charts stress σ – strain ε having the configuration shown in Figure 3,a; the processing and the interpretation of these results according to the provisions stipulated by API

Spec 5L / ISO 3183, as it can be seen in Figure 4, led to the estimation that the PF-UCG is a (curved) seamless steel pipe (steel grade X52 N or L360 N).

The determinations regarding the chemical composition led to the results shown in table 2; the chemical composition corresponds to the current provisions regarding X52 N (L360 N) steel pipes, the only exception is represented by the sulphur concentration (which exceeds the maximum level prescribed by API Spec 5L / ISO 3183), and the metallographic examination revealed a fine-grained ferritic-pearlitic structure, typical for manufacturing pipes by classical rolling, as it can be seen in Figure 5.

Table 1. Results of the tensile test on specimens sampled from PF-UCG and PF-CMC

Pipeline fragment	Specimen [a]		Yield strength R_{eH}, N/mm^2	Tensile strength R_m, N/mm^2	Elongation A, [b] %	Ductility $d_t = R_{eH}/R_m$
	$S_0 = l \times s$, mm^2	L_0, mm				
PF-UCG	20.0 x 7.5	50.8	372	518	38.8	0.72
	20.1 x 7.5		402	560	31.8	0.72
	20.1 x 7.5		380	530	31.0	0.72
PF-CMC Pipe I	12.0 x 7.6	50.8	360	501	34.0	0.72
	11.9 x 7.6		356	505	33.4	0.70
	12.0 x 7.6		362	475	31.0	0.76
PF-CMC Pipe II	11.7 x 8.5	50.8	376	509	32.2	0.74
	11.6 x 8.5		420	532	35.0	0.79
	11.7 x 8.5		345	478	26.8	0.72
Steel pipe	Yield strength $R_{t0,5}$ or R_{eH}, N/mm^2		Tensile strength R_m, N/mm^2		Elongation A, [c] %	Ductility $d_t = R_{eH}/R_m$
	min.	max.	min.	max.	min.	max.
X52 N (L360 N) API Spec 5L ISO 3184	360	530	460	760	22 (PF-UCG) 20 (PF-CMC) [d]	0.93

a) S_0 – cross-sectional area of specimen; L_0 – gage length of specimen; b) elongation in L_0 = 50,8 mm (2 in); c) minimum elongation in L_0 = 50,8 mm (2 in) is determined by the equation $A_f = 1940 S^{0,2}/R_m^{0,9}$, $S = \min(S_0;\ 485\ \text{mm}^2)$ and R_m specified minimum tensile strength in N/mm^2; d) for PF-UCG specimens: S_0 = 150 mm^2 and A_f = 21 %; for PF-CMC specimens: S_0 = 91...100 mm^2 and A_f = 19 % (steel pipe grade X52: R_m = 460 N/mm^2)

The impact test, performed at the temperature $t_t = 0\ ^{\circ}\text{C}$, led to the results synthetized in table 3, the fracture surfaces of the loaded specimens and the estimated values of the percent shear fracture are shown in Figure 6. For the interpretation of the results it was calculated the maximum intensity of hoop stresses σ_θ, generated in the pipe wall (where the pipe's outer diameter is D_e = 273.1 mm and the thickness s = 7.8 mm) under the action of pressure p_c = 25 bar (2.5 MPa) and it resulted $\sigma_\theta = p_c D_e/(2s) \cong 44$ N/mm^2; under these circumstances, according to the provisions stipulated in API Spec 5L / ISO 3183, a level of the absorbed energy $KV \geq 27$ J is sufficient to prevent the danger of brittle failure and to assure the arrest of the extension of possible cracks generated in the pipe wall.

The last stage of the experimental programme performed on PF-UCG had the following objectives and led to following results: a) the determination of the *HV* hardness of the samples drawed from the wrinkled area on the intrados of the curved PF-UCG and the analysis of the *HV* measured values, mentioned in Figure 7, revealed the fact that the material in the wrinkled area is not cold-hardened and, consequently, it was deducted that the pipe was curved by hot forming; b) the analysis of the samples drawed from the strong corroded areas of the PF-UCG marked out that the local metal loss defects have a higher depth ($h_d = s =$ 7.6 mm), as it can be seen in the images of Figure 8, the external corrosion rate could be estimated at the level v_{co} = 7.6 mm / 83 years = 0.09 mm/year; if the testing of the condition and the remaking of possible damages of the anticorrosion protection insulation would have been made periodically, the pipeline from which the PF-UCG was taken could have been characterized even now by structural integrity and safe operation.

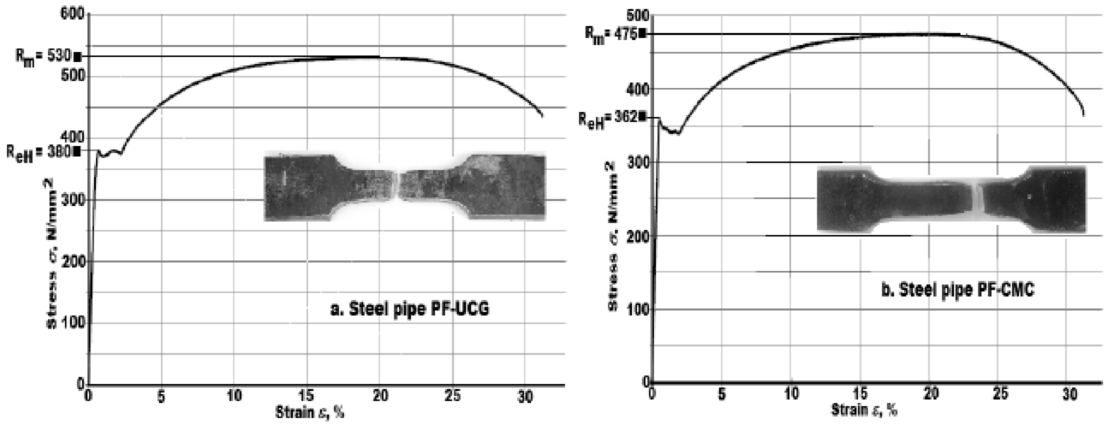

Fig. 3. Configuration of the characteristic curves stress σ – specific strain ε of PF-UCG and PF-CMC steel pipes

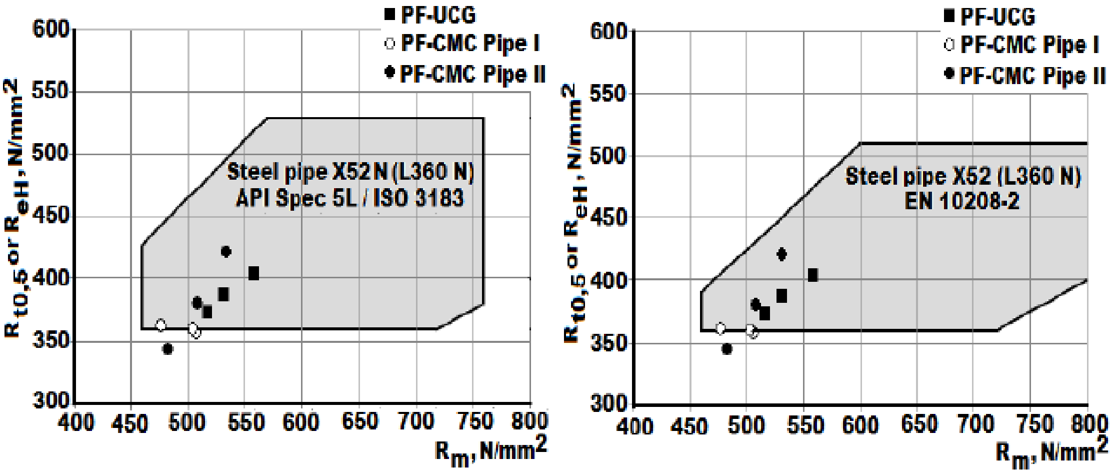

Fig. 4. Determination of the steel strength grade of PF-UCG and PF-CMC

Results of the Experimental Programme Performed on PF-CMC

The tensile test performed on the specimens sampled from the two PF-CMC pipes led to the results shown in table 1, the configuration of the flow-charts stress σ – specific strain ε is shown in Figure 3,b; the processing and the interpretation of these results according to the provisions stipulated by API Spec 5L / ISO 3183, as it can be seen in Figure 4, led to the estimation that the PF-UCG are seamless steel grade X52 N) (L360 N) pipes.

The determinations regarding the chemical composition led to the results shown in table 2; the chemical composition of the two PF-CMS pipes corresponds to the current provisions regarding X52 N (L360 N) steel pipes and the metallographic examination revealed a ferritic-pearlitic structure, typical for manufacturing pipes by classical rolling, as it can be seen in Figure 5.

Table 2. Results of the determination of the chemical composition of PF-UCG and PF-CMC

Pipeline fragment	Chemical composition – mass fraction, % ^{a}									CE_{IIW}
	C	Si	Mn	P	S	V	Nb	Ti	Others	
PF-UCG	0.17	0.23	0.65	0.015	0.028	0.007	0.005	0.008	*c*	0.30
PF-CMC Pipe I	0.23	0.28	0.49	0.005	0.012	0.006	0.005	0.005	*d*	0.35
PF-CMC Pipe II	0.20	0.23	0.39	0.005	0.013	0.006	0.005	0.005	*e*	0.30
X52 N (L360 N)^{b} API Spec 5L ISO 3184	0.24	0.45	1.40	0.025	0.015	0.10	0.05	0.04	*f*	0.43

a) average of three determinations; b) seamless and welded pipe, product specification level PSL 2; c) 0.18 % Cu; 0.05 % Ni; 0.05 % Cr; 0.005 %Mo; d) 0.28 % Cu; 0.07 % Ni; 0.07% Cr; 0.007 %Mo; e) 0.23 % Cu; 0.06 % Ni; 0.04 % Cr; 0.006 %Mo; *f*) %Nb + %V + %Ti ≤ 0.15 %; unless otherwise agreed, %Cu ≤ 0.50%; %Ni ≤ 0.30%; %Cr ≤ 0.30% and %Mo ≤ 0.15%.

Table 3. Results of the impact test on PF-UCG and PF-CMC specimens

Pipeline fragment	Absorbed energy (1/2 subsize specimens 10 × 5 × 55)		Absorbed energy (standard specimens 10 × 10 × 55)		Percent shear fracture	
	$KV_{1/2,i}$, J	$KV_{1/2}$ ^{a}, J	KV_i , J	KV^{b}, J	$F_{sa,i}$, %	F_{sa}, %
PF-UCG	32.4	33.0	64.8	66.1	70	61
	35.5		71.0		65	
	33.4		66.8		55	
	30.9		61.8		55	
PF-CMC Pipe I	42.0	45.2	84.0	90.3	70	68
	58.9		117.8		75	
	34.6		69.2		60	
PF-CMC Pipe II	27.6	27.7	55.2	55.4	55	57
	28.3		56.6		60	
	27.2		54.4		55	
X52 N (L360 N)^{b} API Spec 5L / ISO 3184			min 21	min 27	-	min 85

a) $KV_{1/2}$ is the average of the values $KV_{1/2,i}$; $KV_i = N_f KV_{1/2,i}$ and $KV = N_f KV_{1/2}$, the normalization factor $N_f = 2$

The impact test, performed at the temperature $t_t = 0$ °C, led to the results synthetized in table 3, the fracture surfaces of the loaded specimens and the estimated values of the percent shear fracture are shown in Figure 6. The same as for the analysis of the toughness of PF-UCG, for the interpretation of the results there was calculated the maximum intensity of hoop stresses σ_θ, generated in the pipe wall (pipe I having an outer diameter of $D_e = 323.9$ mm and the thickness $s = 7.8$ mm and pipe II having the outer diameter $D_e = 323.9$ mm and the thickness $s = 8.7$ mm) under the action of pressure $p_c = 25$ bar (2.5 MPa) and it resulted $\sigma_\theta = p_c D_e/(2s) \cong 52$ N/mm^2 in the pipe I wall and $\sigma_\theta \cong 47$ N/mm^2 in the pipe II wall; under these circumstances, according to the provisions stipulated in API Spec 5L / ISO 3183, a level of the fracture energy $KV \geq 27$ J is sufficient to prevent the danger of brittle failure and to assure the arrest of the extension of possible cracks generated in the PF-CMC pipe wall.

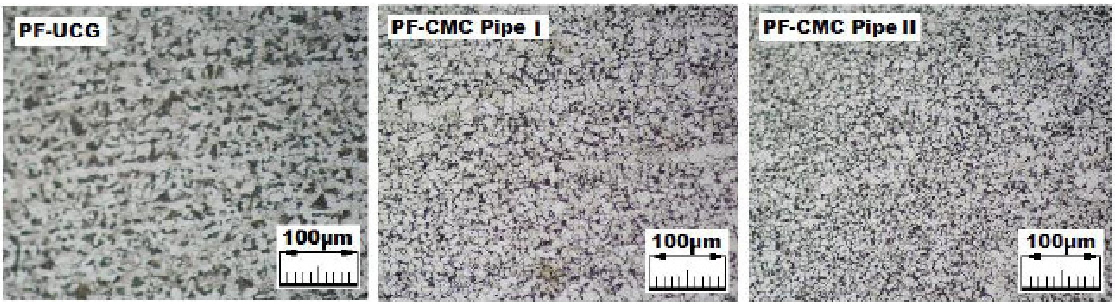

Fig. 5. Microstructures of the PF-UCG and PF-CMC

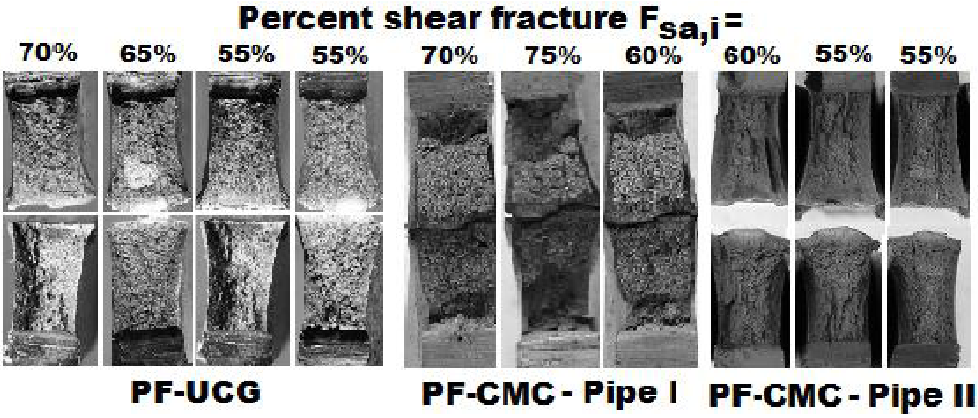

Fig. 6. Fracture appearance of impact testing specimens

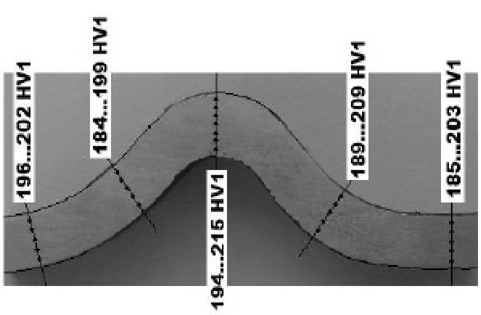

Fig. 7. Hardness in the wrinkled areas of the PF-UCG

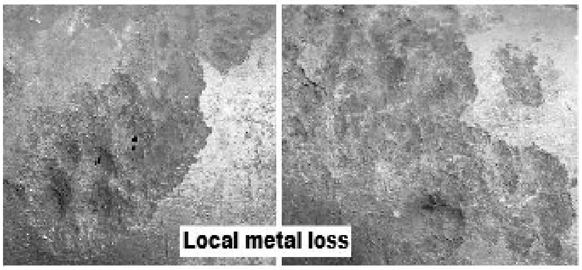

Fig. 8. Local metal loss defects on the PF-UCG

The last stage of the experimental programme performed on PF-CMC had the following objectives and led to following results: a) the determination of the *HV* hardness and microsctructure of the samples drawed from the fillet weld joint area on the PF-CMC pipes led to the results synthetized in Figure 9; the structure of WDS reveals the use for the welded joint of one of the procedures 111 or 311 – ISO 4063, and the microstructure and the hardness values (which don't exceed 177 HV << 350 HV) in the characteristic areas of the joint (WDS, HAZ or BM) show that its strength and toughness are adequate; b) performing of the Nick Break Test on two specimens (sampled and loaded as it can be seen in Figure 10) revealed that WDS is of very good quality, with no discontinuities (pores, inclusions or cracks); c) the bend test performed on two specimens (sampled and loaded as it can be seen in Figure 11) also indicated a good quality of the welded joints on the stretched fibres of the bend loaded specimens (situated in the WDS and HAZ of the welded joint) and no shallow defects such as crack-like flaws were found.

As in the case of the analysis performed on PF-UCG, it can be estimated that the NGTP pipe section the PF-CMC was sampled from is of good quality, both the pipes and their welded joints being characterized by a level of strength and toughness high enough to continue its operation safely.

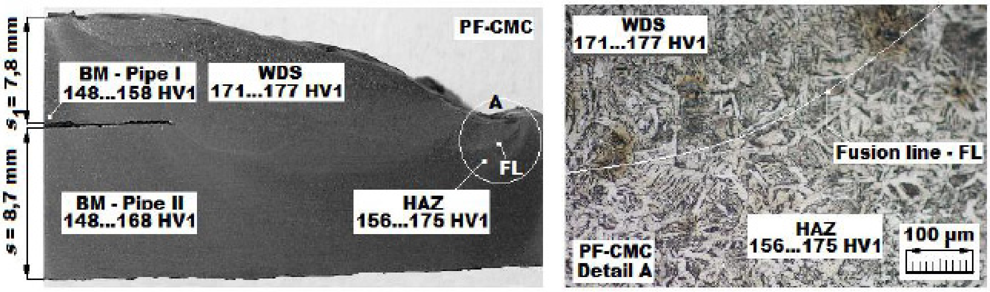

Fig. 9. Microstructure and hardness of the PF-CMC welded joint

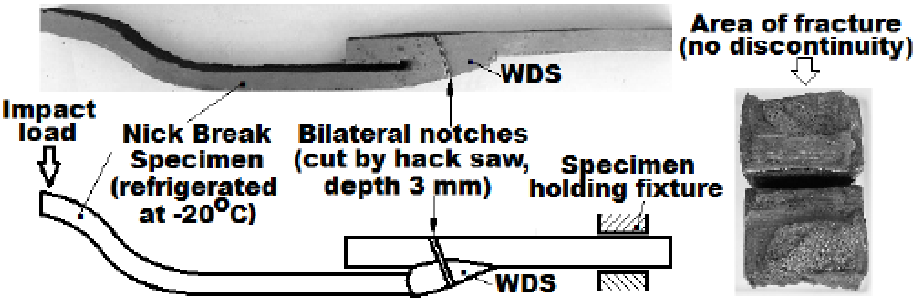

Fig. 10. Way of performing the Nick Break test on the PF-CMC welded joint and the results of this test

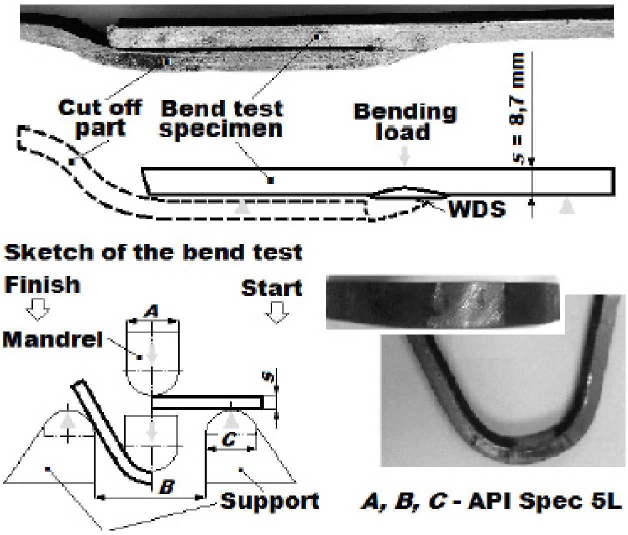

Fig. 11. Way of performing the bend test on the PF-CMC welded joint and the results of this test

Conclusions

The issues discussed within this paper led to the following conclusions regarding the structural integrity of superannuated NGTP, which exceeded the normal length of service, pipelines belonging to the NTS:

- The experimental programmes performed indicated that the superannuated NGTP were designed and constructed so that they fully complied with the requirements imposed by current normative documents regarding the characteristics of strength, ductility, toughnes and weldability and, consequently, if no anomalies occur generated during their operation, they can be operated safely further on.
- NGTP which exceeded the length of service and which revealed during periodical inspections different anomalies (local shallow anomalies caused by corrosion, dents, gouges etc.), can be subjected to corrective maintenance works, including the reinforcement of the damaged areas by applying patches or welded sleeves or composite wraps; because the areas with no anomalies of the NGTP are characterized by a good strength, ductility, toughness and weldability, it is not necessary to completely replace the pipe sections with anomalies, which implies reduced costs necessary for repairing, rehabilitating or modernizing the NGTP of the SNT.
- The performing of experimental programmes like those described within this paper can lead to a setting up of a consistent database regarding the technical condition of the NGTP belonging to the NTS, very useful when making important decisions regarding maintenance programmes by S.N.T.G.N. „TRANSGAZ" S.A., the technical operator of NTS.

Acknowledgements

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The experimental programmes were performed by using equipments (Laboratory spectrometer with optical emission FOUNDRY-MASTER PRO / OXFORD Instruments, Micro-hardness testers DURASCAN 20 / EMCOTEST, Static and dynamic universal testing machine Walter Bai LF300 and Charpy pendulum impact testing machines Walter Bai 450) acquired as part of the project with the title "**Regional centre for the determination of the characteristics and monitoring of the technical state of OCTG – oil country tubular goods – CRDPMTP** ", co-financed by the **European Regional Development Fund**, on the basis of a financing contract from **European funds**, **POSCCE-A2-O2.2.1-2009-4.**

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Caracteristicile de rezistență mecanică şi tenacitate ale unor conducte cu vechime foarte mare din sistemul național de transport al gazelor naturale

Rezumat

Lucrarea prezintă, analizează şi comentează rezultatele obținute prin realizarea unui program experimental vizând determinarea caracteristicilor de rezistență mecanică şi tenacitate ale țevilor şi îmbinărilor sudate ale unor conducte foarte vechi din sistemul de transport al gazelor naturale. Epruvetele folosite la realizarea programului experimental au fost obținute din două eşantioane prelevate din tubulatura unor conducte vechi: un eşantion prelevat din tubulatura conductei Ungheni – Găneşti, pusă în funcțiune în 1928 şi un eşantion prelevat din tubulatura conductei Ceanu Mare – Cluj, pusă în funcțiune în 1948. Rezultatele experimentale sunt analizate şi comentate prin prisma cerințelor actuale privind rezistența mecanică şi tenacitatea țevilor din oțel pentru conductele de transport al gazelor naturale.