Evaluation of mechanical properties of gas pipeline DN 500 after more than 40 years of its operation

Hodnotenie mechanických vlastností plynového rozvodu DN 500 po viac ako 40 rokoch jeho prevádzky

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The paper deals with the mechanical properties of steel gas pipeline DN 500 after more than 40 years of operation. Mechanical properties of the pipeline were established by a tensile test at an ambient temperature according to the standard EN ISO 6892-1. The resistance of the pipeline against brittle failure was evaluated by using Charpy impact test according to EN 10045-1. The character of fracture surface after the Charpy test was analysed by using scanning electron microscopy. A high proportion of transcrystalline cleavage was a characteristic feature of fracture surfaces. Mechanical characteristics obtained by static tensile testing were compared with the values obtained from steel manufacturer. Higher elongation was observed in a parallel direction compared to the perpendicular direction to the axis of the pipe. The observed anisotropy of properties was related to the distribution of inclusions in the direction of the deformation of the steel sheets used for the pipeline construction.

Práca sa zaoberá mechanickými vlastnosťami oceľového plynovodného potrubia DN 500 po viac ako 40 rokoch prevádzky. Mechanické vlastnosti potrubia boli stanovené ťahovou skúškou pri teplote okolia podľa normy EN ISO 6892-1. Odolnosť potrubia voči krehkému lomu bola hodnotená Charpyho skúškou rázom v ohybe podľa EN 10045-1. Charakter lomovej plochy po Charpyho teste bol analyzovaný pomocou skenovacieho elektrónoveho mikroskopu. Vysoký podiel transkryštalického štiepenia bol charakteristickým znakom lomových povrchov. Mechanické charakteristiky získané po ťahovej skúške boli porovnané s hodnotami získanými od výrobcu ocele. Bola zistená vyššia ťažnosť v smere rovnobežnom s osou potrubia v porovnaní s kolmým smerom k osi potrubia. Pozorovaná anizotropia vlastností súvisela s rozložením inklúzií v smere deformácie oceľových pásov na výrobu potrubia.

INTRODUCTION

The system for transportation of natural gas is projected for a period of ten years. The operation of gas pipelines for more than planned lifetime is a potential risk due to corrosion degradation (degree of aggressiveness of various types of soils along which the pipes pass, level of corrosion protection, undermining the pipe wall by ground water), changes in operation pressure, mechanical stresses (landslides and vibrations, general site excavations) [1-3].

Additional important issues in the construction and operation of pipelines include the way of its location to a previously determined site and calculation of investment and operation costs. Due to the above mentioned factors, it is necessary to have sufficient knowledge of both the condition of the pipeline surface and changes in its structure, which affect considerably mechanical and brittle fracture properties of the steel [4-10].

For several years, they are undertaken assessment of wear of devices and forecasting their future safe operation. In both cases, it is necessary to determine the general condition of the equipment, including an assessment of the degree of degradation of the material properties after the operation. To evaluate the degree degradation of the material can be used in the study of mechanical properties, metallographic examination, the study of the chemical and phase composition isolated precipitations and magnetic studies [11-13].

While the assessment of the material after the operation is based on routine destructive tests, whereas forecasting further safe operation of petrochemical plants is a too complex problem to solve and there are no generally accepted methods. The most commonly used calculation methods allow the determination of allowable stresses and strains to achieve the long-term operation including the corrosion attack [14-17].

However, a widely used method to assess the possibility of further safe operation of the material is to evaluate changes in the basic mechanical properties and stability of the structure. Quantitative assessment of changes in material properties is possible when you have the material properties in the initial state (before the operation) [18,19].

The research in this paper is to evaluate the mechanical properties (tensile test, impact test) and evaluation of microstructure and fracture morphology steel pipeline P295 GH after more than 40 years of operation.

EXPERIMENTAL

For experiments were used samples of steel pipeline DN 500 after more than 40 years its operation. In Table 1 is shown the chemical composition of tested steel, which was determined using the microanalysis INCAx_Sight to determination of actual chemical composition (EDS analysis) and compared with chemical composition steel according to EN–10028/2-93. The carbon content was found using the atomic emission spectroscopy (AES) [20].

The tensile test was used to determine mechanical characteristics: yield strength R_e, tensile strength R_m and ductility A_5 of pipeline made from steel P295 GH. The tensile test was carried out using a mechanical testing machine ZWICK 1387 in a laboratory environment at temperature T = 20 ± 3 °C, using test loading in the range of F = 0 ÷ 200 kN and a loading rate of 1 mm.min^{-1}. Test rods of dimensions d_0 = 6 mm and L_0 = 30 mm were collected in the direction parallel to the longitudinal pipe axis (L) and perpendicular to the axis (T), according to the scheme illustrated in Fig. 1. The test was carried out according to instructions specified by the standard EN ISO 6892-1 [21].

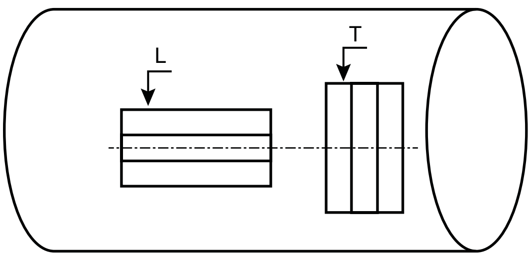


Fig. 1. The scheme of obtaining specimens on the tensile test
Obr. 1. Schéma odberu vzoriek na ťahovú skúšku

The structure of P295 GH steel was determined by a light microscope OLYMPUS VANOX-T (LM). The brittle fracture properties of materials is most often examined by using Charpy impact test in dependence on the temperature of test. The test was carried out on a Charpy pendelum according to the standard EN 10045-2 under the conditions defined by standards EN 10045-1 and EN 10045-2. Specimens of dimensions 55 × 10 × × 10 mm with 2 mm notch were broken by the Charpy pendulum in the temperature range from –60 °C up to 20 °C, using three specimens for each temperature. After a fracture the specimens were cleaned with ethanol and dried in a stream of hot air. The Charpy impact test established the amount of energy absorbed by a steel material during fracture. The result of Charpy impact test was transition curve of the dependence absorbed energy KV on the test temperature. The criterion of absorbed energy K = 27 J was used to determination the transition temperature [22]. Fracture surfaces of specimens after test were evaluated by a scanning electron microscope JEOL JSM-7000F (SEM).

RESULTS AND DISCUSSION

Microstructure of steel in the direction parallel to the longitudinal axis of the pipe was banded pearlitic-ferritic with the grains of non-uniform size, as documented in Figure 2. The values of the mechanical

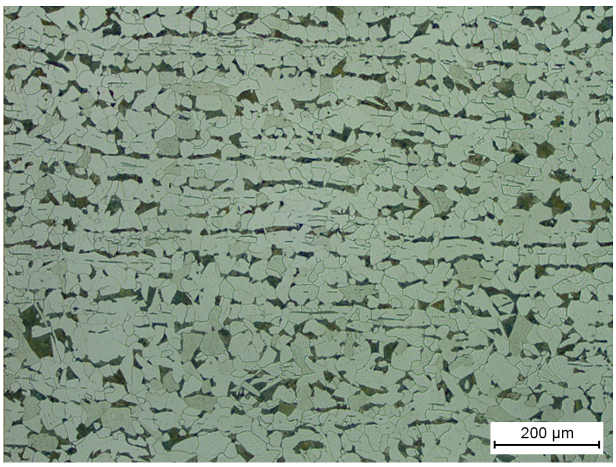


Fig. 2. Ferrite – pearlite banded structure of P295 GH steel (LM)
Obr. 2. Feriticko – perlitická riadková štruktúra ocele P295 GH (LM)

Tab. 1. Chemical composition of P295 GH steel according to EN 10028/2-93 in wt. % / *Chemické zloženie ocele P295 GH podľa EN 10028/2-93 v hm. %*

P295 GH	C	Si	Mn	Ni	S	Cr	Al
EN 10028/2-93	0.08 – 0.2	max. 0.4	0.9 – 1.5	max. 0.3	max. 0.025	–	min. 0.02
INCAx_Sight/AES	0.17	0.3	1.28	0.31	0.1	0.2	0.13

characteristics obtained by the tensile test according to the standard EN ISO 6892-1:2009: yield strength Re, tensile strength Rm and elongation A_5 of specimens (L) directed parallel with the longitudinal pipeline axis were following: Re = 275 MPa, Rm = 464 MPa and A_5 = 27.6 %. The values of the mechanical characteristics of specimens (T) directed perpendicular to the longitudinal pipeline axis were: Re = 280 MPa, Rm = 465 MPa, A_5 = 33.0 %. The measured values are presented in Table 2. The values of elongation A_5 measured in directions L and T (according to Table 2) differed due to anisotropy of properties resulting from the texture of the material processed by rolling and distribution of inclusions elongated in the direction of steel rolling.

This is a general phenomenon related to texture, orientation of structural components in the direction of forming, braking effects of grain boundaries during the movement of dislocations at plastic deformation, etc. [23]. Comparison of the measured values of strength characteristics of the initial and exposed material allowed us to conclude that the exposure of the test material during the operation only slightly increased the yield strength but on the other hand led to increase in its ductility, as shown in Table 2. The graphical illustration of the tensile test diagram is illustrated in Figure 3.

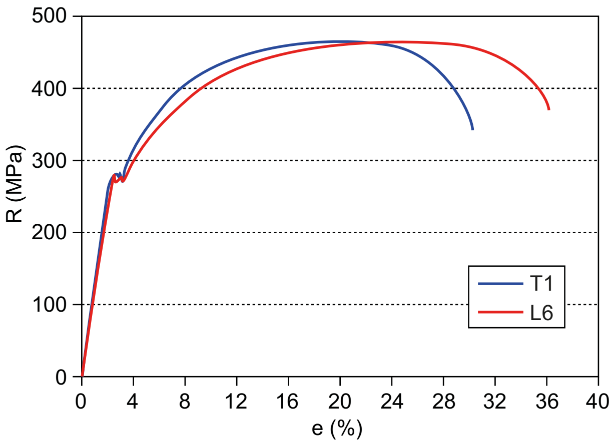
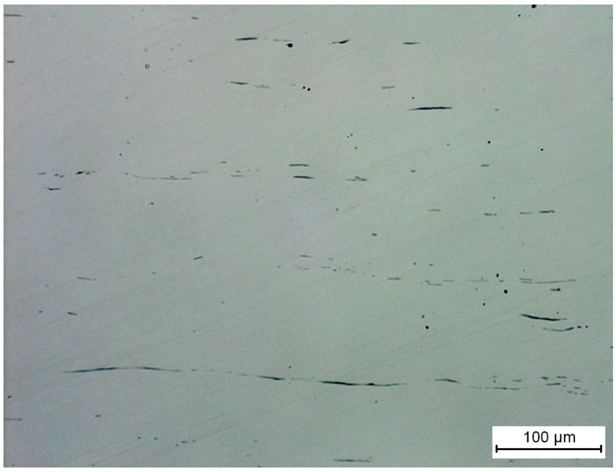
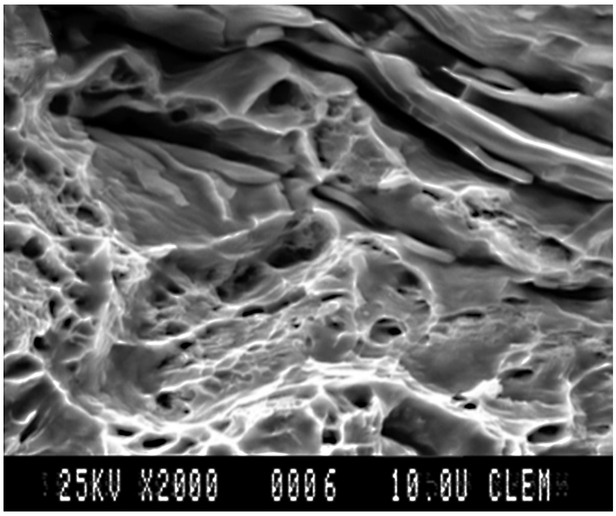


Fig. 3. Comparison of mechanical properties of samples oriented parallel (L) and perpendicular (T) to the longitudinal axis of the pipe
Obr. 3. Porovnanie mechanických vlastnosti vzoriek orientovaných paralelne (L) a kolmo (T) na pozdĺžnu os potrubia

In Figure 4 are documented inclusions which affected a fracture initiation places elongated in the direction of rolling. The area of elongated inclusion particles in the direction of rolling was bigger and thus the load-bearing cross section of specimens collected in



a)



b)

Fig. 4. a) The presence of inclusions elongated in the direction of steel rolling. Magn. 50× (LM); b) The fracture surface of steel with inclusions elongated in the direction of steel rolling (SEM)
Obr. 4. a) Prítomnosť inklúzií predĺžených v smere valcovania ocele. Magn. 50 (LM); b) Lomový povrch ocele s inklúziami predĺženými v smere valcovania ocele (REM)

Tab. 2. Mechanical properties of gas pipeline determined by static tensile test / *Mechanické vlastnosti plynového potrubia stanovené statickou skúškou ťahom*

Specimens of P295GH steel	**Direction of specimen collection**	**R_e (MPa)**	**R_m (MPa)**	**A_5 (%)**
L6	Parallel to pipeline longitudinal axis	280	465	33.0
T1	Perpendicular to pipeline longitudinal axis	275	464	27.6
Mechanical properties according to EN 10028/2-92		$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)
		295	460-580	min 22

the direction perpendicular to direction of forming was reduced, which was reflected in de-creased ductility.

The values of absorbed energy K obtained by Charpy impact test are presented in Table 3. We used the measurements of absorbed energy to construct a transition curve, which is presented in Fig. 5. According to the criterion of absorbed energy K = 27 J, the transition temperature reached the value T_t = -2 °C. The lowest operating temperature of the pipeline is + 4 ° C in winter months. From the point of view of technical practice it is important to ensure that loading of the material takes place above the transition temperature (T_t) [24].

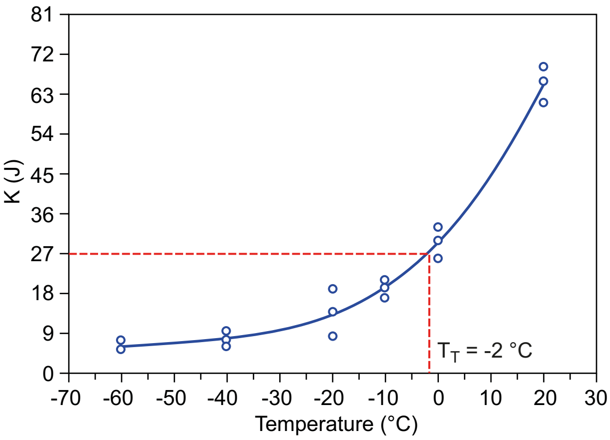


Fig. 5. Transition curve constructed on the basis of absorbed energy criterion
Obr. 5. Prechodová krivka zostrojená na základe kritéria absorbovanej energie

Decrease in absorbing energy at individual temperatures is well reflected in the character of the fracture surface of the tested samples. Figure 6 shows the fracture surface of the specimen fractured by Charpy pendulum at 20 °C. The fracture surface is rough; higher energy was needed to cause specimen failure. We could observe mostly transgranular ductile fracture with dimple morphology in which lines of elongated dimples oriented in the direction of rolling were visible. EDX analysis identified the presence of iron and manganese sulfides of type (Fe,Mn)S in the holes of fracture surface (Fig. 7).

Figure 8 shows the fracture surface of the specimen broken at 0 °C. The relief of fracture surface is less pronounced in comparison with fracture surface illustrated in Fig. 6. Fracture of this specimen after Charpy impact caused only minimal plastic deformation of specimen edges. These observations corresponded to the lower value of absorbed energy necessary for specimen failure.

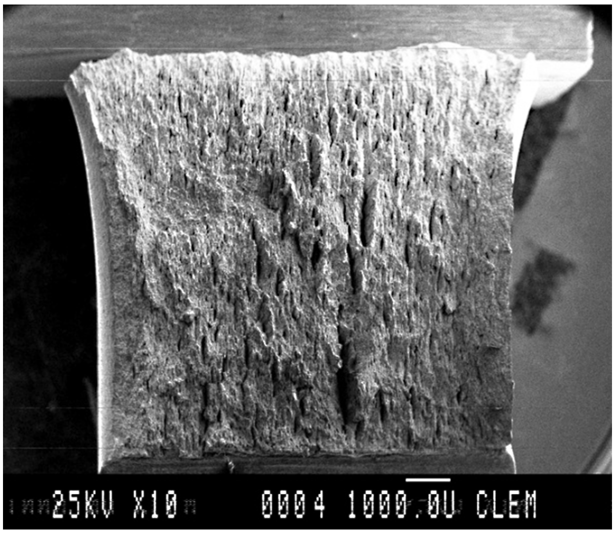


Fig. 6. Morphology of the specimen fracture surface fractured at 20 °C
Obr. 6. Morfológia lomového povrchu vzorky zlomenej pri 20°C

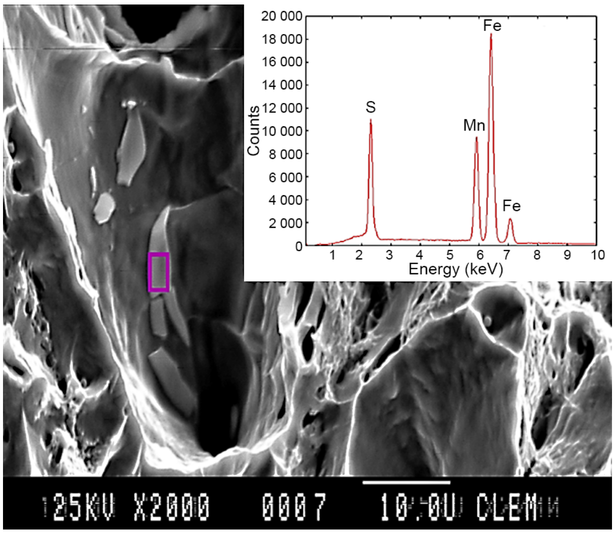


Fig. 7. Inclusions located in the dimples of ductile fracture
Obr. 7. Inklúzie nachádzajúce sa v jamkách tvárneho lomu

Tab. 3. Results of Charpy impact test / *Výsledky Charpyho testu*

Temperature/Absorbed energy	Value								
T (°C)	+20	+20	+20	0	0	0	–10	–10	–10
K (J)	69	61	66	33	30	26	17	19	21
T (°C)	–20	–20	–20	–40	–40	–40	–60	–60	–60
K (J)	19	14	8.5	9.5	7.5	6.0	5.5	7.5	5.5

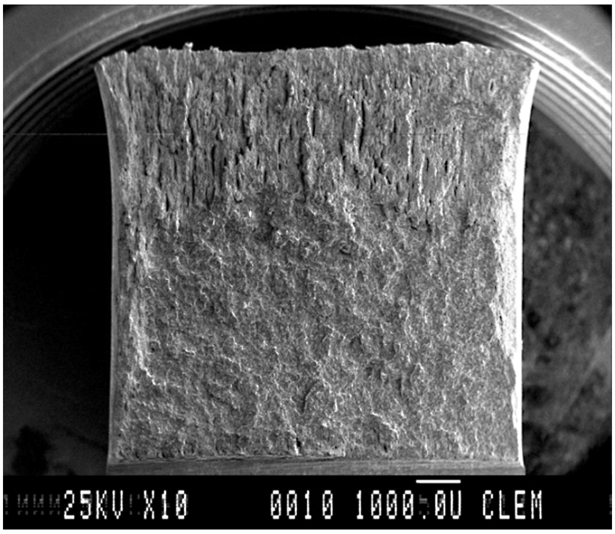


Fig. 8. Morphology of the fracture surface of the specimen fractured at 0 °C
Obr. 8. Morfológia lomového povrchu vzorky zlomenej pri 0°C

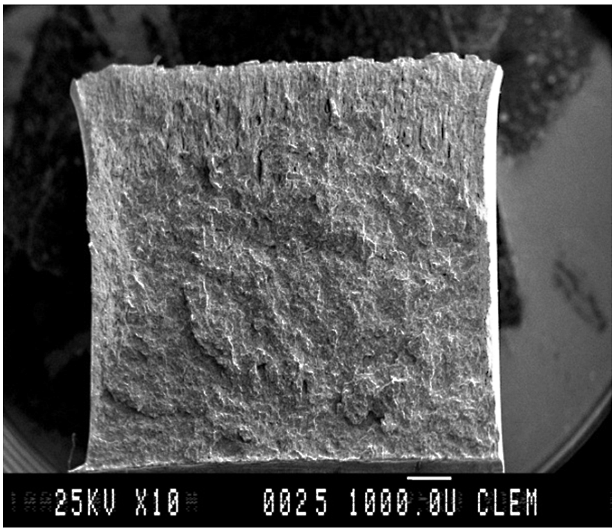


Fig. 10. Morphology of the fracture surface of the specimen fractured at –10 °C
Obr. 10. Morfológia lomového povrchu vzorky zlomenej pri –10°C

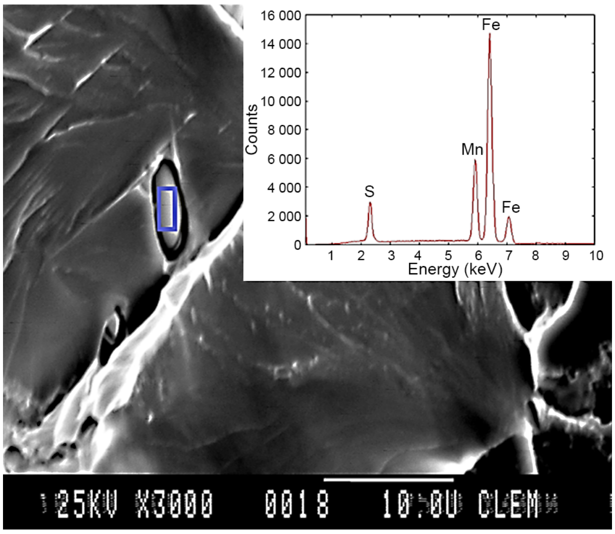


Fig. 9. Detail of the morphology of inclusion particles on the fracture surface
Obr. 9. Detail morfológie inklúzií na lomovom povrchu

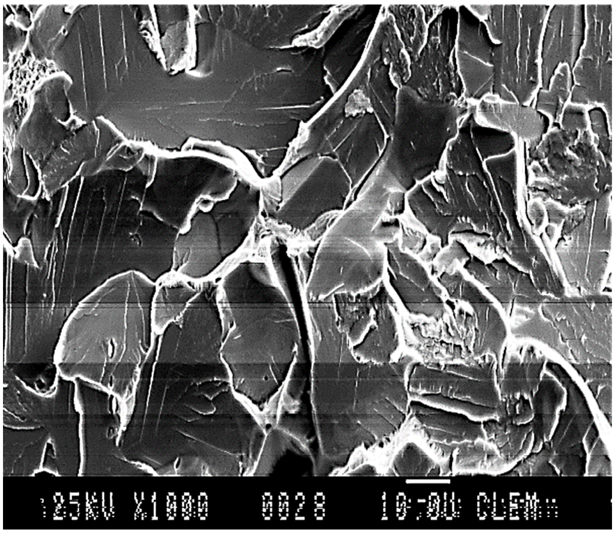


Fig. 11. Facets of transgranular cleavage
Obr. 11. Fazety transkryštalického štiepenia

Figure 9 shows a transgranular character of the fracture surface of specimen fractured in a brittle manner. Fracture surface comprises facets of transgranular cleavage and the inclusion (Fe,Mn)S were located in the area of a cleavage facets.

Figure 10 illustrates the fracture surface of the specimen broken at –10 °C. The fracture surface appears to be embossed and specimen edges show little deformation. Fracture surface in Fig. 11 is composed of transcrystalline cleavage facets.

CONCLUSIONS

The mechanical properties of P295 GH steel gas pipeline after more than 40 years of its operation were analysed. The resistance to brittle fracture is the important characteristic to ensure operational reliability of pipeline. The results of microscopic analysis, tensile test, Charpy impact test and analysis of fracture surface after Charpy test showed:

- Microstructure of steel in the direction parallel to the longitudinal axis of the pipe was banded pearlitic-ferritic with the grains of non-uniform size.

- Elongation of specimens (L) directed parallel to pipeline longitudinal axis reached higher value, namely 33.0 % compared to specimens (T) perpendicular to the longitudinal pipeline axis with value 27.6 %.
- Sulfide inclusion (Fe,Mn)S elongated in the direction of steel sheet formation used to construction of pipeline.
- The transition temperature of P295 GH determined by absorbed energy criteria had the value –2 °C. On the basis of information from pipeline operator is the lowest operating temperature of the pipeline +4 °C in winter months. In our case was fulfilled requirement of pipeline operation at a temperature higher than transition temperature.
- Character fracture surface has varied depending on the temperature: it was observed mostly transgranular ductile fracture with dimple morphology at 20 °C. It was identified cleavage fracture with transcrystalline cleavage facets at the –10 °C. The embrittlement of the steel material represents a risk factor for the further operation of the pipeline

Acknowledgement

The study was carried out within the framework of the national project VEGA 2/0070/17.

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